A Feasibility Study for the Development of Sustainable Theoretical Framework for Smart Air-Conditioning

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Abstract

Air-conditioning as a technical solution to protect inhabitants from excessive heat exposure creates the challenge of expanding global warming and climate change. While air-conditioning has mostly been applied as an improvement to living conditions, health and environmental problems associated with its use frequently occur. Therefore, this study challenges and extends existing knowledge on sustainability-related to smart air-conditioning systems, where social, environmental and economic dynamics were considered. For instance, when exploring renewable-based options, advanced smart control techniques and profitability measures of air-conditioning reinforce the three pillars of sustainability. In addition to eradicating indoor health effects, this also helps to combat climate change through the system's sustainability.

As an exercise in conceptual modelling, the principal component analysis accounts for sustainable planning and its integration into the theoretical framework. The newly proposed photovoltaic solar air-conditioning was optimised using Polysun to demonstrate the significant application of solar energy in air-conditioning systems, thereby reducing the level of energy consumption and carbon emissions. The newly proposed fuzzy proportional-integral-derivative controller and backpropagation neural network were optimised using Matlab to control the indoor temperature and CO_2 level appropriately. The controller of the indoor environment was designed, and the proportional-integral-derivative control was utilised as a result of its suitability. The smart controllers were designed to regulate the parameters automatically to ensure an optimised control output.

The performance of photovoltaic solar air-conditioning in different temperate climates of Rome, Toulouse and London districts achieved a higher coefficient of performance of 3.37, 3.69 and 3.97, respectively. The system saved significant amount of energy and carbon emissions. The indoor temperature and indoor CO_2 possess an appropriate time constant and settling time, respectively. The profitability assessment of the system revealed its adequate efficiency with an overall payback period of 5.5 years.

Publications

a) Oye, T. T., Goh, K., Gupta, N., & Oye, T. K., "Assessment of Renewable Air-Conditioning Using Economic Feasibility Procedures", *International Journal of Innovative Science and Research Technology,* Volume 5, Issue 3, pp. 1375-1381, ISSN 2456-2165, March 2020.

b) Oye, T. T., Gupta, N., Goh, K., & Oye, T. K., "Theoretical Assessment of Sustainability Principles for Renewable Smart Air-Conditioning", *Journal of Environmental Management and Sustainable Development*, Volume 9, No. 3, pp. 18-46, ISSN 2164-7682, doi:10.5296/emsd.v9i3.16953, June 2020.

c) Oye, T. T., Gupta, N., Goh, K., & Oye, T. K., "A Feasibility Study for the Development of Renewable Air-Conditioning for Different Climatic Conditions", *Journal of Environmental Management and Sustainable Development*, Volume 9, No. 3, pp. 87-109, ISSN 2164-7682, doi:10.5296/emsd.v9i3.17459, September 2020.

d) Oye, T. T., Goh, K., Gupta, N., & Oye, T. K., "Development of Optimised Smart Indoor Control for Renewable Air-Conditioning", *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, IEEE Xplore, Glasgow, United Kingdom, pp. 175-179, ISSN 2572-6013, doi: 10.1109/ICRERA49962.2020.9242846, November 2020.

e) Oye, T. T., Gupta, N., Goh, K., & Oye, T. K., "Air-Conditioning and the Transmission of COVID-19 in Indoor Environment", *Journal of Environmental Management and Sustainable Development*, Volume 10, No. 3, pp. 18-46, ISSN 2164-7682, doi:10.5296/emsd.v10i3.18461, May 2021.

f) Oye, T. T., Gupta, N., Goh, K., & Oye, T. K., "Development of Sustainable Indoor Air Quality for Air-Conditioning System Using Smart Control Techniques", *Journal of Environmental Management and Sustainable Development*, Volume 11, No. 1, pp. 1-37, ISSN 2164-7682, doi: 10.5296/emsd.v11i1.19027, November 2021.

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Declaration

To the best of my knowledge, this thesis contains no copy or paraphrase of work published by another person, except where duly acknowledged in the text. This thesis contains no material that has been previously presented for a degree at Edinburgh Napier University or any other university.

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Abbreviations

AC	Alternating Current
AHU	Air Handling Unit
AI	Artificial Intelligence
AIS	Artificial Intelligence in Society
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
ARR	Accounting Rate of Return, %
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIEMS	Building Intelligent Energy Management Systems
CAC	Conventional or Customary Air-Conditioning
CAC&H	Conventional Air-Conditioning and Heating
CEN	European Committee for Standardisation
CI	Computational Intelligence
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COP	Coefficient of Performance
COP 21	21st Conference of the Parties
COVID-19	Coronavirus Disease 2019
DC	Direct Current
DHW	Domestic Hot Water
DOAS	Dedicated Outdoor Air System
EC	European Commission
EEA	European Environment Agency
EF	Emission Factor, kg of CO_2/Wh
EPA	Environmental Protection Agency
FLC	Fuzzy Logic Control
FR	France
GA	Genetic Algorithm
GHG	Greenhouse gas

GEA	Global Energy Assessment
HVAC	Heating, Ventilating and Air-Conditioning
HVAC&R	Heating, Ventilating, Air-Conditioning, and Refrigerating
HVASE	Heating and Ventilating, and Air-Conditioning Systems and Equipment
I/O	Input/Output
IAE	Indoor Air Environment
IAQ	Indoor Air Quality
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IOSH	Institution of Occupational Safety and Health
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return, %
IT	Italy
KF	Kalman Filter
L	Mechanical Energy, J
LOD	Level of Detail
MLP	Multilayer Perceptron
MPC	Model Predictive Control
MPP	Maximum Power Point
MW	Molecular Weight, g/mcl
NB	Negative Big
NG	Natural Gas
NM	Negative Medium
NN	Neural Network
NN-PID	Neural Network – Proportional Integral Derivative
NPV	Net Present Value
NS	Negative Small
nT	Number of time periods
PID	Proportional Integral Derivative
RT	Room Temperature, °C
SARS	Severe Acute Respiratory Syndrome
SBS	Sick Building Syndrome

SDGs	Sustainable Development Goals
SHW	Solar Heat Worldwide
SPE	Solar Power Europe
STC	Standard Test Conditions
TEPCO	Tokyo Electric Power Company
UK	United Kingdom
UN	United Nation
UNFCCC	United Nation Framework Convention on Climate Change
UV	Ultraviolet
VOCs	Volatile Organic Compounds
WCED	World Commission on Environment and Development

List of Symbols

A	Area, m^2
A_w	Area of the wall, m^2
Bn	Direct normal radiation arising from a narrow solid angle of 6℃ at sun's disk
B_9, B_{10}	Decoupling elements
B_{19}, B_{20}	Decoupling elements
C^*	Capacity rate ratio
C_l	The level of CO_2
C_t	Net currency inflow
C_0	Total initial investment
$CO_{2,save}$	CO_2 saving
$CO_{2conver\ elec}$	Emission rate for production of electricity 0.52
C_{ion}	Indoor CO_2 concentration at the moment when the ventilation system is turned on, ppm
C_{oco_2}	Outdoor CO_2 concentration ppm
C_p	Heat capacity, J/kg ·℃
C_{ico_2}	Indoor CO_2 concentration, ppm
Cs	Saline solution heat capacity
d	Diameter, m
Dh	Diffuse radiation by direct solar radiation
d_w	Thickness of the wall, m
e	Emittance
ε	Effectiveness
E_9, E_{10}	Transfer function matrix
E_{19}, E_{20}	Transfer function matrix
E_{AC}	Annual energy output, kWh
$E_{AC,d}$	Total daily AC energy generated by the photovoltaic system
$E_{AC,m}$	Total monthly AC energy generated by the photovoltaic system
$E_{battery}$	Power in the battery

E_{co_2}	Average CO_2 emanation rate of each person in the indoor environment
$E_{DC,d}$	Total daily DC energy generated by the photovoltaic array
$E_{DC,m}$	Total monthly DC energy generated by the photovoltaic array
$E_{el,tot}$	Overall electric utilisation of the entire system mechanisms
e_p	Specific potential energy, kj/kg
Eq_{ld}	Storage equipment load
EU_{mix}	Average values in Europe Union countries
f	Volume flow rate of the supplied air, m^3/s
FF	Wind speed – longitudinal and latitudinal part of the wind speed
G	Intensity of solar radiation
Gh	Global solar irradiation of a horizontal surface, $Wh/m^2/a$
H	Height
h_A & h_B	Specific convection fluids transfer of heat coefficients on the wall of each side, $W/m^3 .℃$
h_{air}	Convection heat transfer coefficients of air, $W/m^2 \cdot ℃$
h_{fg}	Heat of water evaporation
$h_{d,ps}$	Peak sun hours in a day
HR_S	Accustomed humidity ratio
$h_{(1\ to\ 10)}$	Thermodynamic condition
I	Electric current, A
I_{cl}	Clothing insulation, $℃/W$
$\mathrm{ICO_2}$	CO_2 intensity of the energy source
If_{ld}	Storage infiltration load
In_{ld}	Storage internal load
K_b	Thermal conductivity of common brick work, $W/m \cdot ℃$
K_{it}	Function of transfer gain
L	Length
m	Mass inside the volume (V) of individual system component
$\dot{m}$	Supply air flow rate
M	Activity level
m_1	Total mass of fluid in the tank (determined by the volume)

m_2	Water flow rate into the tank
$(mC_P)_{min}$	Minimum heat transfer capacitance of the outdoor unit, W/K
$(mC_P)_{max}$	Maximum heat transfer capacitance of the outdoor unit, W/K
N	Number of days in the month
N_d	Number of days in a year
NTU	Number of transfer units
η	Efficiency
η_c	Charge efficiency
η_{el}	Total electric consumption of the system
η_d	Discharge efficiency
η_{inv}	Inverter efficiency
η_0	Ratio of efficiency
ρ	Density, kg/m^3
P	Electrical power, W
ρ_a	Density of air, kg/m^3
p_a	Vapour pressure, kPa
P_{AC}	AC power output, kW
P_c	Battery charging energy
P_d	Battery discharging energy
$PE_{savings}$	Amount of primary energy of the system saved
$P_{el,CC}$	Electric power of the cooling circulation, kWh
$P_{el,HP}$	Electricity consumed by heat pump. kWh
$P_{DC,STC}$	DC power under STC
P_{DHW}	Electricity consumed by the pump serving the DHW, kWh
P_{HP}	Electricity consumed by the pump serving the heat pump, kWh
P_{OS}	Electricity consumed by pump serving the outdoor system, kWh
Pr_{ld}	Storage product load
P_{PC}	Electricity consumed by the pump serving the cold storage, kWh
ρs	Saline solution density
ρTs	Temperature of the density function

Q	Energy, Wh
$\dot{Q}$	Heat flow rate, W
Q	Heat
Q_A	Absorber: rejected heat
Q_{AHP}	Heating energy consumed from the auxiliary heat pump, kWh
Q_C	Condenser: rejected heat
Q_E	Evaporator: heat input (cooling effect)
Q_{ev}	Energy evaporation constituting the suitable outcome of the chiller
Q_G	Generator: heat input from solar
Q & W	Mechanical and net thermal energies
Q_{gain}	Energy gain in the hot water storage tank
Q_h	Work rate of heater, W
Q_{heater}	Supplied power through the stoppage element
Q_{HP}	Overall heating energy supplied by the heat pump
Q_{OU}	Heating energy consumed from the outdoor unit, kWh
Q_{HW}	Heating energy consumed from the hot water storage, kWh
Q_{Loss}	Energy loss in the hot water storage tank
Q_s	Supplied power through the solar accumulators
Q_{TEC}	Total energy consumption
Q_t & Q_s	Total cooling and sensible power
Q_v	Ventilator working power
r	Discount rate, %
R	Thermal resistance, $m^2.K/W$
R_c	Reference of CO_2 in the room
R_t	Reference temperature
Sa_f	Safety factor
St_m	Stanton number of mass transfer
t	Number of 30-minute time intervals in a day
τ	Time, s
T	Temperature, ℃
t_a	Air temperature

Ta	Ambient temperature, ℃
T_b	Building air-temperature
Td	Dew Point temperature, ℃
T_f	Final temperature
T_i	Indoor temperature, ℃
T_{ic}	Temperature of the room to be controlled
T_{il}	Initial temperature
T_{it}	Constant of the time
T_{ico_2}	Time constant of the indoor CO_2 control system, s
T_{ld}	Cold storage total load
Tr_{ld}	Storage transmission load
T_S	The air temperature
T_m	Collector average temperature
t_{mr}	Mean radiant temperature, ℃
T_o	Outdoor temperature, ℃
T_{om}	Mean outdoor temperature of the previous seven days, ℃
Ts	Temperature of the saltwater solution
t_p	Time period, h
U	Electric potential difference (voltage), V
UA	Coefficient area product
u_f	Final internal energy per unit mass inside the volume (V) at the end of time phase Δt
u_f	Heater work rate, (W)
u_i	Initial value
U_w	Total wall heat transfer coefficient, $W/m^2.$℃
$U-value$	Heat loss coefficient of the building, $W/K.m^2$
v	Relative air velocity, m/s
V_i	Volume of the room, m^3
$vol.\%$	Volume percentage, $(v/v)\%$
W_e	Daily consumed energy, kWh
$wt.\%$	Mass percentage, $(w/w)\%$

W_{HP}	Power consumed by the heat pump's compressor
W_P	Pump work
X_1 & X_2	Controllers' outputs
X_{ss}	Mass concentration for strong compound
X_{ws}	Mass concentration for weak compound
Y_1 & Y_2	System outputs
ΔPE_{save}	Energy savings of the system
ΔP_{elec}	Amount of energy saved from the consumption of photovoltaic system
ΔP_{HP}	Amount of energy saved from the use of auxiliary heat pump
α	Heat transfer coefficient, $W/m^2.K$
δ	Layer thickness, m
λ	Thermal conductivity coefficient, $W/m.K$
λ	The CO_2 decay constant s^{-1}

Chapter One

1.1 General Introduction and Background of the Study

Sustainability requires meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. The three bottom-line principles of sustainability namely, environment, economic and social are significant in considering the sustainability of air-conditioning systems (Saner et al. 2019). However, the real issue confronting mankind with respect to these three bottom-line principles of sustainability are whether human action is sustainable. According to Akadiri (2012) and Saner et al. (2019), a system framework is regarded as sustainable if:

a) The system considers the three pillars of sustainability, namely, the environment, economic, and social. While this study will focus on the three arms of sustainability, it will concentrate mainly on the strong sustainability aspect of the system and, or
b) The most efficient means of re-establishing the system's sustainability may necessitate a change in the system. In other words, by combining both renewable and smart control systems as a unique system for system sustainability, which improves human adaptation and occupant wellbeing.

Sustainability was first defined over 30 years ago and is now widely recognised as an important conceptual framework within which to situate municipal development and policy (Zhai and Chang, 2019). According to Dempsey et al. (2011), the basic influence between the related parts of sustainability has subsequently varied amid the understanding of the idea, which has prompted an assortment of municipal structures to be depicted as sustainable. As material utilisation and energy nodes, urban areas are causally connected to quickening worldwide natural deterioration and are not sustainable through themselves. Simultaneously, urban areas and their occupants can undertake significant work in accomplishing worldwide sustainability (Wilhite, 2009; Campbell, 2013; Zhai and Chang, 2019). The scholarly investigation of sustainable development currently holds an assortment of points of view and methodologies. It incorporates various practices and policies based on common agrarian utopianism in the direction of capital-intensive, large-scale client market growth (Aftab et al. 2013). The well-being of humans is at the focal point of investigation when considering the utilisation of air-conditioning systems (Kjellstrom et al. 2009; Lenzer et al. 2020). Likewise, climate change will generate excessive levels of heat exposure and air-conditioning will be required increasingly more in densely populated urban zones.

Consequently, the use of air-conditioning has moved from being a luxury to becoming a necessity for many inhabitants in their daily lives due to the hot summer climate. (Gugulothua et al. 2015). However, one of the most extreme problems confronting humankind in the 21st century is energy. Non-renewable energy sources, such as petroleum, natural gas and coal, have been the fundamental energy assets for human culture (Kirk et al. 2013). The consumption of non-renewable energy sources has caused and is still causing harm to the environment. By 2050, the demand for energy could be doubled, or possibly triple, as the worldwide populace develops, and emerging districts grow their economies (Gielen et al. 2019). This has recently raised concerns in sustainable development over climate change, global warming, accelerating environmental influences like ozone layer reduction, energy resource reduction, insufficient thermal comfort, health issues, high cost and possible supply problems (Yu and Lin, 2015). Although air-conditioning has mostly been used as a result of improvements in living conditions, health and environmental challenges related to use of air-conditioning systems frequently unfold (Buranyi, 2019).

Research studies by the Intergovernmental Panel on Climate Change (2007), Schulte and Chun (2009), Ford and Berrang-Ford (2011), and Moda et al. (2019) suggest that worldwide climate change will escalate indoor and outdoor heat loads and can damage wellbeing and harm work profitability for many individuals. Recent research subsequently reveal that the climate crisis hit the headlines when the UK experienced its warmest winter day in February with a high peak temperature of 38.7°C on July 25, 2019, in Cambridge (Watts, 2019). Moreover, Henning (2009) and D’Amato et al. (2018) suggest that air-conditioning is a typical specialised answer to issues of expanding temperatures, which incorporates both humidity and temperature control of the Indoor Air Environment (IAE). The use of air-conditioning increases the level of energy consumption and carbon emissions. It leads to climate change if the source of energy is unrenewable (Campbell, 2013). The role of urban areas in sustainable development has turned out to be increasingly conspicuous because of the developing urban population around the world (Dempsey et al. 2011; Riffat et al. 2016).

Consequently, studies suggest that IAQ (Indoor Air Quality) might be a higher priority than outside air quality since inhabitants devote over 70% of their time indoors (Guo et al. 2012; Schieweck et al. 2018). Air-conditioning system applications are known to change the IAQ by means of cooling, dilution, humidification and filtering the outside air entering the space occupied (Kukadia and Upton, 2019; Saran et al. 2020). Moreover, the purpose of most air-conditioning systems is to provide satisfactory IAQ and thermal comfort for inhabitants. A study by Seppanen and Fisk (2002) established that there is an expansion in the commonness of Sick Building Syndrome (SBS) somewhere in the range of 30% – 200% in structures with air-conditioning when contrasted with normal ventilation systems. Research suggested that deaths brought about by Legionnaires' illness even happened in air-conditioned structures (Prussin et al. 2017). In 2003 and 2019, SARS (Severe Acute Respiratory Syndrome) and COVID-19 (Coronavirus Disease 2019) happened, respectively; these occasions are an admonition for indoor environmental issues identified with air-conditioning systems. Any realistic person would agree that indoor environmental issues still exist in numerous mechanically ventilated and air-conditioned structures, even though current standards might be met. One of the results of the overall energy crises of the 1970s is the municipal acknowledgment of energy-saving importance (Levasseur et al. 2017). The structures built from that point forward are increasingly airtight and use a lot of protection materials to limit energy loss through the structure envelope. Natural air is diminished in air-conditioning systems in order to decrease their energy consumption (Levasseur et al. 2017). Chemical products and engineered materials (for instance, decorating and building materials) have broadly been used indoors (Schieweck et al. 2018). The mix of low ventilation rates and the existence of various manufactured synthetics brings about raised convergences of indoor molecule poisons and Volatile Organic Compounds (VOCs) (for example, toluene, formaldehyde and benzene). This is esteemed to be a noteworthy contributing influence to compound extreme hypersensitiveness (Wang et al. 2004a; Schieweck et al. 2018). As a result, Joshi et al. (2006) and Jiang et al. (2016) propose that controlling quality of air produced by air-conditioning systems is critical, given that a significant portion of the population now faces the dangers of lung chronic ailments, such as chronic bronchitis and asthma, which are primarily caused by airborne pathogens. Even though microorganisms and organisms existing in the air might perhaps be defeated by the germicidal lights, such radiation does not assist in decreasing carbon emissions or regulating IAE temperature and foul odours (Yu and Lin, 2015; Jiang et al. 2016; Saini et al. 2020). Nevertheless, there is a need for a smart control system that better regulates and improves the human adaptation to the well-being of occupants, which is focussed on embracing sustainable future developments.

Albeit smart/intelligent air-conditioning is a system with innovative computational dimensions and utilises a variety of occupational and environmental parameters to give occupants the ideal intertemporal comfort, it is restricted to foreseen retail energy costs (Thomas et al. 2012; Auffenberg et al. 2018). Lessening the degree of energy utilisation and guaranteeing an ideal level of comfort in designing a smart air-conditioning system contributes considerably to the level of absolute energy utilisation (Yu and Lin, 2015). Areas like assembly rooms, indoor arenas and meeting lobbies contribute as much as 75% of the overall energy consumption related to air-conditioning utilisation (Shahid et al. 2016). However, Wang et al. (2012) and Omar (2018) proposed that the decrease of energy utilisation and CO_2 (carbon dioxide) in buildings requires an intelligent control system because energy consumption has been legitimately connected with wellbeing and eventually to operational expenses. The structure's indoor environmental essential factors of comfort as indicated by the users' inclinations are IAQ, visual and thermal (Siddqui et al. 2015; Auffenberg et al. 2018). Thus, studies have demonstrated that intelligent Fuzzy Logic Control (FLC) models produce promising outcomes and can be applied to a considerable number of cases in structures while showing a broad overall energy utilisation decrease and a decline in CO_2 as opposed to the current control system and accomplishing the level of ideal comfort (Yu and Lin, 2015; Siddqui et al. 2015; Kambalimath et al. 2020). In this manner, controlling system designers have been taking a step towards creating different control methodologies for air-conditioning systems to optimise the air-conditioning performance. Studies uncover that indoor structure environmental control systems can be mostly characterised into two classifications as per the methodologies utilised: computational intelligent procedures and conventional controllers (Siddqui et al. 2015; Shahid et al. 2016). The Proportional Integral Derivative (PID) controller is one of the most well-known air-conditioning system customary controllers. The Neural Network (NN) and intelligent controller have turned out to be applied as a flexible, accurate and fast device in the control methodology design, modelling and simulation of air-conditioning (Doroshenko, 2017). Through an appropriately structured controller, the performance of an air-conditioning system can be altogether improved. Then, it merits creating innovative control techniques to optimise the energy efficiency and indoor environmental quality of air-conditioning systems.

Ongoing investigations have shown that structures are accountable for the utilisation of around 40% of the essential energy and the outflow of about 33% of Greenhouse Gases (GHGs) on the planet (International Energy Agency, 2018). Similarly, established researchers have committed significant effort to securing housing energy sustainability in two primary ways: those utilising renewable energy for the remaining tasks and those reducing outside energy supply (Gugulothua et al. 2015; Zheng et al. 2016). In two different ways, solar assets are picking up acceptance since they increase energy autonomy and sustainability simultaneously, contributing to almost zero effect on the environment (Zheng et al. 2019). However, solar air-conditioning involves changing solar energy into conditioned air in the indoor environment. It embraces the universal air-conditioning task with more positive environmental effects and less energy usage. Solar cooling reduces energy requirements, operational expenses and the emissions of GHGs (Jafari and Poshtiri, 2017). The adverse effects of air-conditioning reveal the need to consider the use of renewable energy sources. Hao and Ghaffarian (2012), and Zheng et al. (2019) propose that it is essential to replace conventional energy with solar energy for the end goal of sustainable growth. Climate change mitigation, for instance, using renewable energy sources and other sustainable approaches to reduce heat exposure, is needed to make future urban areas more climate resilient. Therefore, solar air-conditioning with a smart indoor system is a reasonable answer to sustainable smart air-conditioning prerequisites.

1.2 Research Aim

The aim of this study is to challenge and extend existing knowledge on sustainability-related to smart air-conditioning systems. Social, environmental and economic dynamics were considered.

1.3 Research Objectives

To achieve the research aim, the following research objectives have been set:

i. Conducting a comprehensive literature review of sustainable-based smart air-conditioning systems with a holistic view;
ii. Development of scenario modelling of sustainable-based smart air-conditioning;
iii. Using computer model to analyse efficiency and effectiveness of the developed sustainable theoretical framework;
iv. Assessment of the economic impact of the renewable-based system;
v. Refine and validate the theoretical framework, resulting in the sustainability of the system.

1.4 Research Questions

A number of research questions have been drawn from the background study in Section 1.1, as well as the stated objectives in the preceding section.

i. Is renewable energy from smart air-conditioning likely to be energy efficient and reduce the level of energy consumption and carbon emissions?
ii. Is fuzzy PID likely to ascertain the desired level of indoor temperature for optimum thermal comfort?
iii. Can a PID controller with backpropagation NN tackle unwanted indoor CO_2 and maintain the desired IAQ without health effects?
iv. Is the proposed system likely to be sustainable?

1.5 Research Approach

The research theoretical framework approach designed for this study to efficiently solve the research problems is revealed in Figure 1.1.

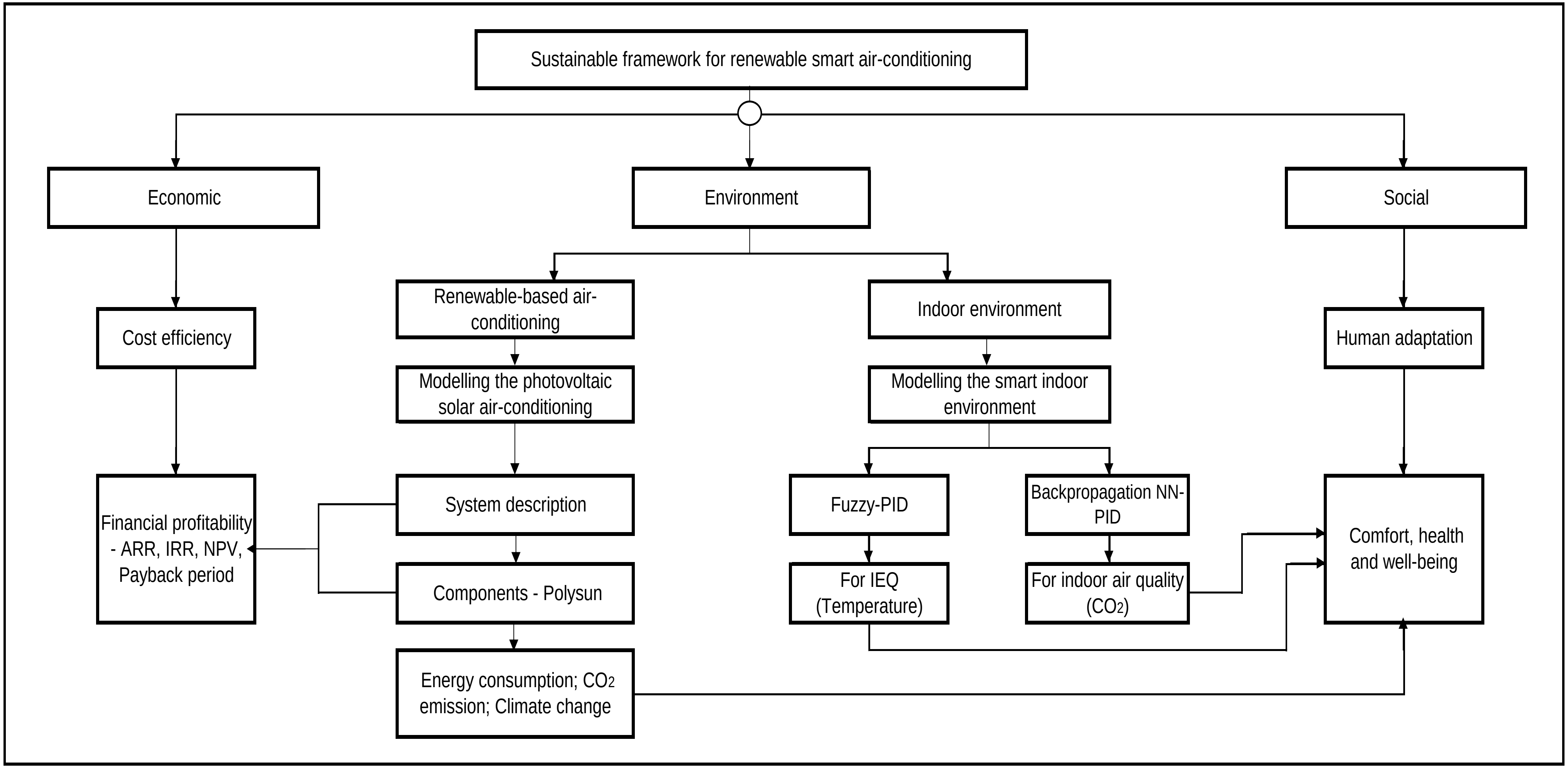

Figure 1.1: Research theoretical framework for sustainable smart air-conditioning.

This analytical grid is subsequently augmented by the three pillars of sustainability, namely environmental, social and economic, which, in turn, unfold the basis of sustainable smart air-conditioning in this study. The theoretical framework of the proposed system is thoroughly designed as an adaptation strategy of the three bottom line principles of sustainability, where the environment is technically influenced by both social and economic sustainability. Therefore, moving from top-to-bottom; this, in turn, indicates two forms of sustainable environment for sustainable-based smart air-conditioning, namely, renewable air-conditioning and the indoor environment. The renewable-based air-conditioning reveals the modelling of the photovoltaic solar air-conditioning while the modelling of the indoor environment reveals two forms of smart indoor environment namely, fuzzy PID and backpropagation NN based on PID for the manageability of both indoor temperature and indoor CO_2, respectively. Therefore, attention is drawn to the connection between the environmental and social sustainability of the system, where photovoltaic solar air-conditioning (energy consumption, CO_2 emissions and climate change), indoor environmental quality (temperature), and the IAQ (CO_2) are horizontally linked to the wellbeing and comfort of the inhabitants or users of the building through human adaptation. Moving horizontally, particular attention is also drawn to the connection between both the environment and the economic sustainability of the system, where the depicted system and components unfolded the financial profitability of the system namely, NPV (Net Present Value), IRR (Internal Rate of Return), ARR (Accounting Rate of Return) and payback period, through the cost efficiency of the proposed system.

1.6 Research Hypothesis and Contributions

The hypothesis of this study underpins that renewable energy and smart control of air-conditioning are key drivers in sustainability planning that not only tackles health effects but also combats climate change. The literature review provides evidence of the research gap in this field.

The principles of sustainability, namely, environmental, economic and social, which, in turn, reinforce renewable and smart options for more sustainable and energy-efficient control systems, are the main points in developing a sustainable theoretical framework for future smart air-conditioning systems. Past issues and current challenges highlight the requirement for detailed analysis of environmental, economic and social aspects of smart air-conditioning systems focused on supporting sustainable future developments.

The projected growth in the cooling loads for inhabitants' comfort needs in residential and commercial buildings calls for substitutes to conventional energy supplies to reduce energy consumption and lessen global GHG emissions. Renewable energy sources such as solar energy are available at the same time when the room air-conditioning is required. Solar energy is a sustainable, clean energy source that comes from natural sources or processes that are constantly replenished. Therefore, photovoltaic solar air-conditioning has been selected in this study as a sensible alternative to environmentally unfriendly systems for promoting Sustainable Development Goals (SDGs) in the built environment.

Indoor temperature is one of the main factors that changes the quality of the indoor environment. The control approach for indoor air temperature has been designed in this study. The challenges and difficulties of indoor temperature control have been the mismeasurement occurrence and time delay. Therefore, the designed controller must have good adaptability, small overshot, quick response, and an intelligent algorithm. Also, the IAQ is another key factor that influences the indoor environment quality, particularly the health and wellbeing of building inhabitants. Control of IAQ is an intricate issue because there are several sorts of indoor air pollutants. The indoor CO_2 concentration is applied as the control signal of this control approach. Indoor CO_2 control challenges involve uncertain parameters' disturbance and mismeasurement occurrences. Therefore, the controller must have good adaptability, stability and an intelligent algorithm.

To evaluate the possibility of improving the indoor environment quality with advanced control technologies, a FLC-PID controller is designed for the improvement of indoor environment quality. The control algorithm is developed based on the fuzzy PID controller's performance for the improvement of the indoor environment. Also, the controller of PID is applied for the control of indoor CO_2 concentration. The NN is utilised for PID parameter tuning and the backpropagation algorithm is employed for updating the weights of the NN for appropriate control of indoor CO_2.

This thesis contributes to cover this research gap by developing a sustainable-based framework through examining, applying and consolidating the three bottom-line principles of sustainability, namely, environmental, social and economic dynamics, for the overall sustainability of renewable smart air-conditioning. Therefore, this study deliberated upon the below to achieve a strong sustainability of the system.

a) The feasibility of combining both the renewable and indoor smart systems as a unique system to reflect the greater sustainability of the system is explored.
b) Environmental sustainability as a core part of the system framework for photovoltaic solar air-conditioning and the indoor environment. In other words, combatting the level of energy consumption and carbon emissions vis-à-vis eliminating the major indoor air pollutant (CO_2) while maintaining the maximum IAQ with the use of advanced smart indoor systems.
c) Sustainable smart system that clearly consider the three pillars of sustainability namely environment, economic and social, as a whole
d) A methodological sustainable theoretical framework that is underlined by the three sustainable principles as a pathway to achieving the overall sustainability of the system.

1.7 Thesis Structure

The thesis report is structured as follows:

Chapter One: This chapter includes a clear introduction to the background of the study, the logic behind the proposed research and the purpose of the study, the aims and objectives of the research, the research's sustainable theoretical framework, the hypothesis and contribution of the research, and the structure of the research.

Chapter Two: This chapter consists of a critical appraisal of previous research and publications carried out on sustainability and air-conditioning; it focuses upon the principles of sustainability for air-conditioning. This chapter also reveals the existing issues between air-conditioning and the system sustainability strategy by way of revealing the three bottom line principles of sustainability, namely, environmental, social and economic, that are connected with air-conditioning sustainability. The system sustainability study strategy revealed the indicators of environmental, economic and social air-conditioning sustainability for the purpose of achieving the overall sustainability of the solar photovoltaic smart air-conditioning system. The problems with the existing research are summarised. A further study is suggested on the requirement for renewable-based air-conditioning and smart computational control technologies for healthy IAE quality.

Chapter Three: This chapter focussed on a critical evaluation of the requirement of the renewable-based air-conditioning and the smart computational control innovation. Adsorption and absorption solar air-conditioning are introduced while highlighting the efficiency and strategy principles of both. This chapter also unfolded the pathway for achieving a strong sustainability associated with the use of air-conditioning systems. Previous researchers were unsuccessful in their approach to sustainability. Research concentrated on one or two aspects of sustainability and thereby leaving a significant gap in knowledge. The indoor environment which constitutes the IAQ, energy efficiency and the requirement of smart control strategy that is focussed on sustainability approach is discussed in detail. Discrepancies in gaps and options in the study area are scrutinised and are employed as the source for the research thesis modelling approach.

Chapter Four: This chapter evidently focussed on conceptual modelling of photovoltaic solar air-conditioning and the indoor environment. The modelling of photovoltaic solar air-conditioning is designed with the goal of achieving a strong sustainability strategy. The system modelling technique with its justification and basis in an existing study is also discussed in this chapter. The overall sustainable mechanism of the photovoltaic solar air-conditioning system was deliberated upon. This chapter also deliberated upon the IAE – the indoor temperature and indoor CO_2 control. Subsequently, developments of the two newly designed controllers are presented together with their algorithms, structures and the controllers' working process. For strategies of the control process, the designs were grounded upon the challenges and difficulties of individually controlling factors of the indoor environment.

Besides, the performance of the controllers is theoretically scrutinised and their indoor environmental control potentials and advantages are synopsised.

Chapter Five: This chapter presents the simulation results of the photovoltaic solar air-conditioning and the smart indoor environmental system controllers, performed on the platforms of Polysun and Matlab, respectively. The simulating tests of photovoltaic solar air-conditioning and the control processes are technically based upon the modelling of photovoltaic solar air-conditioning and the indoor environment that were discussed in the previous chapter. Simulating tests were performed to evaluate the proposed photovoltaic solar air-conditioning, fuzzy PID controller for indoor temperature and backpropagation NN grounded upon PID controller for the control of IAQ. Consequently, the simulation results of the photovoltaic solar air-conditioning and the smart indoor environmental system were discussed while thoroughly considering the sustainability and efficiency of the system – that is, the system controllers' performance together with stability, adaptability, speed response and overshoot, which, in turn, portrays the social sustainability of wellbeing and comfort of the inhabitants.

Chapter Six: This chapter reveals the economic assessment of the proposed system by means of calculating the ARR, NPV, IRR, and payback period – the financial profitability of the system. The advantages and drawbacks of each financial assessment indicator are subsequently considered for proper assessment of the system. The financial profitability of the system is analysed and discussed while considering the economic sustainability and profit of the system. This chapter demonstrates how significant savings can be achieved through utilising an economically sustainable and renewable means of technology – photovoltaic solar air-conditioning technology.

Chapter Seven: This chapter unfolds the discussion and external result validation of the study. It offers the conceptual issues of sustainability and the assessment of a sustainable theoretical framework. The three bottom-line principles of sustainability, namely, environment, economics and social, are discussed in relation to the scope of the study. Climate change, human health and wellbeing are also discussed in relation to sustainability principles. This chapter likewise presents the outcome of the semi-structured interviews with the system experts, which were used to externally validate the proposed system.

Chapter Eight: This chapter presents the overall conclusion of the study. It systematically summarises the entire study and reviews the stated research objectives. This chapter also details the main findings from the study and discusses their implications for the sustainable theoretical framework. This, in turn, presents the academic significance and relevance to practice. It also presents the contribution to knowledge of the study and recommendations for future studies.

Chapter Two

2.0 Sustainability and Air-Conditioning

2.1 Introduction

In this chapter, a recent study is reviewed on the principles of sustainability for air-conditioning. It further considers the air-conditioning and existing issues, which, in turn, presents the system sustainability study strategy through the three pillars of sustainability, namely, environmental, social and economic. Various perspectives of sustainability and sustainable development have been proposed, along with their connection to sustainable-based air-conditioning. The intrinsic relationship that climate change actions, responses, and impacts have with equitable access to sustainable development has been discussed. The air-conditioning issues in association with health, wellbeing, carbon emissions and energy consumption were likewise discussed. Moreover, air-conditioning, which poses one of the most significant threats to the built environment, must be sustainable by considering renewable energy, optimum thermal comfort and the wellbeing of the indoor occupants. Therefore, the sustainability indicators cover the environmental, social and economic dynamics that subsequently unlocked the key domain upon which this study is based. Similarly, worldwide and localised investigations connecting climate factors and sustainability with solar photovoltaic smart air-conditioning are deficient, which, in turn, reveals the necessity to reduce the level of energy consumption and carbon emissions that cause climate change and health effects on inhabitants. Research explains that thorough information is required in relation to the impacts of expanding air-conditioning use, which leads to energy consumption, carbon emissions and health effects. The mitigation of climate change, for example, utilising renewable-based energy sources and smart technologies, particularly photovoltaic electricity generation to power smart air-conditioning, has been considered. More sustainable procedures to reduce high temperature exposure is needed to make future municipal zones more climate resilient.

2.2 Principles of Sustainability for Air-Conditioning

The most generally utilised meaning of sustainability is the Brundtland report's meaning of sustainable development, which, according to Mebratu (1998), means *meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987)*. Moreover, sustainability usually alludes to economic, social and environmental; albeit the accurate connection between environmental, social and economic sustainability is vague (Stoddart et al. 2011). Research studies by Darker et al. (2006) and Ben-Eli (2015) portray the connection between the economy and the environment as pursues: distinctive systems give the specific circumstance and sustenance to social systems and subsequently must be regarded, supported, and continued. Social systems give the reason and unique circumstance for economic systems. Especially, the economy is a subset of society which thus is a subset of the environment. As indicated by Van der Vorst et al. (1999) and Thomas (2015), environmental sustainability requires economic and social sustainability relies on environmental sustainability. On the other hand, the three areas of sustainability can be treated with equality as suggested by Newton (2003), Thomas (2015) and Hak et al. (2016). This implies that the three pillars of sustainability can be treated with equality to achieve a sustainable-based air-conditioning.

Consequently, the real issue confronting mankind with respect to the three bottom line principles of sustainability is whether human action is sustainable. More importantly, can human movement as accomplished at present withstand an economic, social and healthy environment? Also, through what means can humans be able to change the air-conditioning (system) technique with the goal that the environment and society can withstand it? These are worldwide inquiries, air-conditioning influences society and the environment in an enormous way. The impacts of a system in one territory may influence the society and environment in regions far away. In this study, the system is ‘air-conditioning’. On a fundamental level, it eliminates the heat from one region and supplants it with chilled dry air and hot air is expelled, typically to the outside environment. It incorporates sustainability with the indoor smart control of air-conditioning. Additionally, there are inquiries regarding the future: can the society and environment be continued both for the time being and in the long run? Social and environmental harm can be created temporarily; however, it might have great impacts; it can take numerous years to reverse the harm done by one year's movement.

The end goal of this investigation is the sustainability of smart air-conditioning – that is, the economic, social and environmental effects of the system. This is taken to be sustainable if, accepting its uncertain continuation, the impacts of that system will add to empower the environment, economic viewpoint and the human culture to accomplish and keep up a condition of comfort. The proof provided suggests that, as far as the sustainable definition is concerned, the present system is unsustainable. The inquiry into whether a system is sustainable should be considered in light of the three bottom line principles of sustainability. However, there are different interpretations of sustainable development, as presented in Table 2.1.

Table 2.1: The sustainable development challenging opinions.

Interpretations of Sustainable Development			References
ECO-CENTRIC Interpretation	Environmental	Focusing on the consumption of resources, this approach seeks to avoid having a lasting adverse impact on the world's stock of natural resources.	Meadows et al. (1972); Bruntland, (1987); Borland and Lindgreen, (2013).
	Ecological	The ecological approach emphasises the characteristics of living organisms in communities, such as the ability to self-regenerate, self-sustain and respond to change.	Bruntland, (1987); Washington et al. (2017); Molina-Motos, (2019).

ANTROPO-CENTRIC Interpretation	Endurance	Sustainability is achieved by undertaking activities which produce lasting benefits, like training, or deal with long-term problems.	Local Agenda 21, (1996); Jakobsen, (2016).
	Demand Based	Undertaking activities that encourage people to live in communities, equating the definition with popularity and/or quality of life.	Smith and Patterson, (1999); Youatt, (2017).
	Environmental	This approach seeks to optimise both environmental and human resources, with an emphasis on democratic and participative outcomes.	Hatley, (2016); Kopnina et al. (2018).

Subsequently, there have been continuous investigations, particularly all through the 1990s, into two kinds of sustainability, which have contrasted for the most part as far as the expenses brought about in accomplishing them were considered: Weak Sustainability and Strong Sustainability, as demonstrated in Table 2.2 (Bell and Morse, 1999; Davies, 2013). Hence, weak sustainability can be identified with the anthropo-driven position and strong sustainability can be identified with an eco-centric translation of sustainability.

Table 2.2: Sustainability explanations

Sustainability explanations		References
Strong sustainability	It takes little consideration of the financial or cost aspects of attaining sustainability and focuses mainly on the environment. Some equate this with so-called ecological sustainability.	Bell and Morse, (1999); Davies, (2013).
Weak sustainability	The financial and cost aspects associated with attaining sustainability are important and typically based on a cost-benefit analysis, which inevitably involves trade-offs between the environment and other social and economic benefits. This can be equated with some sort of economic sustainability where the emphasis is on the allocation of resources and levels of consumption.	Bell and Morse, (1999); Davies, (2013).

For the Economist (2009: 2017), associated with the meaning of the three pillars of sustainability and sustainable development are the different hypothetical frameworks given inside findings endeavouring to help our comprehension of sustainability. However, the most commonly used of these theoretical models of sustainability is the Three Arms Concerns – thereby applied as the theoretical framework origin for the sustainability of smart air-conditioning.

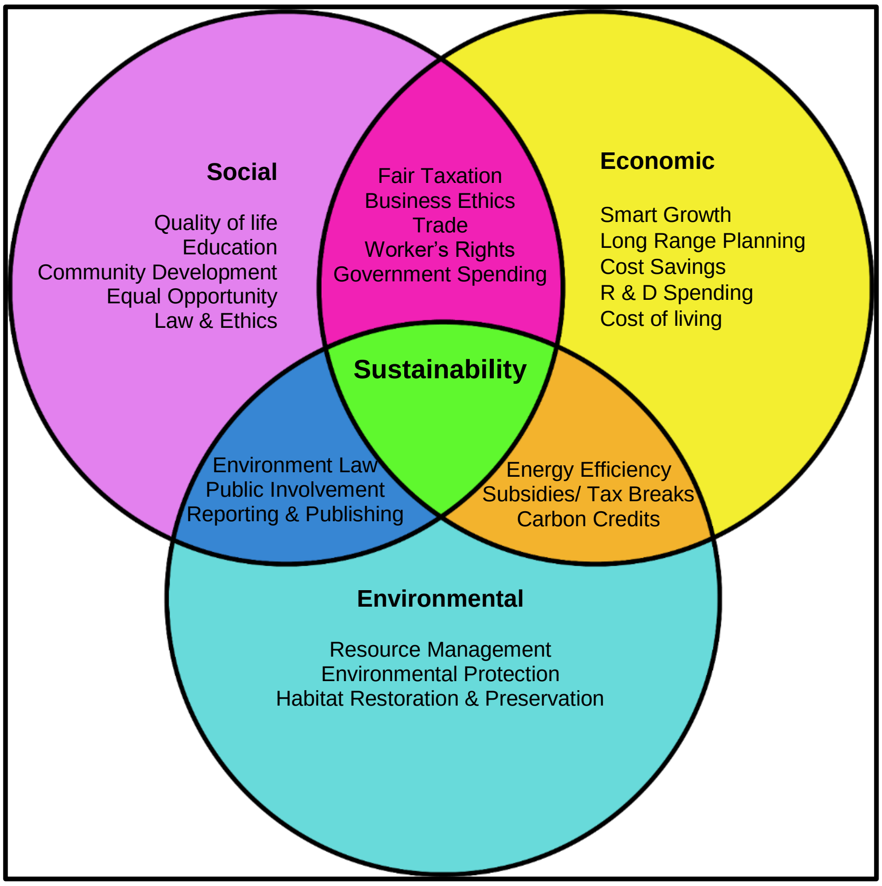

Figure 2.1: The three spheres of sustainability (Wanamaker, 2020).

Despite the fact that the framework demonstrated in Figure 2.1 commenced from the business world, it has now turned into a by and large acknowledged framework for the achievement of a system sustainability, as it obviously proves the significance of the interchange between environmental, economic and social performers in the making of sustainable development. Thus, the plan of sustainable air-conditioning proposed that the three circles of sustainability are all equivalent in significance, exhibiting the likelihood of a dimension playing field. Yang (2019) and Wanamaker (2020) recommended that such substitutions are crucial to actualising the standards of sustainable development for a system. However, Poston et al. (2010), Zabihi and Leila (2012), and Akadiri et al. (2012) earlier suggested that most of the current systems used inside the built environment for a system receive a technique that looks to adjust the three arms of sustainability, trying to accomplish a development that adjusts economic costs, social change and the unavoidable environmental results.

2.3 Air-Conditioning and the Existing Issues

A number of research studies characterised air-conditioning as a combined procedure that performs numerous purposes at the same time (Goetzler, 2016; Seyam, 2018). It conditions the air, conveys it, and acquaints it with the habituated space. It gives cooling and heating from its housetop units or focal plant. It likewise keeps up with and controls the air movement, sound dimension, temperature, pressure differential and air cleanliness in a space inside fore-ordained breaking points for the solace and wellbeing of the inhabitants of the habituated space (Wang, 2000; Seyam, 2018). The term HVAC&R is an abbreviation of Heating, Ventilating, Air-conditioning, and Refrigerating (McDowall, 2006). Likewise, the mix of procedures in this ordinarily received term is proportional to the present meaning of air-conditioning. Since all these individual segment procedures were created before the more complete idea of air-conditioning, the term HVAC&R is regularly used by professionals (Wang, 2000; Darling, 2018). Similarly, air-conditioning frequently utilises a fan to disperse the moulded air to a consumed space, for example, a building or a vehicle, to improve IAQ and thermal comfort. Electric refrigerant-based air-conditioning components go from little units that can cool a little room, which can be conveyed by a solitary grown-up, to monstrous units introduced on the top of office towers that can cool a whole building (Seyam, 2018). Also, cooling is done on a regular basis using a refrigeration cycle; however, most of the time, free cooling or evaporation is used. Air-conditioning can likewise be made dependent on subterraneous funnels (which disperse the heated refrigerant to the ground for cooling) and desiccants (chemicals that eliminate vapours from the air) (Wang, 2000; McDowall, 2006; Darling, 2018).

Thus, studies explain that people are naturally introduced to an antagonistic environment, yet the level of hostile atmosphere fluctuates with the period of the year and with the geological area (Goetzler, 2016; Seyam, 2018). This implies that air-conditioning arguments may be based solely on climatic considerations, which, while valid in subtropical and tropical regions, are not valid in cool climates with industrialised social buildings and rising ways of life. Jones (2001) and Goetzler (2016) explain that air-conditioning is essential for the accompanying reasons, namely, business machines, electric lighting and heat, and gains from daylight. Specifically, it may cause horrendously high temperatures in rooms, except if windows are opened.

In the event that windows are opened, at that point, even moderate drought rates cause extreme breezes, ending up more terrible on the upper floors of tall buildings. Besides, if windows were opened, dirt and noise enter and are questionable, ending up more undesirable on the lower floors of buildings, especially in industrial regions and municipal regions (Date, 2017). Regardless, the comfort given by normal airflow via open windows is efficacious for a profundity of *ca.* 6 meters from the coating (Goetzler, 2016). For it pursues that the inner regions of profound buildings will not generally profit at all from opened windows. Combined with the requirement for high power ceaseless electric lighting in these principal zones, the absence of satisfactory ventilation implies a proper composition of uneasiness for the inhabitants (McLachlan, 2016). A study by Jones (2001) proposed that mechanical ventilation without refrigeration is just a partial solution. It is true that it provides a controlled and uniform means of air distribution in place of the unsatisfactory results obtained with open windows (the vagaries of wind and stack effect, particularly with tall buildings, produce discontinuous natural ventilation), but tolerable internal temperatures will prevail only during the winter months. For a significant part of the spring and fall, just as in the late spring, the inner room temperature will be a few degrees higher than that outside, and it will be important to open windows to expand the mechanical ventilation (Wang, 2000; Jones, 2001; Date, 2017).

Research studies by Jones (2001) and Date (2017) further explained that the structure details for a wellbeing condition are planned to be the structure for giving an agreeable environment to individuals consistently, within the sight of sensible heat losses in winter and realistic heat gains in summer. Also, dehumidification would be accomplished in the summer. However, the relative stickiness in the habited space would be permitted to decrease as winter drew closer. For ASHRAE (2016), there are two reasons why this is adequate: first, people are agreeable inside a fairly enormous scope of humidity conditions, from *ca.* 65% to *ca.* 20% and, furthermore, if single coating is utilised, it will make the internal surfaces of windows stream with consolidated humidity, and it is endeavoured to keep up too high humidity in winter. McLachlan (2016) suggested that significant market for air-conditioning is to manage office obstructs in urban zones. Subsequently, the increasing area costs have prompted the development of profound arrangements and tall buildings that must be air-conditioned, and engineers discovered that these could receive an expansion in lease that would be greater than the pay for the capital devaluation and running expense of the air-conditioning introduced (Al-horr et al. 2016). The basic component of wellbeing conditioning means to create an environment which is agreeable to most of the inhabitants (Wang, 2000; ASHRAE, 2016; McLachlan, 2016). Fundamentally, Jones (2001) and Al-horr et al. (2016) recommended that a definitive in well-being of air-conditioning may never be accomplished, yet the utilisation of air-conditioning helps extensively in fulfilling many people's needs and is basic. The following subsections systematically presented the effects of air-conditioning.

2.3.1 Health and Wellbeing

Research studies by Parsons (2003) and Cheshire (2016) suggest that when the surrounding temperature comes to or surpasses the human body's centre temperature of 37°C, there are well-archived physiological impacts on the human body, presenting dangers to some organ systems and, furthermore, making it logically harder to work lucratively. As the centre temperature rises, the skin's blood stream increases, and perspiring starts. Perspiring is an incredible method for dispelling heat, be that as it may; it also puts a stress on the human body, as drying out will occur whenever lost fluid is not supplanted (Lundgren, 2014; Cheshire, 2016). Parsons (2003) earlier explained that at body centre temperatures past 38 – 39°C, there is an increased danger of heat weariness and past these temperatures, heat stroke and other temperate illnesses can happen. Wellbeing outcomes range from dehydration, sores, and heat weakness to kidney distress and demise (Gao et al. 2018). The body's heat parity is controlled by the surrounding air, intense temperature, air development, moisture, metabolic heat, and the attire worn by human physical movement (Parsons, 2003; Gao et al. 2018). When confronting expanding heat levels as a result of climate change, these physiological breaking points will happen every time, and choices to cool physiologically and behaviourally will turn out to be increasingly troublesome, irrespective of familiarised people (Kjellström et al. 2009; Stillmanm, 2019). Figure 2.2 blueprints the pathways for wellbeing and physiological impacts.

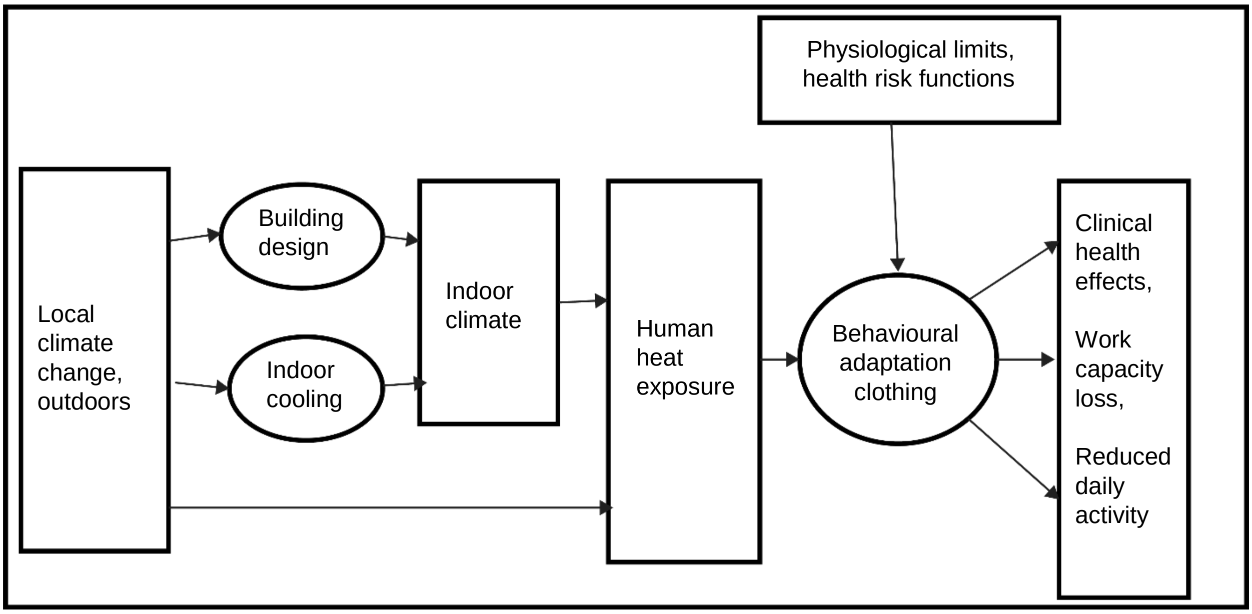

Figure 2.2: Extreme heat exposure, wellbeing impacts and climate change (Kjellström et al. 2009).

As indicated by the Intergovernmental Panel on Climate Change (2007: 2018), climate change will prompt variations in surrounding temperature, stickiness, wind speed, precipitation and cloud cover, influencing energy mandates in various ways. Also, the Fourth Evaluation Report of IPCC states that heat waves, hot evenings and hot days have progressed towards becoming and will turn out to be increasingly common over most land zones. A heating of 0.8°C at present has been seen above pre-industrial levels (IPCC, 2018). In spite of the fact that, the worldwide network has conceded to holding warming beneath 2°C during this century so as to avert risky climate change; current emission patterns put the world conceivably on a way towards 4°C heating inside the century and 6°C for the following century (World Bank, 2012). This converts into phenomenal warmth waves and long-haul heat contact in numerous spots and hence a substantial reliance and requirement for indoor cooling systems (World Bank, 2012, IPCC, 2018).

Kjellström et al. (2009) and Cronin et al. (2018) suggest that the undesirable effects of expanded energy costs for cooling are anticipated to be grouped in the subtropics and tropics, where a large portion of the total population lives and is quickly developing. In a considerable number of these territories, the most extreme temperatures during the hottest part of the year are above or near to 40°C and are expected to rise (Kjellström et al. 2009). The limit to keep up wellbeing and every day exercises is much of the time circumvented in these zones (Cronin et al. 2018). Therefore, air-conditioning is probably going to be progressively utilised all year around in homes and work environments (IEA, 2018). At the local scale, impressive effects can be realised, especially in South-East and South Asia, where energy interest for private air-conditioning built in excess of multiple times in 2001 in contrast with 2000, with an overall 7% development for every year (IEA, 2018). This growth is without the extra effects of climate change, which may signify an additional half in utilisation to this. The vast majority of the anticipated development in air-conditioning is relied upon to happen in Asia, while the utilisation in Africa will develop all the more gradually (Isaac and van Vuuren, 2009; IEA, 2018).

2.3.2 Emissions of the Greenhouse Gas

Lundgren and Kjellstrom (2013) and IPCC (2018) suggested that the mitigation of climate change converts into the balance of GHG clusters in the air at a dimension that would forestall risky anthropogenic intrusion into the climate system. Worldwide relief endeavours can improve sustainable development prospects to a limited extent by lessening the danger of unfavourable effects of climate change and, furthermore, give co-benefits, for example, better wellbeing results (IPCC, 2007: 2018). In spite of non-stop improvements in energy powers, worldwide energy use and supply are anticipated to keep on developing. Mitigation and adaptation should be correlative as independent of the size of the relief estimates that are actualised; adaptation estimates will at present be required because of the idleness in the climate system (Lundgren and Kjellstrom 2013). The outcome of this inactivity is that alleviation activities should be started in the present moment to have medium and long-term benefits and to maintain a strategic distance from the institutional "lock-in" and technology of carbon-concentrated advancements (IPCC, 2018). Likewise, the Global Energy Assessment (2012) recognises that social decisions about cooling innovation will become progressively significant in the future. These decisions are, as of now, causing issues in numerous places in the world. For instance, in Delhi, India, air-conditioning represents the most astounding use of energy during the hottest months, representing 28% of the complete month-to-month energy usage (Centre for Science and

Environment, 2016). This puts a high weight on the energy supply system and creates an increasing threat of power outages. Also, there is a greater likelihood of critical outcomes, with increased high wellbeing dangers from heat stress, particularly during heat waves, as energy power outages, similar to the one found in India throughout the late spring of 2012, may end up being normal (GEA, 2012). The India power outage left in excess of 600 million individuals without power and was the world's biggest power outage to date (Lundgren and Kjellstrom, 2013). Moreover, this was mostly started by a frail rainstorm that kept temperatures high and set off an increased use of fans and air-conditioners (IPCC, 2018).

2.3.3 Impact of the Municipal Warmth Island

Studies by Anderberg (2011), Ritchie and Roser (2018) suggested that over half of the total populace lives in urban communities. Regardless of worldwide climate change, urbanisation modifies the neighbourhood's intra-urban climate, especially by lessening precipitation and expanding temperatures (Kovats and Akhtar, 2008; Chapman et al. 2017). Developed zones have an impact on the rejection and absorption of solar-based radiation, the capacity to store heat, the emittance and absorption of winds, longwave radiation and evapo-transpiration (the release of fluid water from the earth's surface to move toward becoming water vapour in the air) (Chapman et al. 2017). Also, the built environment is portrayed by human exercises influencing the climate, for example, the cooling and heating of buildings, industrial construction and motor traffic. These exercises discharge moisture and heat and transmit air contamination, which influences outward and inward heat radiation (Johansson, 2006; Pineo and Rydin, 2018). Likewise, the set number of vegetation and trees in numerous urban regions diminishes the ability to cool the air via evapo-transpiration (Gunawardena et al. 2017). Correspondingly, Gunawardena et al. (2017) proposed the municipal warmth island impact is an aftereffect of the warmth assimilation in urban areas and alludes to the distinction in temperatures estimated outside and inside the metropolitan. Nonetheless, Takane et al. (2019) suggested that raised temperatures can build the extent and span of heat waves and cause extra energy consumption from air-conditioning. As the municipal and worldwide climate changes, the capacity of buildings to keep on giving thermally comfortable and healthy environments for occupants will be additionally tested.

A research study by Liu et al. (2011) demonstrated that air-conditioning directly influences the municipal warmth island impact; he displayed the impact on an ordinary place of business and found that the biggest warmth island force contributed via air-conditioning can achieve 0.7°C at noontime and the everyday normal ascent is 0.53°C. The low set-point indoor temperature of the air-conditioner can increase the anthropogenic open-air temperature rise significantly more (Liu et al. 2011). Moreover, Hsieh et al. (2007) earlier completed an examination in Taipei Town, situated in a subtropical region with humid and hot summers. The infiltration of air-conditioning is higher than 90% in the town. The heat released from air-conditioning raised the outside temperature by somewhere in the range of 0.5 to 2°C during night-times (7 pm to 2 am) (Hsieh et al. 2007). Likewise, it was additionally discovered that the geometry and materials of buildings and the elevations and position of warmth discharges change the surrounding climate. Recent studies suggested that a low-level area of warmth discharge influenced the surrounding air temperature, causing an extra power usage of up to 11% compared with a region having a high infiltration of window-type air-conditioners (IEA, 2018; Giridharan and Emmanuel, 2018).

2.3.4 The Energy Usage

Research study by Dahl (2013) assessed that the world consumes around 1 trillion kilowatt hours (kWh) of power for air-conditioning every year; more than double the all-out energy utilisation of Africa for all reasons. Likewise, it is evaluated that the electricity for cooling could significantly rise ten times by 2050 (University of Birmingham, 2018). Investigations by Isaac and van Vuuren (2009) and Keramidas et al. (2018) disclosed that air-conditioning will rise quickly in the 21st century as a result of world energy interest. The expansion in the average situation is from near 300 TWh in 2000, to around 4000 TWh in 2050 and more than 10,000 TWh in 2100 (Keramidas et al. 2018). This growth is part-determined by salary development and alleged neediness, yet because of intensifying temperatures and defence from warmth contact. Interestingly, energy interest in warming will rise until 2030 and afterwards settle. Despite the fact that heating is generally carried-out with biomass, petroleum gas and non-renewable energy sources, air-conditioning relies upon water evaporation and electric power (Tremeac et al. 2012). The developing utilisation of electricity expands the hazard of power outages during heat waves and summer peak demand (Keramidas et al. 2018).

Consequently, exploration endeavours to decrease the related electricity use include increasingly productive coolant gases and air-conditioning, for example, refrigerant-grade propane which limits emissions and electricity use (Lundgren and Kjellstrom, 2013). In any case, the enhancements have been predominated by rising customer demand, social boundaries, specialised and money related margins (Dahl, 2013; McMillan et al. 2016). Investigation regarding the matter connecting temperature directly to air-conditioning use is constrained despite the fact that examination has distinguished climate factors being connected with electricity utilisation (Randazzo et al. 2020). Research has earlier measurably examined interest effects utilising fluctuations in cooling or heating degree days from meteorological data and energy consumption (Izquierdo et al. 2011; Damm et al. 2017). These two markers are utilised in displaying the connection between electricity utilisation and climate. They calculate the amount of the everyday energy of the temperature underneath or over a specific edge, where deviations from the safe place can be investigated on hotter and cooler days. Besides, air temperature is observed to be the largest climate variable influencing energy demand within an encompassing air interim of 15 – 21°C. (Jovanović et al. 2015). For it has been discovered that the electricity burden is moderately indifferent to temperature, which characterises the supposed "safe place". Above or underneath this interim, the energy consumption increases (Lenoir, 2013). Lundgren and Kjellstrom (2013) and Nguyen et al. (2014) suggested that it is additionally notable that the temperature between the outdoor and indoor air temperature incredibly influences the electricity consumption of the air-conditioning system. Besides, electricity loads are additionally observed to be reliant on the earlier hour load impacts and season of the day, regular and day-by-day climate forms, weekday as opposed to end of the week impacts, and occasions (Lundgren and Kjellstrom, 2013; Seyam, 2018).

An imitation of the energy consumption over the hot month of July in Pennsylvania-New Jersey-Maryland (PJM) region of the United States of America (USA) found the effect of a 1.1°C (2°F) growth in the everyday temperature on hourly pinnacle loads brought about a normal interest rise of about 4% (Ismail, 2016). Likewise, the temperature boundaries in Spain are related to yearly pinnacle energy consumption causing a difficult issue for the reliability and stability of electricity dispersion systems (Deloitte, 2015). GHGs occurring because of the electric power era have risen sharply in Spain and temperature is a standout between the most significant factors influencing the energy demand of the population (Deloitte, 2015). In Madrid, for instance, the greatest "top utilisation" was seen on 30 June in the late spring of 2008, when the open-air temperature was 39°C. Private air-conditioning was seen to represent roughly 30% of this greatest "top utilisation" (Izquierdo et al. 2011; Deloitte, 2015).

Besides, it has been accounted in Japan that the peak power load in the Tokyo area ascended by around 180 MW for each 1°C ascent in the year 2004 air temperature (Ihara et al. 2008). In light of this, Miyamoto et al. (2012), appraised the electric power utilisation in three commercial regions in Tokyo as indicated by humidity and air temperature. The Automated Meteorological Data Acquisition System in Japan was utilised for data analysis from a power company called Tokyo Electric Power Company (TEPCO). Also, the air temperature inside the buildings was controlled for comfort and it was discovered that the base heap of around 40 W/m^2 began to rise at 21°C by around 2 W/m^2 per 1°C outer temperature increment (Miyamoto et al. 2012). A direct connection between outer air temperature and electric power consumption was determined utilising a numerous relapse examination. Subsequently, a similar relationship was discovered for humidity. The energy consumption rise throughout the late spring was observed to be fundamentally connected to indoor space cooling (Ihara et al. 2008; Miyamoto et al. 2012). Besides, it should be noticed that the air temperature association with expanding energy usage may vary in different areas, as it relies upon, for instance, the kind of building and furthermore the set-point temperature of the proposed air-conditioning. Subsequently, the general pattern can be expected to apply to most locations and may even be worsened because of energy efficiency and significantly poor development.

Also, the anticipated variations in ecosphere energy interest for cooling and heating in the private division and found the related worldwide carbon discharges to ascend from about 0.8 GtC in 2000 to about 2.2 GtC in 2100, for the most part because of the usage of energy for cooling (IPCC, 2014). In Thailand, the mean yearly temperatures will ascend by 1.7 °C to 3.4 °C by 2080 which will essentially expand the country's peak power via 3.7% – 8.3% in 2050 and 6.6% – 15.3% in 2080 (IPCC, 2014). This means genuine assessed energy use increments of a few 100 GW by 2080, contingent upon the climate change forecast. On the off chance that the expansion is restricted to 200 GW, which fits with the IPCC situation, this climate change effect would be an extra 100 run of the mill power stations creating 2,000 MW (IPCC, 2014). Considering these projections, the utilisation and cost of air-conditioning will rise as an outcome of climate change. However, these patterns make extra imbalance among high and low-pay nations as "maladaptation" will expand essential energy and energy demand in most subtropical and tropical nations, whereas there might be a helpful impact in increasingly mild high-pay nations (International Institute for Applied Systems Analysis, 2012; IPCC, 2018). In any case, Lundgren-Kownacki et al. (2018) recommended that increments in humidity in combination with temperature will build energy utilisation further, particularly in hot climates. When confronting forecasts of extra global warming of 4°C (World Bank, 2012; IPCC, 2018), the expense of extra energy will end up being exceptional.

2.4 Solar Photovoltaic Smart Air-Conditioning

The increasing demand for energy in developing countries and global environmental concerns are opening up new opportunities for utilisation of renewable energy resources, especially solar energy (Kumar, 2020). Solar system is one of the renewable energy systems which uses photovoltaic modules to convert sunlight into electricity (Nwaigwe et al. 2020). The electricity generated can be stored or used directly, fed back into the grid line or combined with one or more other electricity generators or more renewable energy sources (EPA, 2020). Solar photovoltaic systems are very reliable and clean source of electricity that can suit a wide range of applications such as residential, industry, agriculture, livestock, etc. (Tawalbeh et al.

2021). The photovoltaic technologies are attracting more and more attention because the solar cell converts sunlight into electricity without heat engine (Tuller, 2017; Almosni et al. 2018; Kumar, 2020) and its price is decreasing significantly in recent years (Jager-Waldau, 2019). Solar energy has already been widely used as an energy source for heating (Owusu and Asumadu-Sarkodie, 2016; Raheem, 2016; Kumar, 2020) and cooling (Gugulothu, 2015; Inayat and Raza, 2019; Bi et al. 2020). As there is a high coincidence of the solar radiation and the building cooling load in summer, the solar-powered cooling machine can provide the indoor environment with maximum cooling capacity.

Recently, several studies have been done to develop efficient air-conditioning systems using solar energy (Pan et al. 2017; Huang et al. 2019). Pan et al. (2017) studied a portable renewable solar energy-powered cooling system based on wireless power. Ma et al. (2017) compared different solar-assisted air conditioning systems for Australian office buildings. Similarly, Huang et al. (2019) studied the performance of solar-thermal air conditioning systems installed in an office building. Roumpedakis et al. (2020) studied the performance of a solar adsorption cooling system. Boero and Agyenim (2020) performed modelling and simulation of a small-scale solar-powered absorption cooling system in three cities with a tropical climate. Al-Falahi et al. (2020) developed the design and thermo-economic comparisons of an absorption air-conditioning system based on parabolic trough and evacuated tube solar collectors. Kuder et al. (2020) investigated the design and performance of air conditioning systems using photovoltaic in Iraq.

However, the solar absorption and adsorption air-conditioning systems are the most widely used method (Ibrahim et al. 2017). Absorption solar refrigeration systems are environmentally unfriendly and commonly use ammonia-water as working fluids, which require high temperatures in the generator, provided by parabolic cylindrical collectors (Karki, 2018). Its use is mainly in refrigeration for food preservation and very little for air-conditioning systems. It is confirmed that absorption refrigeration systems that employ vacuum tube solar collectors are more efficient than those that use flat solar collectors (Stanciu et al. 2017). The absorption refrigeration system uses a process of chemical absorption; therefore, its design is complicated. In addition, the installation cost of such solar cooling systems is high (Al-Falahi et al. 2020). The most widely used solar photovoltaic air-conditioning (absorption and adsorption systems) are studied further in the next chapter.

Several studies have recently explored the use of smart methods to control solar air-conditioning systems (Hakimi, 2017; Avedian-González et al. 2018). This category of controllers includes NN, FLC, PID, Genetic Algorithms (GAs) and other evolutionary techniques (Hakimi, 2017). These methods are popular due to their attractive features like human knowledge and reasoning as well as advanced optimisation methods (Ahmad et al. 2016). NNs are useful when the system models are not analytically known fully (Ahmad et al. 2016). FLC is another popular controlling choice. It is robust to changes in environments as it is based on the operational experience of human experts (Yu and Lin, 2015). The main advantage of FLC as compared to conventional control approaches resides in the fact that no mathematical modelling is required for the design of the controller (Huang et al. 2019).

GA is attractive for optimisation purposes without involving mathematical theory (Jaen-Cuellar et al. 2013). Both NN and FLC methods can be combined with GA for further optimisation (Ahmad et al. 2016). A research study by Çakır et al. (2019) proposed smart comfort control systems by using human learning strategies for solar air-conditioning systems. Based on a standard thermal comfort model, a human learning strategy was designed to tune the user's comfort zone by learning the specific user's comfort preference using a NN controller. The integration of the comfort zone with the human learning strategy was applied for thermal comfort control (Çakır et al. 2019). Yao and Jaiteh (2017) proposed a multi-objective optimisation algorithm, embedded in a controller. The algorithm was used to determine the amount of energy dispatched to air-conditioning equipment based on utilising intelligence techniques.

A method based on FLC dedicated to the control of air-conditioning systems has been proposed (Yu and Lin, 2015; Ahamed et al. 2016). They obtained the initial knowledge base required by FLC from human experts and control engineering knowledge which they subsequently tuned by a GA. Research study by Serale et al. (2018) proposed hierarchical structure for the control of an air-conditioning system using the Model Predictive Control (MPC) algorithms and fuzzy control algorithms. The main task of the proposed hierarchical control system is to provide thermal comfort and minimise energy consumption. Their technique showed a good comparison between two conflicted objectives: thermal comfort and energy consumption. Kardos and Kutasi (2019) applied MPC technique to learn and compensate for the amount of heat due to occupants and equipment. They used statistical methods together with a mathematical model of thermal dynamics of the room to estimate heating loads due to inhabitants and equipment and control the air-conditioner accordingly. Majority of the existing smart control techniques rely on stochastic knowledge about the input which makes them less robust in uncertain environments. For instance, NN, although useful in cases where there is no mathematical model, suffers from the enormous time taken for off-line training.

Consequently, previous studies fail to recognise the importance of sustainability principles and thereby capitalising on one aspect of sustainability. Therefore, this study considered the environment, social and economic dynamics of the system to address the shortcomings in the literature.

Environment: This study addressed the environmental aspects by proposing to optimise the solar air-conditioning to achieve an efficient performance of the system through using appropriate design and other subsystem components to further improve its innovation. It was clear that the energy savings and COP of the system in previous studies is low as detailed in the research studies by Ibrahim et al. (2017), Stanciu et al. (2017) and Kuder et al. (2020). Therefore, this study aims to achieve the best performance of the system to save significant energy usage while having a higher COP for environmental benefits. The optimisation of the proposed system components will save significant energy usage with high carbon emission savings while combatting global warming and climate change. Therefore, providing an improvement of the system through combining the three sustainability principles to achieve the overall system sustainability will make future urban suburbs more climate resilient.

Social: This study addressed the social aspects by proposing newly innovative control methods that combine advanced and conventional control techniques (Fuzzy PID and Back propagation NN). That is, a new technique through which analogies between these are overlapped, and another through which specific merits are merged. Previous studies are unable to offer proper algorithm control which can observe the level of habitation and adjust the change of the air-conditioned area to improve energy efficiency and IAQ as detailed in the research studies by Ahmad et al. (2016); Hakimi, (2017) and Avedian-González et al. (2018). Therefore, the indoor level of air pollutants must be incorporated in the process of control, which will allow to regulate air changing rate precisely to enhance the system energy efficiency. This is the smart approach for observing human behaviour, to enable it to be adapted into the process of control for precise control response for occupant comfort requirements.

Economic: This study addressed the economic aspect by proposing the use of cost saving techniques having reduced running cost with minimum maintenance to achieve economic sustainability of a system. Previous research studies by Ibrahim et al. (2017), Stanciu et al. (2017) and Kuder et al. (2020) fail to recognise the importance of economic profitability assessment (ARR, NPV, payback period and IRR) that reveals the concept of net earnings and is a vital factor in the appraisal of a system investment proposal. It facilitates the comparison of new product projects with that of cost reducing projects or other projects of competitive nature. While other studies ignore the economic assessment in their approach, studies by Ibrahim et al. (2017) and Stanciu et al. (2017) only focussed on one profitability assessment having high payback period and thereby unsustainable. This study proposed to improve on previous studies by offering a sustainable and efficient system having a lower payback period while considering all financial assessment indicators namely ARR, NPV, payback period and IRR.

Therefore, this study addressed the shortcomings in the literature by developing a sustainable-based framework through examining, applying and consolidating the three bottom-line principles of sustainability namely, environment, social and economic dynamics for the overall sustainability of renewable smart air-conditioning. It focuses on optimising the solar air-conditioning components and smart control techniques to reduce the level of energy consumption and carbon emission while maintaining optimum thermal comfort.

2.4.1 Ventilation System

Controlling temperature and indoor CO_2 inside an enclosed environment can be accomplished with a smart control system for solar air-conditioning (Yu and Lin, 2015). With the use of filters and the introduction of fresh air using regulated valves and vents, pollutants can be removed and diluted (Kukadia and Upton, 2019). Using smart control systems can be effective in ventilating enclosed places and minimising sources of indoor pollution (Ding et al. 2020). Places adhering to guidance from ASHRAE Standards 55-2017 for home ventilation will have better IAQ. The rate at which outdoor air is supplied to an enclosed area is specified by the ASHRAE Standards (Kukadia and Upton, 2019). Supply rates are based primarily on the need to control the air quality inside an enclosed place. The supply rates determine how to control odours, CO_2, and indoor contaminants. CO_2 is a component of the air, but excessive amounts of CO_2 indicate inadequate ventilation (ASHRAE Standards 55-2017).

Control of pollutants at the source is the most effective strategy for maintaining clean indoor air (Carlsten et al. 2019). Unfortunately, it is not always possible or practical to control pollutants at the source (Ioannis et al. 2020). Ventilation and circulation are the next most effective methods to control and manage good air quality inside any enclosed environment. Common practice in the past was to open windows to air out stuffy rooms (Mikola et al. 2019). Also, the air pressure differences between indoors and outdoors provided ventilation through leaks that allowed fresh air from the outside to get inside an enclosed place (Carlsten et al. 2019; Ioannis et al. 2020).

Natural ventilation, unlike forced ventilation, uses the natural forces of wind to deliver fresh air into buildings (Schieweck et al. 2018). Some enclosed places use only natural ventilation or exhaust fans to remove odours and contaminants (Khalil et al. 2020). Also, Kukadia (2019) earlier suggested that thermal discomfort and unacceptable IAQ are likely to occur when the occupants keep the windows closed because of extreme hot or cold temperatures. According to the Institution of Occupational Safety and Health (IOSH), under-ventilation is also likely to happen during swing seasons (IOSH, 2021). Keeping the air quality inside an enclosed environment within an acceptable level is difficult when natural ventilation is used, especially when natural ventilation affects the temperature and humidity levels without proper control or regulation (Schieweck et al. 2018). This requires the use of a control system that manages the air-conditioning system. Air-conditioning systems maintain the comfort conditions for occupants inside an enclosed environment. Traditionally, air-conditioning is controlled with just a temperature sensor (Ahamed et al. 2016; Çakır et al. 2019). In this study, the proposed photovoltaic smart solar air-conditioning will depend on indoor temperature and CO_2 control factors.

The quality of air inside workplaces, offices, and homes is important for the occupants' health and comfort. In a building, outside air can be introduced unintentionally to the enclosed space (IOSH, 2021). However, this is problematic as the uncontrollable introduction of fresh air can cause increased energy usage and indoor CO_2. With spaces being built tighter for high energy efficiency, mechanical ventilation seems to be the best solution for managing air quality. The IAQ standard defined by ASHRAE Standard 62 states: 'for comfort, indoor air quality may be said to be acceptable if not more than 50% of the occupants can detect any odour and not more than 20% feel discomfort, and not more than 10% suffer from mucosal irritation, and not more than 5% experience annoyance, for less than 2% of the time' (Meng et al. 2016). To be able to influence most of these factors, proper control strategies have been designed to comply with ASHRAE Standard for operating the smart air-conditioning systems in order to optimise occupant comfort and energy saving in the built environment.

In general, thermal comfort for air-conditioning systems must be designed based on nationally specified criteria or international standards, and they should be used for thermal comfort in informative annexes (Meng et al. 2016). There are several recommended criteria given for general thermal comfort and they can be concluded as PMV (Predicted Mean Vote), PPD (Predicted Percentage Dissatisfied) model or operative temperature for local thermal comfort parameters like vertical temperature differences, radiant temperature asymmetry, draft and surface temperatures (ASHRAE Standard 55-2017).

An index called the Predicted Mean Vote (PMV) that has been widely used to predict acceptable thermal environment have been designed by Sadia and Hong (2019) as expressed as follows:

$$MPV = ft_{a,}\, t_{mr,}\, v,\, p_{a,}\, M,\, I_{cl} \tag{2.1}$$

Where, air temperature (t_a), mean radiant temperature (t_{mr}), relative air velocity (v), air vapour pressure (p_a), activity level (M) and the clothing insulation (I_{cl}).

PMV represents the mean thermal sensation vote on a standard scale for a group of building occupants for any given combination of the environment variables, prevailing activity level and clothing (Sadia and Hong, 2019). For the modelling and simulation in this study, the control strategy evaluates the difference between the measured value and the set point and also evaluates the change of this difference in order to decide whether to increase or decrease the control variables of the thermal comfort. A FLC can implement nonlinear control strategies. Therefore, if the comfort condition (PMV) is 'cold', the increase will be strong, regardless of its tendency, but if the PMV error is small, the tendency is taken into account. This, in turn, conforms with ASHRAE Standard for IAQ.

2.4.1.1 Dedicated Outdoor Air System

According to research studies by Levasseur et al. (2017) and Saini et al. (2020) air-conditioning systems are applied to offer both thermal comfort and a good IAQ in most buildings. Methods as well as varying air volume have been established to enhance the performance of air-conditioning (Chuah and Yang, 2020). Nevertheless, indications from studies in preceding decades already demonstrated that it is almost impossible that an all-air system can attain its purposes particularly air ventilation in an energy efficient way (Rane et al. 2016; Zhanga et al. 2017). Currently, the DOAS (Dedicated Outdoor Air System) has become an attraction owing to its benefits over the all-air system. Air-conditioning systems have DOAS that comprises two parallel systems: a parallel air terminal system and a dedicated outdoor air ventilation system (Elnaggar and Alnahhal, 2020).

The renowned characteristic of the DOAS is to deliver dedicated ventilation instead of ventilation as part of conditioned air. The fresh air is brought into a building to fulfil the latent load, ventilation prerequisite and part of space sensible load (Rane et al. 2016). Contrasted to all air systems, DOAS have lower draft, a reduced amount of noise and good quality thermal comfort for inhabitants and also possibly reduce energy consumption and indoor CO_2 (Zhanga et al. 2017).

DOAS can conserve energy via employing water as heat carrier to reduce energy use connected to air transport. It likewise permits decreasing duct size as they only cater for the outside air intake (Elnaggar and Alnahhal, 2020). Furthermore, the Air Handling Unit (AHU) parallel system is classified as a cooling system having high temperature, which may lead to a refrigeration cycle possessing higher COP (Coefficient of Performance) (Kim et al. 2019). Concerning the DOAS, different components are associated collectively for managing the building load through humidification, dehumidification, heating and cooling. The system feature includes control loops for the performance of air processes (Zhanga et al. 2017). Research studies demonstrate that the DOAS is sustainable unlike the all-air system and the DOAS provides a great potential for reduction of energy consumption, carbon emission and operational costs (Rane et al. 2016; Chuah and Yang, 2020). As a result, DOAS control strategy has been proposed for the air system supply and cooling process for solar smart air-conditioning in this study.

2.5 System Sustainability Study Strategy

Exploration by IIASA (2012) and IPCC (2014) reveal that system study examination and a life cycle approach are fundamental when taking a gander at the issue and potential arrangements. Financial contemplations, for example, just introducing unsustainable sorts of air-conditioning during warm summers, are not sustainable answers (IPCC, 2014). In the long-term, this change can convert into one innovation dominating the total market to the detriment of the other; alluded to as technical "lock-in". As of now, this can be seen and has likewise caused an established lock-in, as the growth of technologies impacts, and is affected by the three bottom line principles namely, economic, social and environment in which they create (Karen et al. 2016). When this lock-in is accomplished, it can anticipate the take up of possibly predominant choices (Clift et al. 2017). The European Environment Agency (2018) found that the system approach emphasises that discrete technologies are not just upheld by the more extensive technological system, but in addition by the framework of economic, environmental and social standards that fortify that innovative system.

These incorporate formal limitations, for example, economic viewpoints, policies and casual requirements, for example, behavioural and social hindrances.

Consequently, studies by Akadiri (2012) and Saner et al. (2019) recommended that one must deliberate upon all the drivers of sustainability when designing transformations to air-conditioning; one also must take into account that individual technologies are not only buttressed by the extensive technological system, but also the sustainability framework that underpins the technological system. So, it is important to understand the three bottom line principles of sustainability, namely, environmental, economic and social, and how the renewable and smart/intelligent approaches can contribute to the overall sustainability of the system. This can even offer substantiated insight into sustainable approaches to promote the novelty of smart air-conditioning for greater sustainability.

2.5.1 Environmental Sustainability

Research study by Morelli (2011) characterises environmental sustainability as a state of equalisation, interconnectedness and resilience that enables human culture to fulfil its needs while neither surpassing the limit of its supporting biosphere to keep on recovering the amenities important to address those issues nor by our activities reducing biological variety. In any case, the ecosystem that people rely upon is resilient (Folke et al. 2016). This implies it can keep up its uprightness or come back to a condition of balance after an unsettling influence (Briske et al. 2017). Nonetheless, unexpected changes in the biosphere can make it lose its resilience (Ratajczak et al. 2018) and turn out to be “unsustainable” (Folke et al. 2016). The earth’s system has a lot of cut-off points or limits inside which harmony is kept up (Rockström et al. 2009; Clift et al. 2017). Exponential development is forcing more prominent demands on the ecosystem and also putting a more prominent strain on these breaking points (Briske et al. 2017). Rockström et al. (2009) and Steffen et al. (2015) observed nine planetary limits inside which mankind can work securely. These limits portray the major workings of the biosphere. A research study by Steffen et al. (2015) evaluated 7 of these limits and expressed that the transgression of these limits could prompt an unexpected and irreversible change to the worldwide environment. As indicated by their estimations, mankind has just transgressed 3 of the 9 planetary limits: the degree of biodiversity misfortune (estimated by the rate of eradications per million species), changes to the worldwide nitrogen cycle because of exponential development, and climate change (estimated by the CO_2 focus in the environment). Meadows et al. (1972) earlier enquired "Is it superior to attempt to live inside that point of confinement by tolerating a purposeful limitation on development? Or is it desirable to continue developing until some other normal cut-off emerges, with the expectation that around then another innovative jump will enable development to proceed? For the previous few 100 years, human culture has pursued the second course so reliably and effectively that the main decision has been everything except overlooked". For the previous inquiry, sustainability is basic (Rockström et al. 2009; Steffen et al. 2015), nonetheless, for the last, it is expected that the biosphere is strong and ready to withstand any sudden interruptions and is likewise sustainable (Jesse et al. 2019). Albeit people cannot rely upon innovative headway to help proceed with development (European Sustainable Development Network, 2012). Therefore, that would be much the same as considering installed values on strategies not yet issued and items not yet created.

Nevertheless, research studies revealed that the proof to ease concerns about the sustainability of the environment is developing (Gilding, 2011; Dechezleprêtre and Sato, 2014). The impacts of climate change give an undeniable contention to the requirement for environmental sustainability. "Climate change" alludes to the noteworthy and durable changes in the climate system brought about by human exercises or by characteristic climate fluctuation (for example "anthropogenic" climate change) (IPCC, 2014). Despite the protester studies, the standard of designing and assembled environment studies perceives the reality of anthropogenic climate change. The IPCC earlier in 2013 revealed that heating of the climate system is unequivocal, and meanwhile in the 1950s, a considerable lot of the observed changes are remarkable over decades to centuries (IPCC, 2013: 2014). Similarly, the changes incorporate warming of the environment and seas, lessening ice levels, rising ocean level, growing foci of GHGs and intensifying fermentation of the seas. Climate change has just started to influence biodiversity (IPCC, 2014). Specifically, higher temperatures have influenced the planning of propagation in plant and creature species, species circulations, movement patterns of creatures and population sizes (Dechezleprêtre and Sato, 2014). Likewise, the present rate of biodiversity misfortune is more prominent than the common rate of elimination (IPCC, 2014: 2018). Moreover, the limits of the world's biomes are required to transform with climate change as species are relied upon to move to higher altitudes and latitudes and as worldwide vegetation spread changes (Beaumont et al. 2011; Hoffmann et al. 2019). On the off chance that species are not ready to change in accordance with new land dispersions, their odds of survival will be diminished. Also, it is anticipated that, continuously in 2080, about 20% of seaside front wetlands could be lost because of ocean level rise (IPCC, 2018). In any case, proposing a sustainable-based smart system can move to tackle some of the environmental concerns that are considered in this study, vis-à-vis combatting global warming and climate change adaptation as a result of sustainable smart air conditioning. In essence, Figure 2.3 offers the indicators of environmental sustainability for the proposed system.

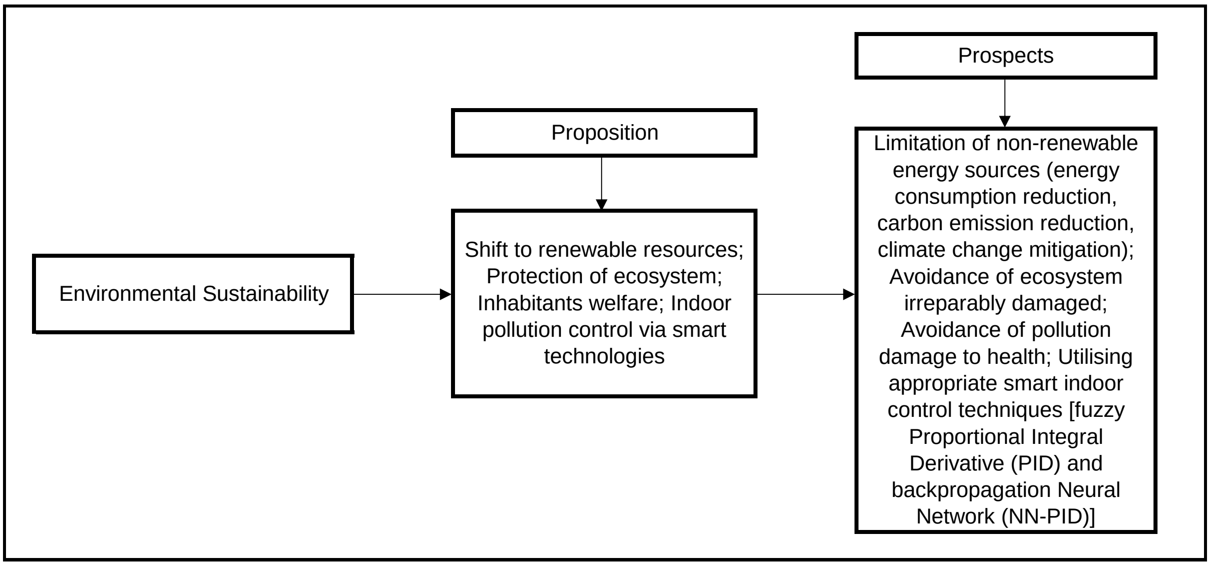

Figure 2.3: Indicators of environmental sustainability for renewable-based smart air-conditioning.

2.5.2 Social Sustainability

Studies depict social sustainability as a procedure for making a sustainable, positive environment that encourages comfort, by means of understanding what individuals need from the suburb they live and work in (Horner et al. 2009; Eizenberg and Jabareen, 2017). It joins the plan of the physical domain with the structure of the social world – framework to help cultural and social life, social comforts, systems for resident commitment and space for individuals and communities to grow (Horner et al. 2009). Moreover, social sustainability can likewise be depicted as a sustainability that happens when the informal and formal procedures, structures, systems and connections effectively bolster the limit of present and future ages to generate liveable and healthy societies (Kolk, 2016). Socially sustainable societies are democratic, connected, diverse and equitable and give a decent quality of life (Magee et al. 2012; Kolk, 2016). In any case, various research studies suggest that social sustainability has had considerably less consideration in open discussion than economic and environmental sustainability (Woodcraft et al. 2012; Eizenberg and Jabareen, 2017; Purvis et al. 2019).

Consequently, the impacts of climate change on wellbeing give proof that social sustainability relies on environmental sustainability (IPCC, 2018). According to the World Health Organisation (WHO), the net impact of climate change will be damaging. Very high air temperatures worsen respiratory and cardiovascular illnesses since they raise the dimension of toxins in the air. Also, municipal air contamination causes roughly 1.2 million demises every year (WHO, 2019). The research study by Campbell-Lendrum (2015) earlier suggested that the rate of infectious diseases is required to rise as the normal air temperature keeps on increasing. In addition, the event of irresistible illnesses, for example, jungle fever is required to rise as the environment turns out to be progressively good for broadcast. Also, increasing ocean levels are expanding the danger of floods. This builds the danger of poor IAQ, interruption of wellbeing amenities, jungle fever, pollution of water supplies, wounds, suffocation and water-borne illnesses (WHO, 2019). Research study by Yu and Lin (2015) additionally stressed that a great number of individuals spend around 80% – 90% of their time indoors, hence, IAQ altogether affects work and wellbeing productivity. The ubiquity of air-conditioning has made relaxed indoor spaces with sensible air quality accessible to numerous individuals. In any case, studies by Nguyen et al. (2014) and Mikola et al. (2019) reveal that the utilisation of the systems increases the amount of contamination in the air in closed spaces in view of an absence of air exchange between outdoors and indoors, showing a noteworthy danger to our wellbeing and health. Therefore, this study recommends that controlling the quality of air radiated via air-conditioning is significant in light of the fact that a significant amount of the total population today lives under the dangers of different kinds of diseases caused by poor IAQ. Therefore, there is a need for an indoor smart system that better controls and improves the human adaptation of the wellbeing of occupants utilising air-conditioning which is, in turn, focussed upon sustainable future development.

Subsequently, studies suggested that health is part of the constituents of comfort and wellbeing (Dempsey et al. 2011; Western and Tomaszewski, 2016). Likewise, further segments consist of freedom, wealth, employment, education, social capital and living standards (Waite, 2018). The idea of social capital alluded to here, and the comparable ideas of environmental capital and human capital are awkward in that they infer a reductionist perspective on humankind and the environment (Western and Tomaszewski, 2016). For example, a perspective that the worldwide ecosystem, individuals and the human culture are nonentity, however, their worth is to the worldwide economy (Dempsey et al. 2011). Investigation uncovers that people are, however, living on an unhappy planet (Happy Planet Index Report, 2012). At this point, "happiness" signifies sustainable wellbeing. Similarly, the Happy Planet Index measures “the extent to which countries deliver long, happy, sustainable lives for the people that live in them” (Happy Planet Index Report, 2019). The report quantifies the degree of bliss by figuring the quantity of "Happy Life Years" attained per unit of asset use (Happy Planet Index Report, 2012: 2019). The account likewise uncovered that happiness does not really need to come at the detriment of the environment because nations with the uppermost comfort and wellbeing did not really have the most noteworthy asset utilisation. This gives proof that social sustainability is influenced by environmental sustainability.

Recently, the Paris Agreement came into power by a legally binding international treaty on climate change. It was adopted by 196 Parties at COP-21 in Paris, on 12 December 2015 and entered into force on 4 November 2016 (United Nation, 2016). Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels (UN, 2016). To achieve this long-term temperature goal, countries aim to reach global peaking of GHG emissions as soon as possible to achieve a climate neutral world by mid-century (IPCC, 2018). The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects (UN, 2016). Moreover, the World Bank recently evaluated that almost 75% of the total populace live on under 4 dollars per day (The World Bank, 2019). This accentuates environmental and economic sustainability and can successfully affect social sustainability. As a result, there is a requirement for smart indoor controllers and renewable-based air-conditioning to combat poor IAQ and improve the human adaptation of the wellbeing of occupants, vis-à-vis serious health problems and climate change adaptation. In essence, Figure 2.4 offers the indicators of social sustainability for the proposed system.

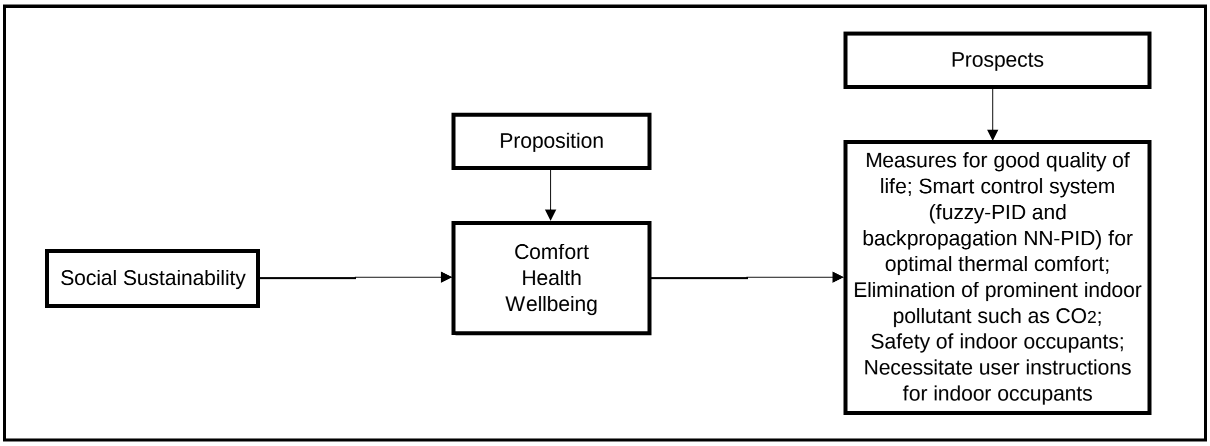

Figure 2.4: Indicators of social sustainability for renewable-based smart air-conditioning.

2.5.3 Economic Sustainability

'Economic sustainability' suggests a system of generation that fulfils present utilisation levels without trading off future needs (Lobo et al. 2015). Inside a commercial setting, economic sustainability includes utilising the varying resources of the system effectively to enable it to keep working productively after some time without contrarily affecting the environmental and social part of sustainability (Basiago, 1999; Lobo et al. 2015). Nevertheless, economic sustainability is inseparably connected to both social and environmental sustainability (Turner, 2014). This is demonstrated by the limits to growth. In any case, Meadows et al. (1972) suggested that economies are unlikely to be sustainable if society keeps on relying upon marvels that hitherto drove development and if natural assets are utilised past the cut-off points. Also, "The Limits to Growth" as indicated in their book; they contended that human interest would surpass nature's supply from the 1980s forth, with interest surpassing supply by 20% by 2000. Around then, they presumed that, except if a unique move is made, populace development combined with expanded asset utilisation past what the biosphere can continue, will prompt the decrease in or the breakdown of the society, economy and environment. In fact, Meadows et al. (2004) proposed in their 30-year update that mankind has gone past its points of confinement (Meadows et al. 2004). Over 10 years after the fact, Turner (2008: 2014) affirmed that the past movement in global pollution, industrial output per capita, population, services per capita, food per capita and non-renewable resources remaining has been in accordance with the pattern anticipated by the 1972 investigation, and that populace decrease is normal by 2030 after economic breakdown. Gilding (2011) expressed that mankind has outperformed the biosphere's ability to support people. Moreover, Thomson (2013) contended that development in the long-term driven by information technology, debt and cheap oil is coming to an end. Subsequently, studies offered proof to limitations on assets, for example, uranium, flammable gas, coal and oil and delineate that development driven by assets is constrained (Jones et al. 2013; Olson and Lenzmann, 2016; IPCC, 2018). As a result of these existing issues, it is key to focus upon renewable energy options to contribute significantly to the overall sustainability of the system – the sustainability of smart air-conditioning. In essence, Figure 2.5 offers the indicators of economic sustainability for the proposed system.

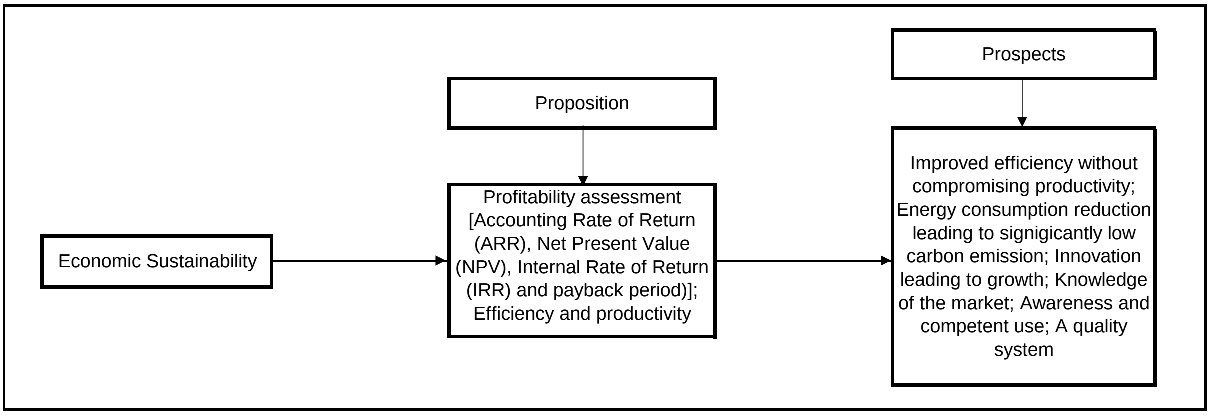

Figure 2.5: Indicators of economic sustainability for renewable-based smart air-conditioning.

2.6 Conclusion

In this chapter, the contextual background of sustainability and sustainable development associated with air-conditioning has been reviewed by way of considering the research aim of the study. The review deliberated upon the principles of sustainability for air-conditioning. This chapter identified the issues associated with air-conditioning unsustainability by way of considering the three pillars of sustainability. As a result, the system study sustainability strategy was revealed that prudently uncovers the indicators of economic, environment and social sustainability of the system for the purpose of achieving the overall sustainability of the air-conditioning system. The link amongst the environment, economic and social sustainability were studied – the impacts of climate change on wellbeing gave proof that social sustainability relies upon environmental sustainability, whereas economic sustainability is inseparable connected to both social and environmental sustainability. The sustainability of air-conditioning is required to reduce the level of energy consumption and carbon emissions, vis-à-vis combatting health effects and climate change. Nevertheless, air-conditioning as a practical answer to shield municipal populaces from extreme heat contact generates the provocation of intensifying carbon emissions, energy consumption and health problems, particularly in municipal territories. The use of air-conditioning causes an expansion in energy consumption leading to global warming and climate change. Besides, the immediate heat rejected from the air-conditioning technically adds to the street level warmth and in this manner the municipal warmth island impact. If not subsided, it can possibly increase climate change, and put additional heaps on the future energy supply, particularly during heat waves. A public that is strong to climate change would guarantee that sustainable and renewable-based air-conditioning fuses every single applicable tactic to deal with decrease of human warmth exposures during the hottest part of the year. As a result of previous research studies, sustainability issues associated with the use of air-conditioning have been unfolded and the indicators of environment, economic and social principles of sustainability underpinned with air-conditioning have been revealed for this study. In the light of this, the next chapter deliberates on the sustainable measures that are reinforced upon the requirement for renewable-based air-conditioning and smart computational control technologies for healthy IAE quality.

Chapter Three

3.0 Renewable-Based System and the Smart Indoor Environment

3.1 Introduction

This chapter deliberates upon the renewable-based system by considering absorption and adsorption systems that are associated with sustainable development. It also concentrates upon the pollutants of the indoor environment causing several health and wellbeing problems; however, underpinning the indoor CO_2 which is the most dominant within the indoor environment. This chapter further dwells upon the requirement of smart computational techniques to control and improve the indoor temperature and IAQ of the proposed system.

Consequently, the extreme use of air-conditioning has caused substantial growth of energy consumption and carbon emissions. This fact clarifies the requirement for considering utilisation of renewable energy sources and computational intelligent control system, vis-à-vis focussing upon sustainability. This study has considered the potential of using renewable energy and smart technologies to reduce the level of energy consumption and carbon emission while promoting sustainable development. Therefore, the use of solar smart air-conditioning to improve inhabitant wellbeing and provide a sustainable environment is needed to make future urban districts more sustainable.

3.2 Renewable Energy for Air-Conditioning

Several studies suggest that the utilisation of renewable energy is gaining a lot of awareness, and considerable examinations are still required for various innovations (Ritchie and Roser, 2019; Holst, 2020). Moreover, the state-of-the-art total world energy utilisation is displayed in Figure 3.1 (Ritchie and Roser, 2019). The increasing utilisation of fossil fuels not only leads to the quick exhaustion of energy sources but also causes the production of destructive gases, which directly affect humankind (Holst, 2020). An outline of immediate and indirect impacts of climatic changes as a result of consuming fossil fuels are revealed in Figure 3.2 (Rafique and Rehman, 2018). Understanding the hidden effects of fossil fuels and their impacts on the wellbeing of humans is crucial for evaluating the sustainability of air-conditioning and for reinforcing more noteworthy decisions for future energy generation. Sustainable smart systems should be considered with the feasibility of utilising cleaner energy sources such as photovoltaic solar energy.

Moreover, cooling represents a significant aspect of the energy used in buildings. With respect to the utilisation of power for air-conditioning, its interest is expanding quickly, as presented in Figure 3.3 (Holst, 2020). Nevertheless, the increasing utilisation of air-conditioning innovation empowers the creation of selective cooling developments, which can proficiently use renewable energy, such as solar-controlled systems, for their task (Rafique and Rehman, 2018). Discrepancies in fossil fuel costs have offered an increase to a dynamic quest for other energy sources (Mugnier, 2013). The idea of using solar power for cooling was introduced in 1869 by a French innovator of the original solar power (Mouchot, 1987). The primary solar cooling system was openly shown by a similar specialist at the General Presentation in Paris, 1878 (Mouchot, 1869). Also, ice fledglings were delivered by the system with an alkali-water ingestion chiller and an illustrative reflector. The solar cooling exhibits were continued as late as the 1980s (Sayigh, 2018). The most current revival of comprehensive solar cooling exploration was made towards the start of the 21st century after the philosophies of joining electric-driven chillers and photovoltaic were spread among scientists (Rafique and Rehman, 2018).

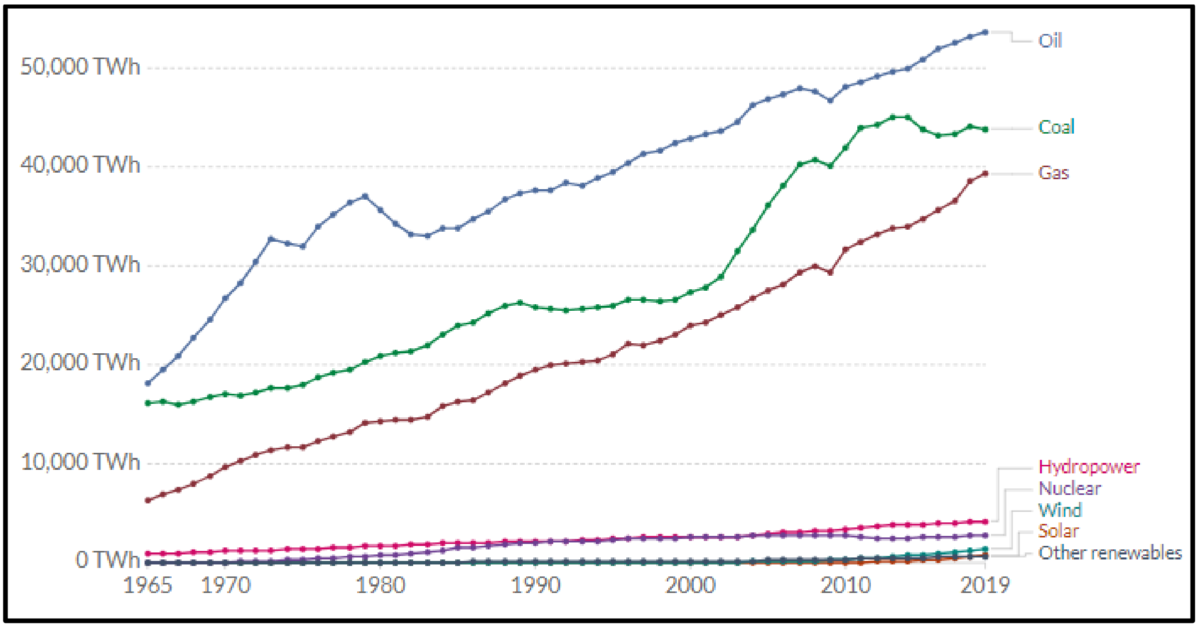

Figure 3.1: The world's consumption of energy (Ritchie and Roser, 2019).

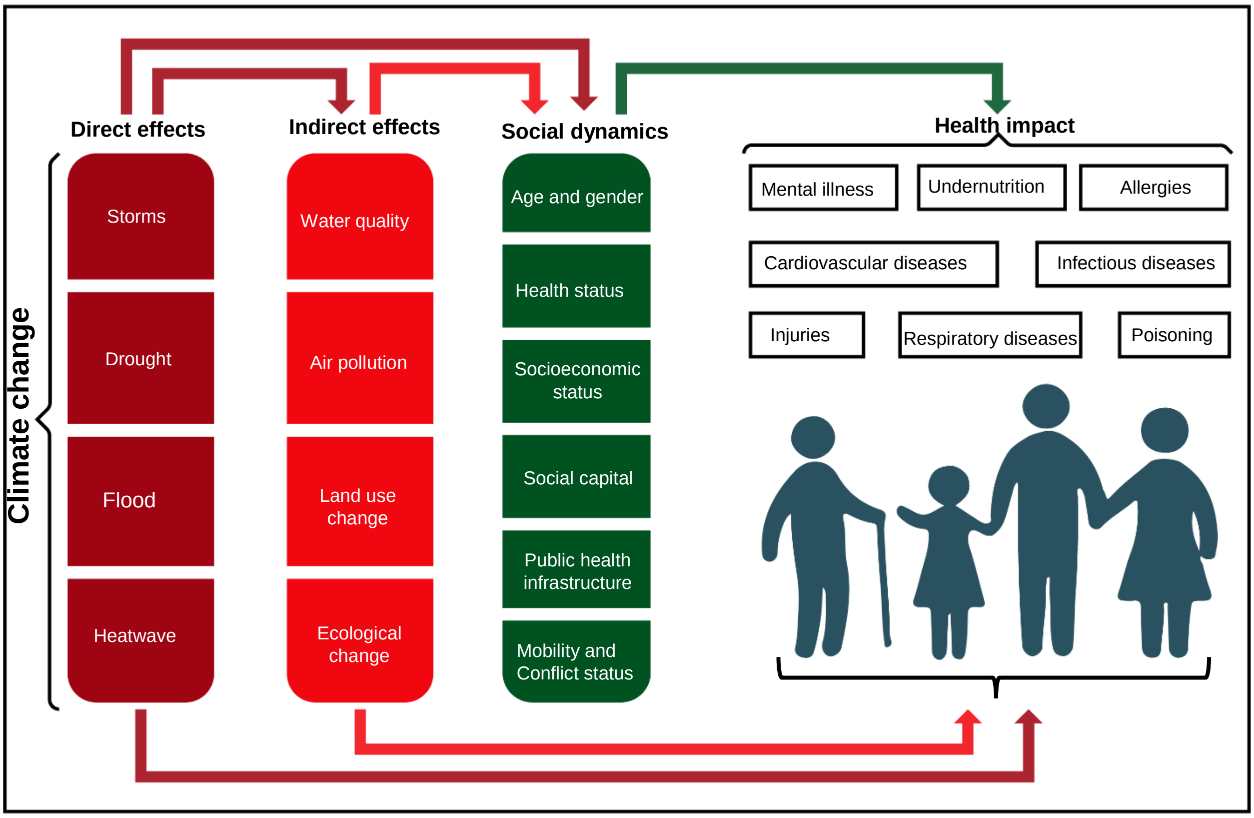

Figure 3.2: The indirect and direct impacts of climate change on public health (Rafique and Rehman, 2018).

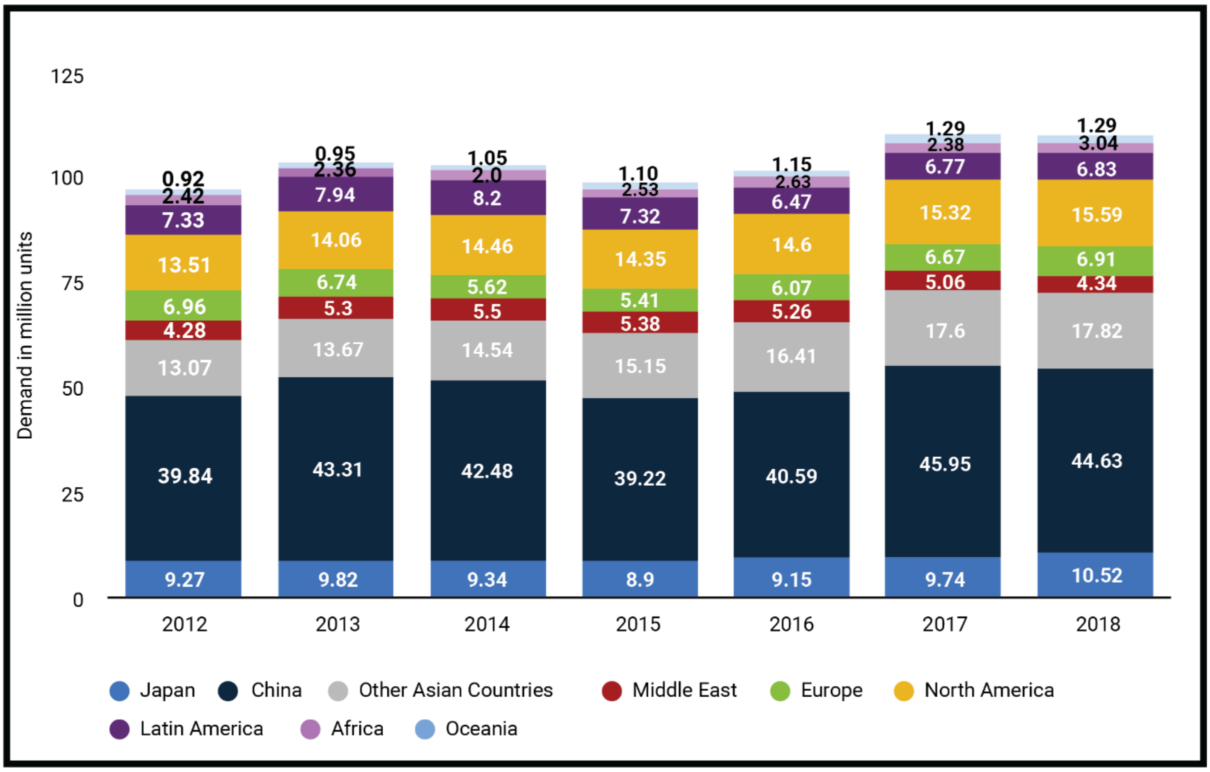

Figure 3.3: Air-conditioning demand worldwide from 2012 to 2018, by region (Holst, 2020).

Regularly rising wellbeing necessities in transportation and buildings make the cooling mandate and reinforces the development of the cooling business sector across the globe (Guo et al. 2012). These wellbeing prerequisites are prompting air-conditioning as a need in business buildings and is no longer observed as a luxury (Schieweck et al. 2018). With these grounds and the goal of reducing CO_2 and energy, a rapidly developing business sector of solar air-conditioning systems can be anticipated (Guo et al. 2012). This has remained generally unnoticed by a number of policy producers, incompletely on the grounds that cooling needs are customarily being met by electrical air conditioners, concealing the cooling component inside the building's general energy consumption (Mugnier, 2013). In Europe, research suggested that an increase in the portion of commercial buildings furnished with cooling systems is relied upon to reach a minimum of 60% constantly by 2020 (Holst, 2020). The greatest potential cooling demand in Europe if 100% of all valuable space would be air-conditioned is evaluated to be 1400 TWh cooling every year (Sanner et al. 2011; Holst, 2020).

Research studies by Mugnier (2013) and Sayigh (2018) suggested that solar cooling societies expect an upsurge of solar cooling growth in these days of emerging utilisation of renewable energy sources. This increase in renewable energy sources execution in energy areas receives support from European Union (EU) mandates and regularities of energy utilisation (International Renewable Energy Agency, 2018; Eyl-Mazzega and Mathieu, 2020). In any case, the ongoing building order has a subtask of diminished cooling load growth (International Renewable Energy Agency, 2018; EU, 2020). Not a small amount of effect relating to "nearly zero energy buildings" has had an order 2020, which implies that immediate electricity utilisations and non-renewable energy sources ought to typically diminish (EU, 2020). Unquestionably, it is conceivable to lessen the carbon emissions and energy utilisation of air-conditioning without decreasing the wellbeing level by utilising renewable energy and smart indoor air controllers for the sustainability of the system. As indicated by Solar Heat Worldwide (2018), the European solar air-conditioning market has developed quickly during the most recent time which is the second largest solar cooling market as appeared in Figure 3.4.

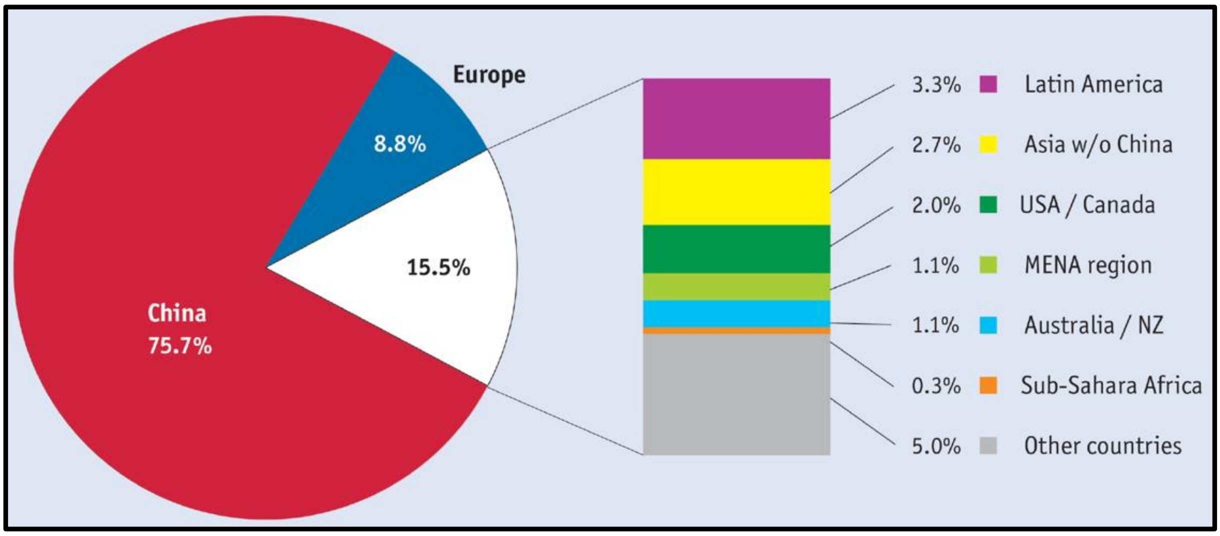

Figure 3.4: Solar cooling growth (SHW, 2018).

Subsequently, a significant percentage of the worldwide solar cooling systems are mounted in Europe – most eminently in Italy, France, Germany and Spain (Mauthner and Weiss, 2014). Most of these systems are equipped with evacuated tube collectors or level plates (SHW, 2018). On the other hand, China is the largest solar cooling market and a few models for warm cooling machines driven by intense solar warm energy were accounted for in other regions. The general number of systems introduced to date shows that solar cooling is yet a specialty showcase, thus far, a system which is growing (Mauthner and Weiss, 2014; SHW, 2018). Study unfolded that air-conditioning market conveyance pursues the development of existing environments (Goetzler et al. 2016). Little scale air-conditionings have a short lifetime (typically from 2 to 5 years), which infers persistent substitution of the components of such a scheme (Armstrong, 2018). Regardless of this, the market development is watched consistently in the most recent time as appeared in Figure 3.5.

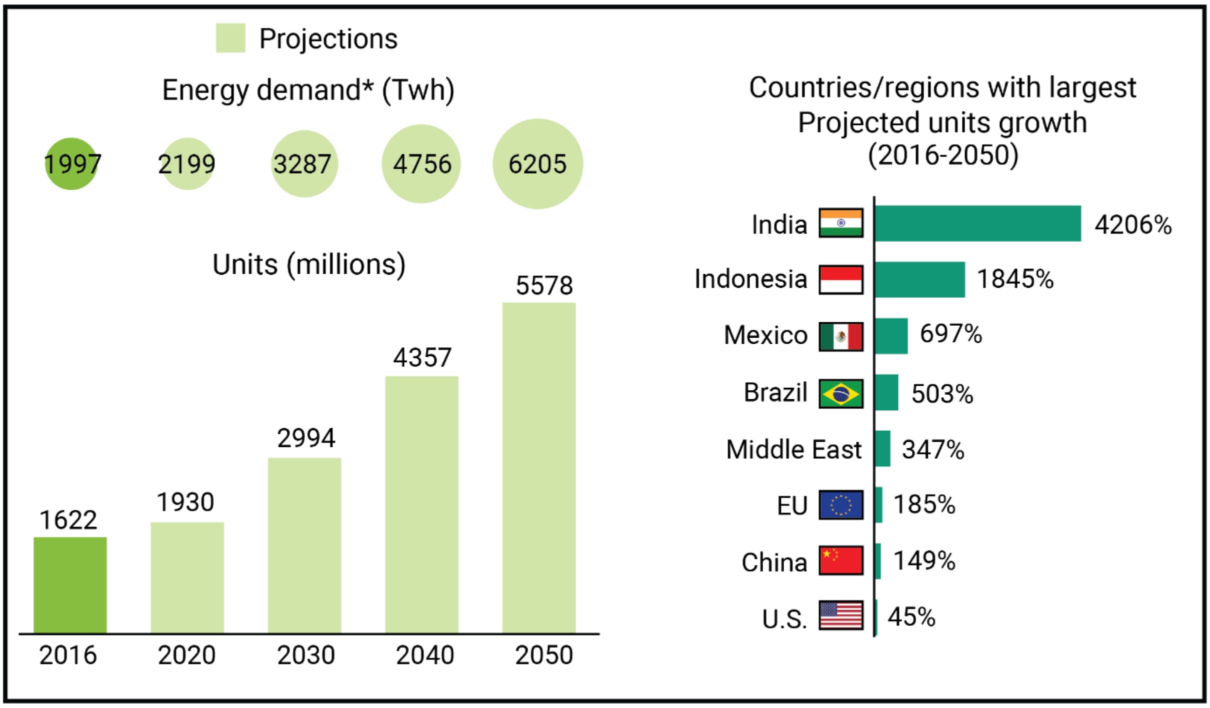

Figure 3.5: Conventional air-conditioning market situation (Armstrong, 2018).

Subsequently, the little scale air-conditioning business sector estimate in the EU is significantly increased from the year 2016 to 2030, with greater prediction of increase from 2030 to 2050 (Armstrong, 2018). In the growth of the market, the impact of variable economic circumstances could be observed universally and particularly in the EU. Distribution of air-conditioning components in the 21st century is diverted from advanced nations to dynamically industrialising districts; innovative appropriation patterns are currently focused for the Asia locale (Jakob, 2013). Therefore, the production of air-conditioning systems has increased in Asia for the past 20 years (Armstrong, 2018).

According to Masson et al. (2014) and Armstrong (2018), the primary energy supply of photovoltaic solar air-conditioning is the power delivered by a photovoltaic cluster. The value decrease for photovoltaic items in the most recent time is in nearness to

10% a year and consistently, the least cost records per introduced photovoltaic ostensible power are considered for the system (Masson et al. 2014). Moreover, the world's total installed photovoltaic threshold was more than 23 GW in late 2009 (Jakob, 2013). After a year it was 40.3 GW, having increased to 70.5 GW before the finish of 2011. The 100 GW imprint was obtained in 2012, and practically 138.9 GW of photovoltaic had been introduced all around in 2013 – a sum fit for delivering at the rate of 160 terawatt hours (TWh) of power each year (Masson et al. 2014). This power capacity is adequate to cover the yearly energy supply requirements of more than 45 million EU family units (Armstrong, 2018). This is additionally what might be compared to the power created through 32 huge coal energy plants (SHW, 2020). The worldwide collective introduced volume could have achieved 140 GW if the extra 1.1 GW in China were considered in 2013 (Masson et al. 2014; SHW, 2020).

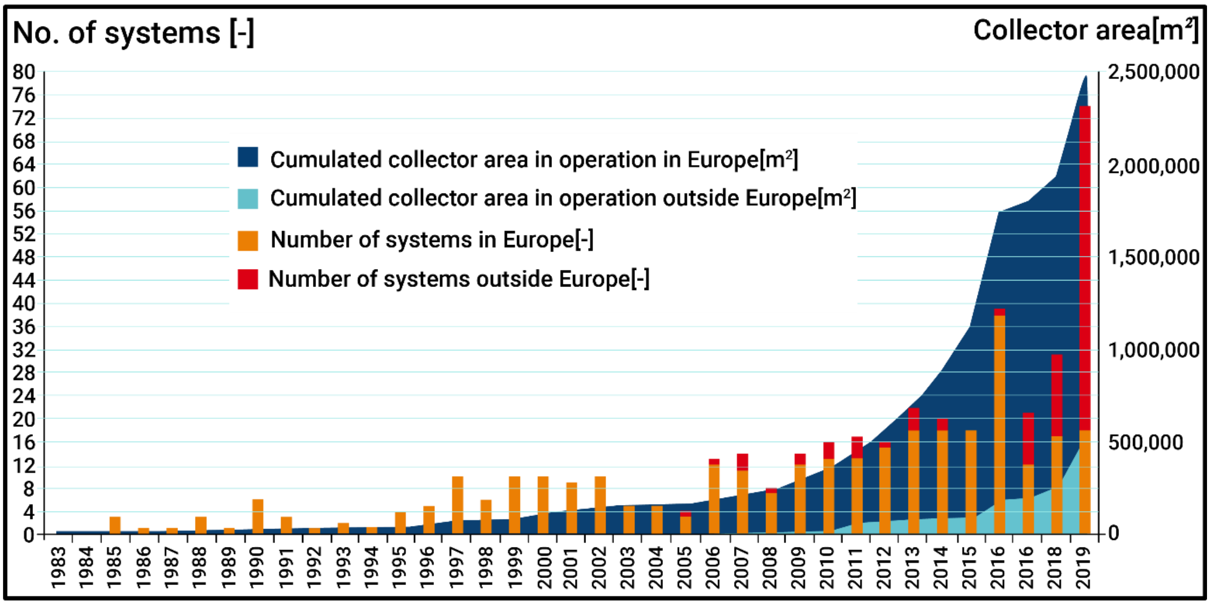

Figure 3.6: Installed cumulative capacity for worldwide development of photovoltaic (SHW, 2020).

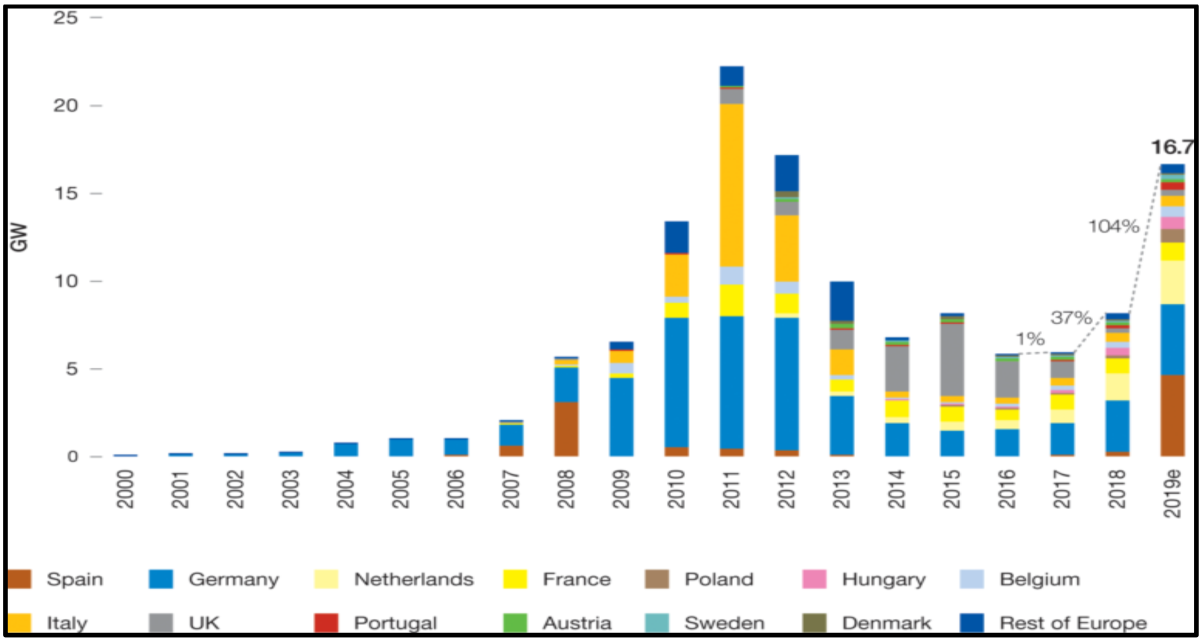

Figure 3.7: 2000-2019 annual installations worldwide development (Solar Power Europe 2020).

Research suggests that the EU remains the world's foremost district regarding the system collective introduced volume (EU, 2020). This characterises around 59% of the biosphere's total photovoltaic volume from 70% to around 75% of the world's volume. As delineated in Figure 3.6, nations outside Europe are developing quick (SHW, 2020). The year 2019 was a record time as that for photovoltaic establishments with over 100% solar market increase (SPE, 2020). These statistics demonstrate that in 2018 the internationalisation pattern of photovoltaic showcases detected was then complemented in the year 2019, with China leading the pack over the EU as the number one district for photovoltaic establishments. Therefore, the following subsection of this chapter detail the most widely recognised system in recent time namely adsorption and absorption of solar air-conditioning.

3.2.1 The Solar Air-Conditioning Absorption-Based

According to Todorovic and Kim (2014), the destructive impacts of conventional air-conditioning (CO_2 discharge and the utilisation of environmentally unfriendly refrigerants) and their high essential energy consumption led researchers to put resources into clean energy assets, particularly the solar power. The absorption innovation is the greatest utilised in air-conditioning (Allouhi et al. 2015; Jasim and Kadhum, 2016; Ibrahim et al. 2017). Rather than the compressor, the system utilises a generator and absorber. Hence, to pressurise the refrigerant (alkali or water), no electrical energy is expected (Aman et al. 2014). The refrigerant is primarily absorbed in an absorbing material and then pressurised in the consumed fluid phase. The pressurised retention blend is then warmed in a solar-controlled generator to recover the pressurised refrigerant vapour (Aman et al. 2014). From that point forward, it is deliquesced in the condenser to end up fluid, which is then extended using an extension valve. The chilled refrigerant causes the cooling impact in the evaporator. At long last, the refrigerant is moved to the absorber and another cycle is started (Aman et al. 2014). Thus, absorption systems add to decreasing the energy costs and GHG emissions to the environment. However, they have a low COP (around 0.3 and 0.75 as indicated by the cooling limit) in relation to electrical vapour compressor air-conditionings that their COP can range up to 3 (Aman et al. 2014). The working guideline for a solar air-conditioning is outlined in Figure 3.8.

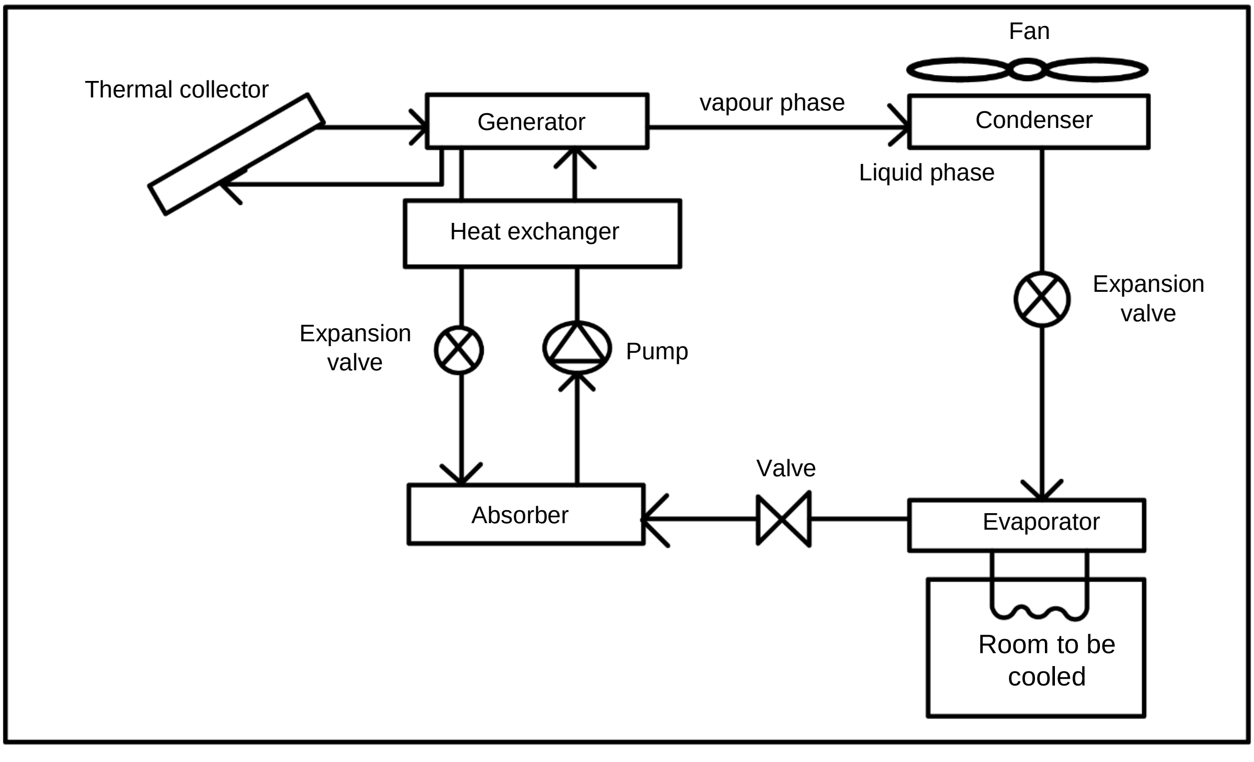

Figure 3.8: The solar air-conditioning absorption-based (Aman et al. 2014).

Subsequently, numerous explorations proposed to structure different contemporary solar plants with energy storage (Shirazi et al. 2016; Porumb et al. 2016). The system allows for reducing the environmental impacts and accomplishing the energy demand (Ibrahim et al. 2017). This examination explored two-fold stage or single-stage absorption systems without crystallisation and using crystallisation. The single-stage systems are supplied with a few storage tanks and two heat exchangers (Ibrahim et al. 2017). However, the twofold stage systems are unique in relation to the performance systems by including the two pairs of generator/absorber and condenser/evaporator. Also, the crystallisation procedure occurs while the refrigerant undergoes three-stage conversion (strong: typically solidified salt, vapour and fluid) (Ibrahim et al. 2017). As well, the presentation of these plants is firmly connected to the climatic conditions of the districts where they are introduced (Allouhi et al. 2015). For example, Mediterranean nations are portrayed by a hot climate, which supports the utilisation of solar air-conditioning (Allouhi et al. 2015). Also, Tunisia generally puts resources into solar power – this nation is described by a radiant climate over significant lots of the year (Balghouthi et al. 2016). An absorption solar establishment is connected in the research study of Balghouthi et al. (2016) to a room of 150 m^2 to limit the energy consumption throughout the late spring. It comprises a high-temperature water storage tank having a volume of 0.8 m^3, a level plate solar gatherer having a zone of 30 m^2 and a water-lithium bromide ingestion chiller having a limit of 11 kW. The COP achieved 0.725 in the simulation results for a cooling limit of 16.5 kW when the warmth source temperature rises. This enables the development of the heat transfer between the amount of heat conveyed in the environment and the system exchangers (Balghouthi et al. 2016). In like manner, another examination analysed the power execution of a solar air-conditioning workplace that most extreme month to month expends around 380 kWh (Soussi et al. 2013). It comprises cooling the rooftop and insulating the walls. Consequently, it permits achieving a power saving of 46% and 80% in summer and winter, respectively, while decreasing the 14.09 to 8.68 kW cooling load (Soussi et al. 2013). Likewise, the examinations by Balghouthi et al. (2012, 2014) expect to improve the efficiency of a solar system equipped with parabolic solar accumulators with an area of 39 m^2, several fan loops are introduced in the building to be cooled, channel back capacity and two tanks for capacity, a reinforcement radiator and an ingestion chiller related to a cooling tower. As indicated by Balghouthi et al. (2012), the concise plan presenting the fundamental segments of the proposed cooling system is represented in Figure 3.9.

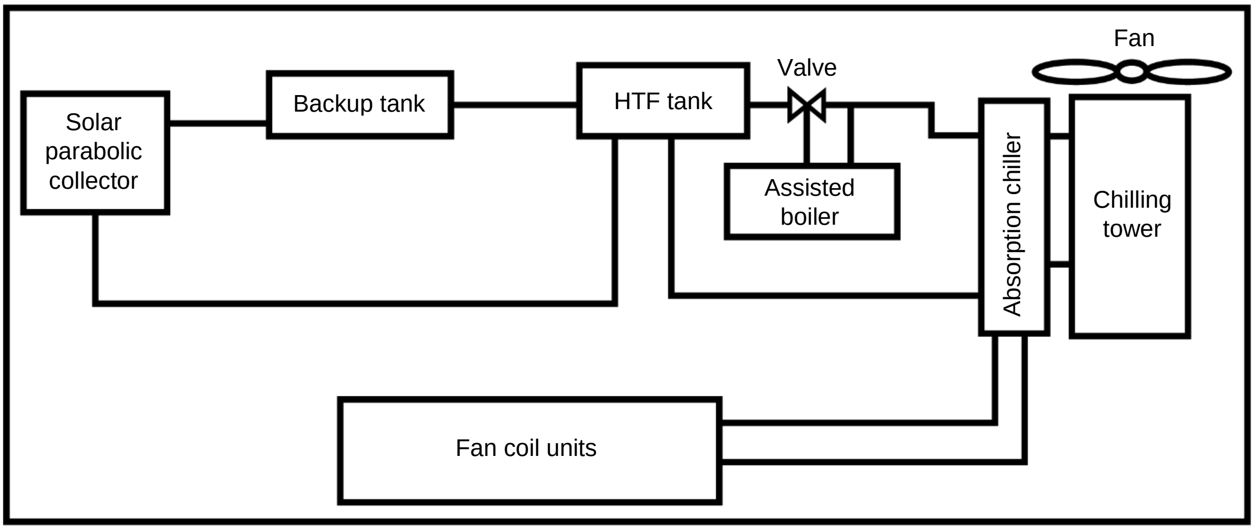

Figure 3.9: Solar cooling synoptic representation utilising parabolic accumulators (Balghouthi et al. 2012).

Thus, the investigation of the system operation demonstrated that the absorption chiller yield could reach up to around 12 kW. Additionally, the system achieves a COP of 0.8 and 0.9, respectively (Beccali et al. 2016). Furthermore, it achieves a power saving of 1154 L of gasoil and lessens the CO_2 discharge of around 3000 kg throughout hot seasons (Beccali et al. 2016). This kind of solar air-conditioning is evaluated in the research studies by Cabrera et al. (2013) and Drosou et al. (2016) for heating and cooling office buildings in Greece. In both studies, it is described by a small gathering surface of around 14 m^2, high productivity and lower thermal losses. Power saving of up to 50% can be acquired (Drosou et al. 2016). However, the implementation costs are higher, around 924 €/m^2 of the solar accumulator (Drosou et al. 2016). The system is unsustainable as the upkeep is recurrent and costly. A research study by Greenaway and Kohlenbach (2017) analysed the performance of a solar air-conditioning established by a twofold impact absorption chiller and parabolic thermal accumulators having an area of 588 m^2. The system has yearly normal effectiveness of 40% and top productivity of 58% (Greenaway and Kohlenbach, 2017). It likewise permits chilling water contained in a capacity tank of 23,000 L that is utilised as a cradle tank. The yearly normal COP of the absorption chiller can achieve about 1.1, which is a water-cooled twofold impact chiller. In any case, its expenses are high and reach up to $ 680,000 which can be paid after around 21 years (Greenaway and Kohlenbach, 2017).

As indicated by Djelloul et al. (2013), solar power is likewise ensemble in Algeria to cool buildings in warm climates. Djelloul et al. (2013) built up a model of the absorption cooling system of 10 kW and the air conditioner, which is established by solar accumulators with a 900-L hot capacity tank, an area of 28 m^2, just as a thermally determined chiller and cooling tower. The outcomes acquired demonstrate that the solar system with a COP equivalent to 0.73 can fulfil the required conditioned air of a home with a superficial of 120 m^2 (Djelloul et al. 2013). Wang and Yang (2016) proposed an effective hybrid system for cooling, power and heating systems driven by biomass and solar energy connected to a building with a 100-kW power load. It comprises of double source fuelled blended impact ingestion water chiller, interior ignition, solar cleared gatherer and a biomass gasification subsystem. Indeed, the system permitted a decrease of the carbon discharge proportion of about 95%, energy saving of about 57%, and giving around 200 kW of cooling power. Also, the COP of 1.1 for the system is high (Wang and Yang, 2016).

Besides, the high encompassing temperatures in numerous nations cause an unending interest in cooling, which permits accomplishing a noteworthy logical development in the solar air-conditioning domain. For example, the exploration by El-Shaarawi and Al-Ugla (2017) presents a solar-controlled LiBr-water absorption air-conditioning in Saudi Arabia. It is furnished with capacity tanks and a level plate accumulator of refrigerant, which guarantees a consistent task of 24 hours in 7 days and the chiller has a cooling limit of 5 kW. El-Shaarawi and Al-Ugla (2017) in like manner give their mathematical model utilising flimsy time-subordinate estimations of the encompassing temperature and the solar power that are thought to be steady over given small-time interims Δt. As well, the summed-up power equation over each Δt, expecting unchanging stream forms is specified via equation 3.1 (El-Shaarawi and Al-Ugla, 2017):

$$Q - W = (\sum m.h)_{out} - (\sum m.h)_{in} + m(u_f - u_i)_{system} \qquad (3.1)$$

Q and W remain the mechanical and net thermal energies ($Q = Q_G + Q_E - Q_A - Q_C$ and $W = W_P$). Also, $u_f - u_i$ is the change in internal energy per unit mass inside the volume (V) during the time Δt (u_i is the initial value, whereas u_f is the final internal energy per unit mass inside the volume (V) at the end of time phase Δt). Likewise, the enthalpy is $h_{(1\ to\ 10)}$ while m is the mass inside the volume (V) of an individual system component. The whole system is working with a medium that has mass, volume, and internal enthalpy. A schematic flow diagram for equation 3.1 is provided in Figure 3.10.

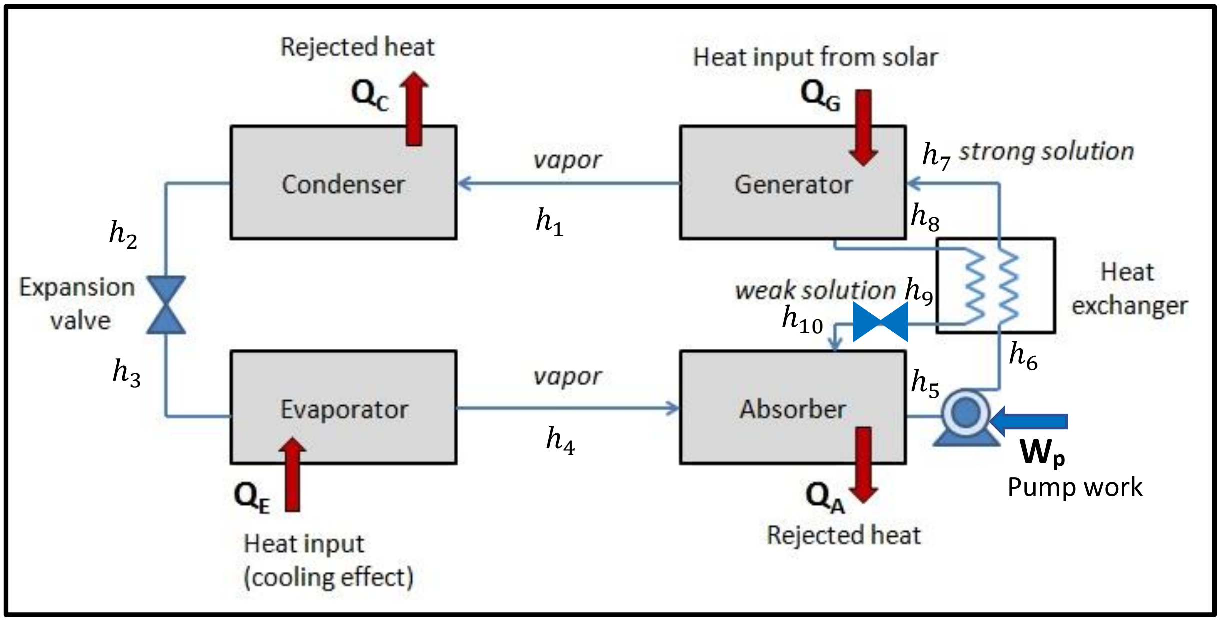

Figure 3.10: Schematic diagram of a typical absorption solar air-conditioning (El-Shaarawi and Al-Ugla, 2017)

Additionally, the mass flow rates of the strong and weak refrigerant-absorbent compounds for lithium bromide-water to prevent crystallisation are based on mass concentrations for strong and weak solutions. These are specified via equations 3.2 and 3.3 (El-Shaarawi and Al-Ugla, 2017).

$$\dot{m}_{ss} = X_{ws}/(X_{ss} - X_{ws}).\dot{m}_r \quad (3.2)$$

$$\dot{m}_{ws} = X_{ss}/(X_{ss} - X_{ws}).\dot{m}_r \quad (3.3)$$

X_{ss} and X_{ws} remain the mass concentrations for strong and weak compounds. By applying the energy balance for the solution, the generator and evaporator heat and pump are presented in equations 3.4, 3.5 and 3.6 (El-Shaarawi and Al-Ugla, 2017).

$$Q_G = (\dot{m}_r h_1 + \dot{m}_{ws} h_8 - \dot{m}_{ss} h_7)\,.\Delta t \quad (3.4)$$

$$Q_E = (\dot{m}_r (h_4 - h_3))\,.\Delta t \quad (3.5)$$

$$W_P = (\dot{m}_{ss}(h_6 - h_5)) \, . \Delta t \quad (3.6)$$

Enthalpy $h_{(1\ to\ 10)}$ is grounded upon the thermodynamic condition as revealed in Figure 3.11 and Δt is a 1-h time-step interval (El-Shaarawi and Al-Ugla, 2017). For a consistent load, a hot storage mass of 1500 kg and an accumulator domain of 48 m^2 – simulation outcomes showed that the COP of the system is around 0.85. In any case, the exploratory outcomes demonstrated that it could achieve 0.9 (El-Shaarawi and Al-Ugla, 2017). At the degree of the size of system segments (tanks and accumulator), they turn out to be smaller in summer when the intensity of solar is high. Therefore, the essential mass storage will be decreased, and the COP will be upgraded.

In a similar setting, several associated investigations were done in Australia. For example, a study by Goldsworthy (2017) demonstrated a building with a volume of 60 m^3 outfitted with a self-governing solar photovoltaic-battery air conditioner to fulfil the ideal wellbeing with the lowest energy consumption. For the accustomed humidity ratio HR_S and air temperature T_S are calculated using equations 3.7 and 3.8 (Goldsworthy, 2017).

$$T_S = T_b - \frac{Q_S}{\dot{m}c_p} \quad (3.7)$$

$$HR_S = HR_b - (Q_t - Q_s)\, \dot{m}h_{fg} \quad (3.8)$$

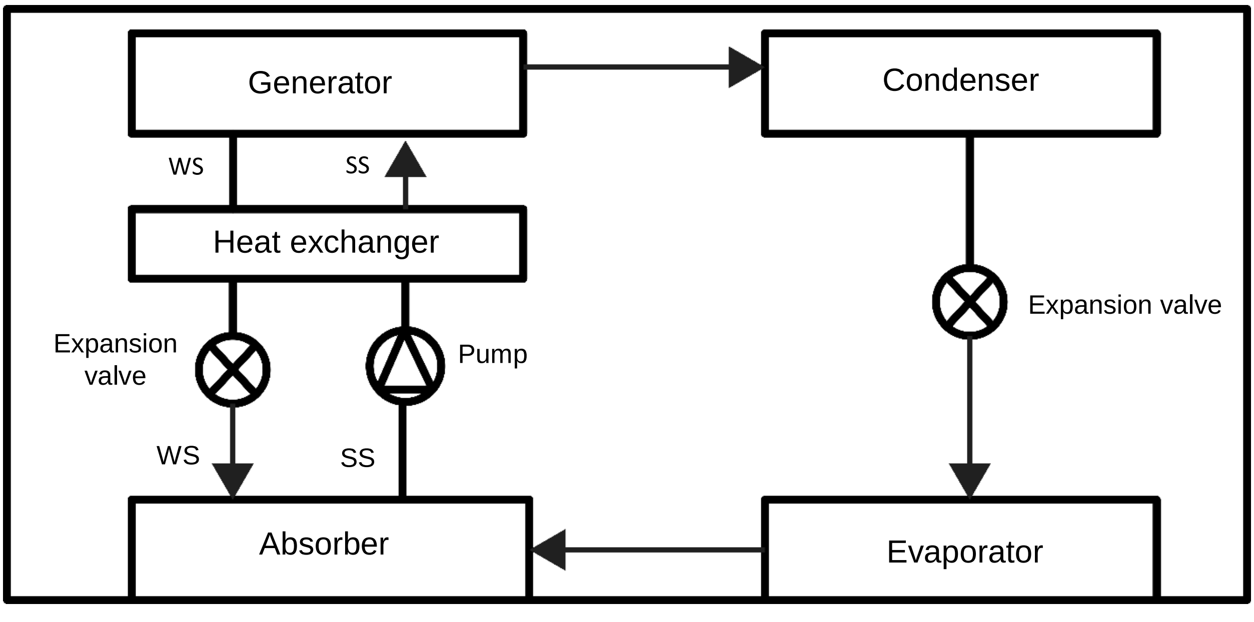

Figure 3.11: LiBr-H_2O absorption thermodynamic state (El-Shaarawi and Al-Ugla, 2017).

Q_t and Q_s remain the total cooling and sensible power, ṁ is the supply air flow rate (0.275 kg/s), h_{fg} is the heat of evaporation of water, and T_b is the building's air-temperature (Goldsworthy, 2017). The nearness of the battery is obligatory, and the system can be utilised throughout highpoint times to give the power mandatory. For sure, the power in the battery $E_{battery}$ is resolute using equation 3.9 (Goldsworthy, 2017).

$$\frac{dE_{battery}}{dt} = \eta_c P_c - 1/\eta_d P_d \tag{3.9}$$

For η_d is the discharge efficiency, η_c is the charge efficiency, P_d is the battery discharging energy and P_c is the battery charging energy. The recreation consequences of the humidity and interior temperature were done for various sorts of climates and buildings utilising TRNSYS. The system improved the solar portion by 30% (Goldsworthy, 2017). Also, foci solar warm accumulators and medium temperature are utilised in an air-conditioning with a two-stage impact absorption chiller and auxiliary heater to cool a building (Li et al. 2017). The fundamental parts of the proposed air-conditioning are presented in Figure 3.12 as indicated through research studies by Li et al. (2017). For a capacity tank volume of 40 L/m^2 and a collector area of 2.4 m^2/kW of cooling, the outcomes of the simulation while utilising TRNSYS demonstrated that the system can cover half of the heap needs of the systems (Li et al. 2017). Furthermore, the COP of the system is 1.4 which uncovers the system efficiency.

In any case, the exploration by Ha and Vakiloroaya (2015) combines the solar power with a customary vapour compressor air conditioner to play out another hybrid solar-driven air-conditioning. The anticipated system was controlled and displayed utilising TRNSYS to improve its energy production. It is comprised of three primary parts namely, a solar storage tank, a solar vacuum accumulator and a vapour compressor system). At steady-state conditions, the blower control utilisation was diminished from 1.45 to 1.24 kW, which is traduced by a global energy saving of around 14 and 7.1% for just the blower (Ha and Vakiloroaya, 2015). Also, a power-saving accomplished by the condenser fan is about 2.6% as shown by Ha and Vakiloroaya (2015), which permits rising COP. In like manner, the investigations by Ha and Vakiloroaya (2015) unfolded that the system can fulfil effective cooling prerequisites. The absorption system uses environmentally unfriendly refrigerants having the risk of corrosion of the components and risk of the crystallisation of the solution at low cooling temperatures (Salman and Ali, 2018).

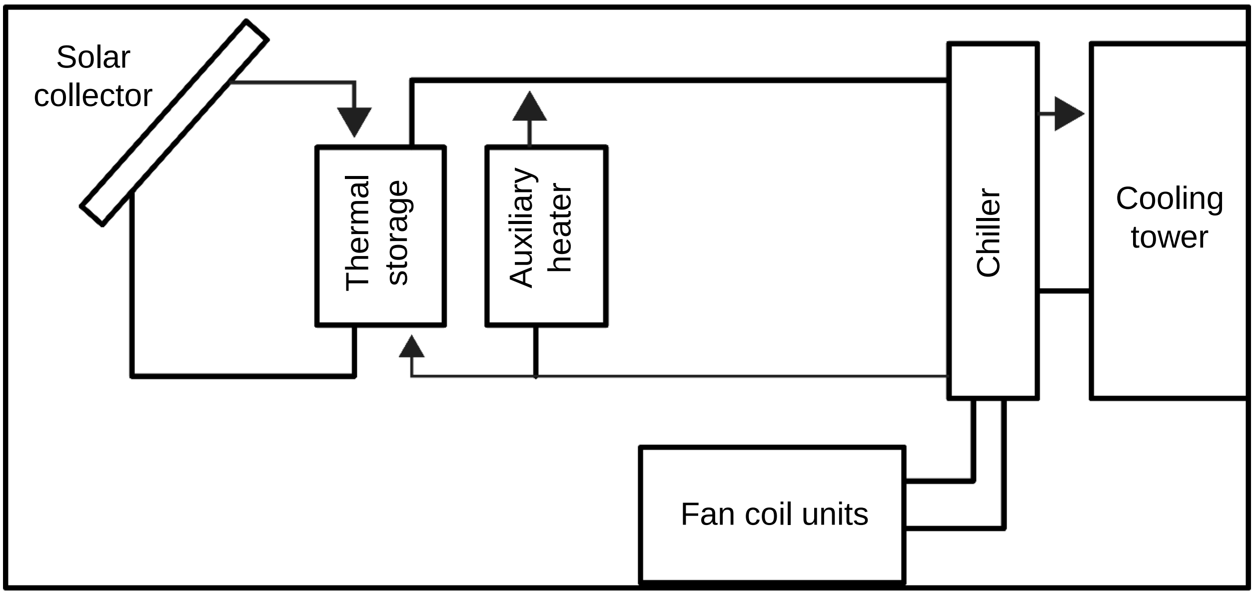

Figure 3.12: Solar air-conditioning system components (Li et al. 2017).

3.2.2 The Solar Air-Conditioning Adsorption-Based

Studies uncovered that solar adsorption systems have long haul environmental advantages and noteworthy energy effectiveness like the of absorption air-conditioning (Hadj et al. 2015; Islam and Morimoto, 2016). For they utilise regular refrigerants as depicted by Vasta et al. (2013) and can be determined by a low-temperature heat source as explored by Hadj et al. (2015).

Various examinations have been centred around the structure of solar adsorption air-conditioning (Vasta et al. 2013; Hadj et al. 2015). In any case, their structure is intricate and a few constraints similar to the heat rejection, are difficult to be resolved by utilising old-style apparatus (Vasta et al. 2013). Research by Vasta et al. (2013) built up an active prototypical in Italy to mimic a solar cooling system fortified with a reinforcement element, adsorption chillers and a heat rejection component, which are determined by solar accumulators conveyed over an area of 27.52 m^2 to cool a level structure region of 130 m^2. Thus, the examinations by Vasta et al. (2013) communicate the heat presentation of the solar accumulators as:

$$\frac{Q}{A} = G\left(\eta_0 - 1.485\ \frac{(T_m - T_a)}{G} - 0.002\ \frac{(T_m - T_a)^2}{G}\right) \tag{3.10}$$

A is their area, η_0 is the ratio of the efficiency measured at actual admitted irradiance to vertical admitted irradiance, G is the intensity of the solar radiation. Q is the power of solar collectors, T_a is the ambient temperature and T_m is the collector average temperature. For 1000 L of water is likewise cooled by the system and can be utilised in several actions. Nevertheless, the COP of the chiller is small equated to the electric one: 0.35 and 2.5, individually. They are calculated via equations 3.11 and 3.12 (Vasta et al. 2013).

$$COP_{chiller} = \frac{Q_{ev}}{Q_s + Q_{heater}} \tag{3.11}$$

$$COP_{electric} = \frac{Q_{ev}}{E_{el,tot}} \tag{3.12}$$

$E_{el,tot}$ is the overall electric utilisation of the entire system mechanisms, Q_{heater} is supplied power through the stoppage element, Q_s is supplied power through the solar accumulators and Q_{ev} is energy evaporation constituting the suitable outcome of the chiller. Similarly, the proportion of the entire energy needed through the whole system and the supplied energy via the warm air accumulators, named solar fraction is specified via equation 3.13 (Vasta et al. 2013).

$$SF = Q_s / Q_{ev} + Q_{heater} \tag{3.13}$$

Furthermore, the establishment expenses are high, around $ 29,022 and the paid back period is subsequently around 13 years. Equally, around 3942.45 kWh and $ 1085 of electric power are spared every year (Vasta et al. 2013). Alternative adsorption cooling system utilising a rounded solar 1-m^2 two-fold coated adsorber/accumulator was structured as appeared in Figure 3.13 according to research by Hadj et al. (2015). In the Sub-Sahara areas in Algeria, the primary target is to diminish the energy consumption of cooling systems. In August, an energy saving of around 28.3 MWh could be achieved (Hadj et al. 2015). On the other hand, the solar COP is excessively low, around 0.21.

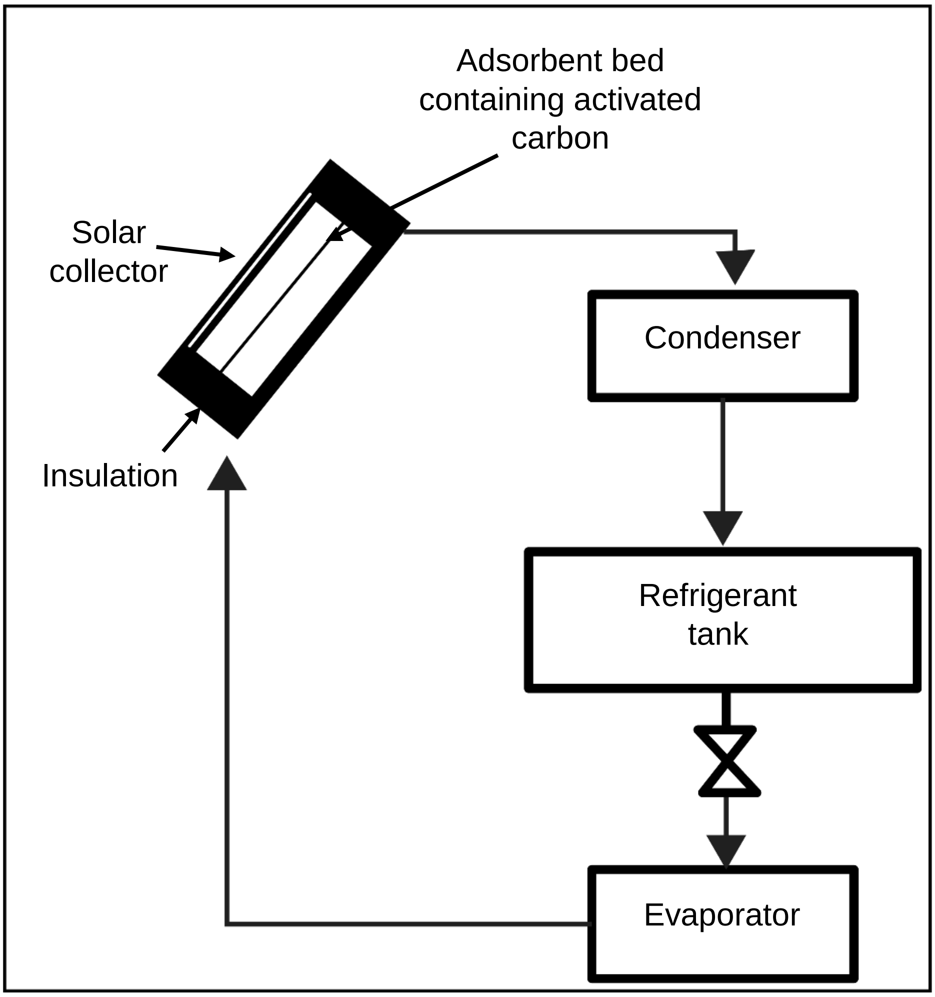

Figure 3.13: Adsorption solar cooling synoptic representation (Hadj et al. 2015).

A study by Zhang et al. (2016) revealed that a decrease of the energy consumption of about 50% was accomplished, particularly in wet and hot climates because of the utilisation of solar energy for the generation of cold temperatures. In like manner, their study exploited a customary cooling system with a drying-out cooling cycle that can be adjusted to the fixed solar cells to air-condition a household volume of 330 m^3 utilising 2 m^3 heated water tank and 20 m^2 level plate accumulator (Zhang et al. 2016), which can be utilised in domestic exercises. In any case, the COP cooling system of 0.6 is low due to the lower operating system. Also, the indoor climate does not satisfy normal wellbeing standards for a couple of hours all through the cooling season (Zhang et al. 2016). Another air-conditioning/water system for structures is exhibited in the exploration studies by Jafari and Poshtiri (2017). It is established by a solar chiller area of 12 m^2, a cooling channel area of 24 m^2 and a solar-driven adsorption chiller, via which the hot air is disseminated and cooled in the assessment chamber having a volume of 200 m^3 under moist and hot, and dry and hot climate. The COP of the chiller and cyclic cooling limit achieved their most extreme qualities of around 0.71 and 16 kW discretely all through the day and somewhere in the range of 15 and 16 h. (Jafari and Poshtiri, 2017). This permitted reducing the room temperature by 26.8%. In addition, the electric energy used up by the system is 37% which is not as much as that used up by a split inverter air conditioner partaking similar cooling energy (Jafari and Poshtiri, 2017).

Thus, the adsorption and absorption innovations can be consolidated in a similar air-conditioning to further improve its performance. As an issue of actualities, a research study by Buonomano et al. (2018) proposed innovative solar poly-generation systems, grounded upon both absorption and adsorption chiller innovations encouraged by level thermal accumulators/photovoltaic and dish-moulded absorbed rather than regular solar accumulators. Buonomano et al. (2018) built up a mathematical model to decide the ideal system arrangements considering the climatic conditions and working parameters. The systems are connected to inhabit office buildings situated in various climatic EU areas. The exploration study by Buonomano et al. (2018) offered high-temperature water and energy, just as they guaranteed cooling and heating of the air-conditioned buildings. However, combining solar air-conditioning with indoor smart control systems will reflect the overall sustainability of the system, vis-a-vis reduction of energy consumption and carbon emissions and tackling poor IAQ within the indoor environment. According to Salman and Ali (2018), adsorption solar air-conditioning is an environmentally friendly cooling technology that is driven by solar energy. In comparison with the absorption system, an adsorption system has no problems such as corrosion at high temperatures and saline crystallisation. In comparison with a vapour compression refrigeration system, it has the benefits of a simple control system. Table 3.1 synopsise the efficiency and strategy principles of the solar air-conditioning system.

Table 3.1: Efficiency and strategy principles of adsorption and absorption of solar air-conditioning.

	Adsorption-based solar air-conditioning	References	Absorption-based solar air-conditioning	References
Strategy Principles	Volume of storage water (small): up to 2 m^3	Zhang et al. (2016).	Volume of storage water (small): 0.8 m^3	Balghouthi et al. (2016)
	Collector area: 1 – 20 m^2	Zhang et al. (2016)	Collector area: 14 – 96 m^2	Drosou et al. (2016)
	Building surface or volume: minimum 130 m^2, up to 330 m^3	Zhang et al. (2016)	Building surface or volume: up to 150 m^2	Balghouthi et al. (2016)
Optimisation strategy	Using tubular solar double-glazed collector/adsorber; Using adsorption chillers that are sustainable; Using low-temperature heat supply.	Vasta et al. (2013); Hadj et al. 2015; Jafari and Poshtiri, 2017	Adding batteries; Small size of collectors and tanks; Associating biomass and solar energy; Using parabolic and concentrated thermal collectors; Insulating the roof of the building and the walls	Soussi et al. 2013; Ha and Vakiloroaya (2015); Wang and Yang, (2016); Goldsworthy (2017); Greenaway and Kohlenbach (2017)

Capacity of cooling	About 16 kW	Jafari and Poshtiri, (2017)	From 5 to 16.5 kW	Balghouthi et al. (2016)
Efficiency – COP	From 0.2 to 0.7	Jafari and Poshtiri, (2017)	From 0.3 to 0.75 and sometimes up to 1.4	Aman et al. (2014); Li et al. (2017)
Benefits to the environment	Saving Energy: up to 28.3 MWh; About 50%.	Hadj et al. (2015); Islam and Morimoto, (2016); Buonomano et al. (2018)	Energy consumption reduction up to 80% during summer; CO_2 emissions reduction of about 95%	Soussi et al. (2013); Wang and Yang, (2016)

Subsequently, this study adopted the adsorption of solar air-conditioning because it has long-term environmental benefits as indicated by Jafari and Poshtiri (2017). It provides an improvement for significant energy efficiency (Palomba et al. 2015). Also, the system is sustainable and the most widely used in recent times (Zhang et al. 2016). Solar thermal systems and photovoltaic ones can be combined to improve their performance (Ramos et al. 2017). A study by Goswami and Kreith (2016) revealed that the solar thermal adsorption system can be modified or replaced with photovoltaic array and other components such as the inverter, heat pumps etc. can be added for optimisation purposes. For the thermal systems, the components of the adsorption system are a solar collector, condenser, tank for hot and cold storage, evaporator, pumps, adsorption chiller, heat rejection element or outdoor unit and pipes (Norhayati et al. 2021), while the components of solar air-conditioning using photovoltaic are photovoltaic array, alternating/direct current inverter, heat pump (includes evaporator and condenser), indoor cold circulation, Domestic Hot Water (DHW), pumps, pipes and outdoor unit (Ronald, 2013; Goswami and Kreith, 2016).

The main difference between solar photovoltaic that were considered in this study and solar thermal can be found in their working principles. Solar photovoltaic is based on the photovoltaic effect, by which a photon (the basic unit of light) impacting a surface made of a special material generates the release of an electron. Solar thermal, on the other hand, uses sunlight to heat a fluid (depending on the application, it can be water or other fluid) (Gugulothu et al. 2015). The photovoltaic effect only takes place in a reduced number of materials, called semiconductors (such as silicon-monocrystalline, polycrystalline, amorphous and cadmium telluride), that allows the generation of an electric current when exposed to light (Numan and Hussein, 2020). Those semiconductors are shaped into thin layers that conform to the core element of solar cells, the basic elements of a solar photovoltaic system, that produce a direct current (Gugulothu et al. 2015; Numan and Hussein, 2020). The working principle of solar thermal systems is far less sophisticated but as useful for the generation of consumable energy as the photovoltaic effect. It consists of the direct heating of water (or other fluids) by sunlight (Ramos et al. 2017). That energy conversion takes place at different devices depending on the range of temperatures at which the working fluid is being heated. Low and medium temperature collectors can be flat plate panels or evacuated tubes (Jafari and Poshtiri, 2017; Ramos et al. 2017).

Regarding the use of these technologies, the first step is to separate small, household solar systems from power plants, in both photovoltaic and adsorption solar air conditioning systems (Ramos et al. 2017). While photovoltaic systems generate electricity directly from solar energy, thermal systems heat a fluid that will run a steam engine, gas turbine or similar. To power the air-conditioning, the photovoltaic and adsorption solar systems share the production of electricity as their aim (Xudong and Xiaoli, 2019). The proposed sustainable system aims to offer a long-term environmental benefit with significant energy efficiency. The next chapter provides the component description and equations for solar air-conditioning while incorporating the modelling equations presented into Polysun. Therefore, the proposed layout of the sustainable system for this study is presented in Chapter four.

Consequently, it has been found that previous researchers were unsuccessful in their approach to sustainability for the air-conditioning system by capitalising on one aspect of sustainability. This study examines, applies, and consolidates the three bottom-line principles of sustainability namely, environment, social and economic dynamics for the overall sustainability of solar smart air-conditioning. Therefore, this study deliberates upon the points below, to achieve strong sustainability of the system.

- The feasibility of combining both the renewable and indoor smart/intelligent system as a unique system to reflect greater sustainability of the system.
- Environmental sustainability is a core part of the system framework for photovoltaic solar air-conditioning and indoor environment. In other words, combatting the level of energy consumption and carbon emission, vis-à-vis eliminating the major indoor air pollutant (CO_2) while maintaining the maximum IAQ with the use of advanced smart indoor systems.
- A sustainable smart system that considers the three pillars of sustainability namely environment, economic and social as a whole.
- A methodological sustainable theoretical framework that is underlined by the three sustainable principles as a pathway to achieve the overall sustainability of the system can, however, serve as a model/framework for future sustainable smart air-conditioning.

Consequently, the next section of this study focuses on the indoor environment quality and the requirement of smart technologies aiming to combat poor IAQ and thermal comfort within the indoor environment. This will even reflect greater sustainability of the system for the building inhabitants.

3.3 The Indoor Environment

A research study suggested that air-conditioning has been utilised in numerous places of the world (Mauthner and Weiss, 2014). The reason for most systems is to give a satisfactory IAQ and thermal comfort for inhabitants (Guo et al. 2012). In like manner, with the development of the way of life, inhabitants require an increasingly healthy and pleasant indoor environment (Gugulothua et al. 2015). In any case, people spend 80% – 90% of their time indoors, and the indoor environment has a significant impact on work proficiency and human wellbeing (Yu and Lin, 2015). The components influencing the indoor environment for the most part consist of gaseous pollutants, biological pollutants, particle pollutants, ventilation, air movement, air exchange rate, humidity and temperature (Leung, 2015). Research studies by Yu et al. (2008) and Leung (2015) also found that there is an expansion in the commonness of SBS somewhere in the range of 30% – 200% in the buildings with air-conditioning when compared with normal ventilation systems.

One of the consequences of the worldwide energy crisis in 1970s is the public recognition of the importance of energy saving. (Yu et al. 2008). The buildings built since then are more airtight and use a great deal of insulation materials to minimize the loss of energy through the building envelope (Gao et al. 2012). Fresh air is reduced in air-conditioning systems in order to reduce the energy consumption. Meanwhile, synthetic materials and chemical products (e.g., building materials and decorating materials) have widely been used indoors (Yu et al. 2008). The combination of low ventilation rates and the presence of numerous synthetic chemicals results in elevated concentrations of VOCs (formaldehyde, toluene and benzene), indoor molecule contaminations, CO and CO_2 emissions. This is regarded to be a major contributing factor to compound hypersensitiveness (Wang et al. 2004a; Yu et al. 2008; Montero-Montoya et al. 2018). It is indoor toxins that lead to poor IAQ. Moreover, several studies accept that IAQ might be the most significant and moderately ignored environmental issue in a recent period (Gao et al. 2012; Tham, 2016; Beama, 2016; WHO, 2018). In essence, the following sessions in this study will explore the IAQ, energy efficiency and the requirement of a smart control strategy that is focused on the sustainability approach of the indoor environment.

3.3.1 The Air-Conditioning Indoor Air Quality

As air-conditioning has been generally utilised for healthier thermal comfort in buildings, the issues triggered via poor IAQ happen regularly (Kabrein, 2017). IAQ is not an idea that can be effectively characterised, since the awareness of air in an indoor environment is a measure related to different parameters like inhabitant comfort and health (Schieweck et al. 2018). Besides, poor IAQ is positioned as one of the uppermost five environmental dangers to inhabitants' wellbeing by the United States Environmental Protection Agency (USEPA) grounded on comparative risk field studies (Kabrein, 2017; Environmental Protection Agency, 2018). Hitherto, subjection to indoor air contaminations is accepted to have expanded because of an assortment of variables, including the development of firmly fixed structures, decrease of ventilation rates for saving energy, and the utilisation of manufactured building materials and decorations just as synthetically defined individual upkeep items, family unit cleaners and pesticides (Kukadia and Upton, 2019).

There are various sorts of indoor toxins, for example, indoor particulate matters, CO_2, and VOCs (Tang et al. 2015, Hamanaka and Mutlu, 2018). As presented in Table 3.2, the poor IAQ may trigger a few kinds of health effects such as fatigue, headache chest pain etc. Another serious issue that can trigger poor IAQ is the scent or odour problem that causes numerous effects on the human body, for example, mental distraction, efficiency decrease, and so forth as exhibited in Table 3.3. Subsequently, it is essential to control and monitor IAQ for improving profitability, and comfort individuals' health in the built environment (Wolkoff, 2013). As indicated by previous investigations, ways to deal with and improve IAQ in the building can be as per the following (Wolkoff, 2013; Kukadia and Upton, 2019; USEPA, 2020):

- Individual contact estimations, for example, nitrogen dioxide as an intermediary for introduction to traffic contaminations/combustion;
- Black carbon particles: a potential intermediary for ignition particles to assess wellbeing dangers;
- UFP (on-line): size-dispersion and number. Elemental carbon analysis and transition metal;
- High volume inspecting; Responsive Oxygen Species (ROS), for example, antioxidant depletion and OH radicals;
- A sampling of prone species, for example, auxiliary ozonides.

Table 3.2: Indoor pollutants and their impacts on human health.

Indoor Pollutants	Causes	Health effects	Reference
Particulate matters	Outdoor environment, cooking, combustion activities (burning of candles, use of fireplaces, heaters, stoves, fireplaces and chimneys, cigarette smoking), cleaning activities.	Premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms.	Brook et al. (2010); Hamanaka and Mutlu, (2018); USEPA (2020).
VOCs	Paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry-cleaned clothing,	- Eye, nose and throat irritation - Headaches, loss of coordination and nausea - Damage to liver, kidney and central nervous system - Some organics can cause cancer	Weschler and Nazaro, (2012: 2014); Tang et al. (2015); USEPA (2020)

	building materials and furnishings.		
CO_2	Cooking stoves; tobacco smoking; fireplaces; generators and other gasoline-powered equipment; outdoor air.	Fatigue, chest pain, impaired vision, reduced brain function, death.	Wolkoff (2013); Liu et al. (2014); USEPA (2020)

Table 3.3: The effects of odour.

Irritation Type	Symptoms	References
Mental	Sleeping difficulties	Atari et al. (2009); Capelli et al. (2019)
Mental	Tension, Anger	Hoenen et al. (2017); Kontaris et al. (2020)
Mental	Depressions	Capelli et al. (2019); Tatiana and Philomena, (2021)
Mental	Confusion	Oltra and Sala (2014); Wolkoff (2018)
Mental	Tiredness	Oltra and Sala (2014); Girard et al. (2016)
Gastric	Nausea	Capelli et al. (2019); Spence (2020); Tatiana and Philomena, (2021)

Gastric	Diarrhoea	Omanga et al. (2014); Steinemann (2017)
Head	Headache	Atari et al. (2009); Kim et al. (2019)
Skin	Skin rashes	Atari et al. (2009); Wolkoff and Nielsen, (2017)
Respiratory	Cough	Atari et al. (2009); Guo et al. (2016)
Throat	Irritation in throat	Blanes-Vidal et al. (2014); Wolkoff (2018)
Eyes	Irritation in eyes	Wolkoff, (2013: 2018)
Nose	Irritation in nose	Blanes-Vidal et al. (2014); Wolkoff (2018); Capelli et al. (2019)

Moreover, research studies reveal that a testing model of IAQ was established in the building setting and grounded upon the European Standard CEN 1752 to decide the outdoor airflow percentage and to confirm the IAQ in housings (Settimo et al. 2020; EC, 2020). Outcomes demonstrate that the climate in rooms influences the wellbeing and the strength of the inhabitants in the meantime. Also, it is exhorted that the architects for structuring and operating of air-conditioning should safeguard the wellbeing parameters at the ideal qualities for healthier running and control performance. For the reason to control and operate air-conditioning with the end goal of sustainability, in relation to improving IAQ – investigations on sustainable approaches for smart control advancements are required.

Subsequently, studies uncover that there are various kinds of indoor air poisons; however, it is an intricate issue to screen every one of them (Tune et al. 2013; EPA, 2018; Manisalidis et al. 2020). Indoor CO_2 concentration analysis and estimation may be valuable for comprehending ventilation and IAQ adequacy (Persily and de-Jonge, 2017; Teleszewski et al. 2019; EC, 2020). Albeit CO_2 near 10,000 ppm is adequate to fit individuals without any wellbeing impact, the CO_2 level ought to be 650 ppm or held underneath 1,000 ppm over the encompassing level to counteract any gathering of related human odour (ASHRAE Standards 62.1, 2019). Moreover, Table 3.4 present the damage to the human body triggered via high CO_2 concentration.

Table 3.4: The concentration effects of CO_2.

CO_2 concentration [ppm]	Health impacts	References
500	Increased heart rate, change in heart rate variability, increased blood pressure, increased peripheral blood circulation	Kajtár and Herczeg, (2012); MacNaughton et al. (2016); Vehviläinen et al. (2016); Zhang et al. (2017)
1000	Level associated with respiratory diseases, headache, fatigue, and difficulty concentrating in classrooms. Oxidative stress and damage to DNA in bacteria (implications for cancer diseases in humans)	Ezraty et al. (2011); Carreiro-Martins et al. (2014); Ferreira and Cardoso (2014); Allen et al. (2016); Carreiro-Martins et al. 2016; Zhang et al. (2017)
10,000	Cognitive impairment, increased diastolic blood pressure, increased respiratory rate, respiratory acidosis, metabolic stress (decreased blood calcium or urine phosphorus), increased	Hazardous Substances Data Bank, (2015); American Conference of Governmental Industrial Hygienists, (2017); Tu et al. (2020)

	brain blood flow, increased minute ventilation	
30,000	Headache, pulse, dizziness, decreased exercise tolerance in workers when breathing against inspiratory and expiratory resistance	National Institute for Occupational Safety and Health, (2014); ACGIH, (2017)
50,000	Dizziness, headache, confusion, dyspnea; May cause death	NIOSH, (2014); HSDB, (2015); ACGIH, (2017)
80,000 – 100,000	Severe headache, dizziness, confusion, dyspnea, sweating, dim vision, hypertension, and loss of consciousness; Unexpected death	NIOSH, (2014); HSDB, (2015); ACGIH, (2017)

ASHRAE stipulated the IAQ Standard 62.1, and it reports that: “for comfort, there may be acceptable IAQ if not more than 50% of the occupants can detect any odour and not more than 20% feel discomfort, and not more than 10% suffer from mucosal irritation, and not more than 5% experience annoyance, for less than 2% of the time” (ASHRAE Standards 62.1, 2019). In essence, to be able to successfully impact most of these issues, sustainable approaches associated with smart control strategies are required to operate renewable-based air-conditioning, in relation to optimise occupant comfort and significantly save energy – combatting global warming and climate change in the built environment.

3.3.2 The Air-Conditioning Energy Efficiency

According to IPCC (2007: 2014) and IEA (2018), the introduction of the use of mechanical means for providing desired comfortable temperature for building users is considered as one of the unfortunate phenomena of modern global development. This pattern has prompted tremendous energy consumption in the building stock, and these days, about 33% of non-renewable energy source is used up in buildings (IEA, 2018).

Nonetheless, there has been a noticeable rise in energy consumption in developed nations, and it is conceived that such a pattern will proceed sooner rather than later (Shan et al. 2018). For example, China is now responsible for more than 27% of total global emissions. The U.S., which is the world's second-highest emitter, accounts for 11% of the global total. India is responsible for 6.6% of global emissions, edging out the 27 nations in the EU, which account for 6.4%. China surpassed the United States and turned into the biggest CO_2 emissions and consuming country in 2015 (Shan et al. 2018). In this way, Fernandez et al. (2017) evaluate that the Chinese primary energy requirement would rise to 6200 Mtce in the year 2050 as indicated by the study of policy and technology alternatives for the progress to a sustainable energy system in China. Also, the utilisation of petroleum derivatives would represent over 70% of overall electricity cost and the relating emissions could achieve 10 $GtCO_2e$ (equivalent to 10×10^9 tonnes of CO_2) (IEA, 2018). Studies suggested that energy utilisation in rising economies in South America, Southeast Asia, the Middle East, and Africa will surpass that in the established nations in New Zealand, Australia, Japan, Western Europe and North America (Fernandez et al. 2017; IEA, 2018; China Renewable Energy Outlook, 2019).

The building sector in several established nations is one of the biggest energy-intense areas, more than both the transportation and industry, representing a bigger extent of the complete electricity utilisation (Global Status Report, 2017). For instance, in 2004, 40%, 39% and 37% of the overall primary energy requirement in the United States of America (USA), the United Kingdom (UK) and the EU respectively, was used for building sector (Fiaschi et al. 2012; EU, 2019). Investigations reveal that about 40% of the complete primary energy requirement used up in buildings additionally adds to over 30% of the CO_2 emissions (Costa et al. 2013; Fernandez et al. 2017). Several worldwide explorations to improve building energy effectiveness were begun as consequences of such apprehension (Senel-Solmaz, 2018; Liu et al. 2019) As indicated by Senel-Solmaz (2018) and Zeferina et al. (2019), they can be synopsised as pursues: optimisation and sensitivity on the strategies and development of building coverings (for example reflective coatings and thermal insulation, and life-cycle examination); the control of air-conditioning establishments and technical and lighting systems and economic investigation of energy effective measures for the remodel of current buildings. Studies unfold that the main consideration as there is a critical rise in energy use is as a result of the spread of the air-conditioning establishments because of the developing interest in the built environment for improved thermal comfort (Goyal et al. 2013; Lundgren-Kownacki et al. 2018). Moreover, representing about a portion of the overall electricity utilisation in buildings, particularly non-local buildings, air-conditioning is the biggest energy end-use in established nations (Albatayneh et al. 2019).

Besides, electricity consumption in both commercial and residential buildings is dominated by heating, ventilation, air-conditioning and lighting as represented in Figure 3.14 and Figure 3.15 (Bertoldi et al. 2018). An ongoing review of indoor environmental conditions has discovered that thermal well-being is positioned by building inhabitants to be of more prominent significance contrasted with acoustic and visual comfort and IAQ (Bertoldi et al. 2018). The plans of the building envelopes particularly the windows as well as coating systems are influenced by this outcome (Gimenez-Molina, 2013; Bertoldi et al. 2018). To have a better-quality comprehension of thermal comfort in recent and past development, IAQ is essential to deal with the power usage in buildings.

In addition, investigations have been done to improve the comprehension of how thermal well-being is identified and the related impact of energy consumption and carbon emissions, and environmental issues including social-economic and climate change. Given the scrutiny of the energy consumption of air-conditioning in buildings; techniques were presented for diminishing the electricity utilisation. Moreover, the energy productivity in buildings incorporates two perspectives: utilisation of renewable energy to power the air-conditioning, improvement the air-conditioning control and technologies. Prospects for decreasing high air-conditioning related power use incorporate the utilisation of normal ventilation, limiting energy wastes in customary systems by redesigning gear or cutting back the size of the hardware, and fitting-in proficient innovations, for example, satisfactory control techniques for the potentiality of saving energy. The state-of-the-act innovations and control techniques to reduce energy consumption for a satisfactory indoor environment are regularly being developed for inhabitants of buildings.

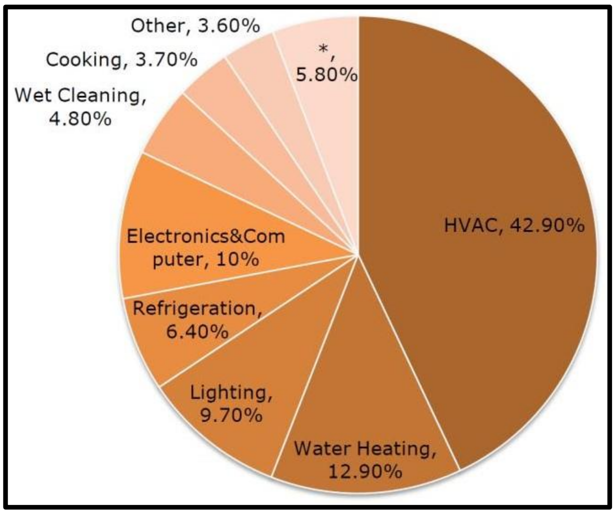

Figure 3.14: Overall energy end-use for residential buildings (Bertoldi et al. 2018).

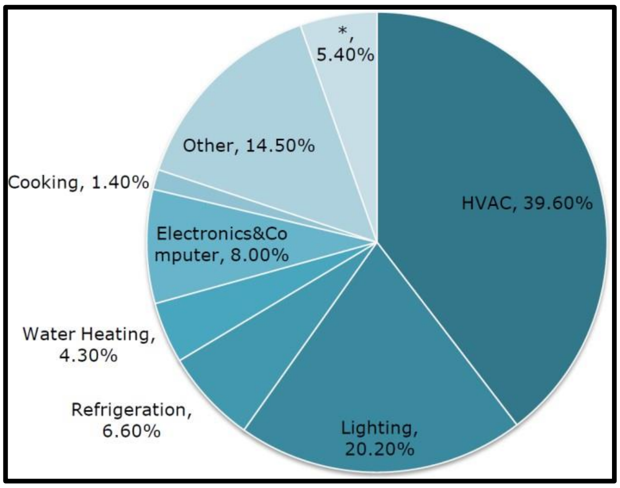

Figure 3.15: Overall energy end-use for commercial sector buildings (Bertoldi et al. 2018)

The purpose of incorporating the thermal wellbeing guides to deal with the energy consumption is one broadly utilising control technique (Taleghani et al. 2013). Information from comprehensive and thorough examinations led in climate chambers was utilised to create heat equalisation models and surveyed/measured information from field studies are utilised to create versatile models (Yang et al. 2015; Randall and Wood, 2018). The upside of the climate chambers test is having reproducible and reliable outcomes, and which of the field studies is the authenticity of the everyday living situations (Randall and Wood, 2018). As an outcome of existing thermal non-mainstream players, it is realised that more extensive scope of the thermal indoor environment can be utilised in circumstances/areas where air-conditioning is unavoidable and such activity would prompt fewer cooling necessities and subsequently less energy consumption for the air-conditionings (Kubba, 2016; Bertoldi et al. 2018). In this manner, the technique to establish a more extensive/changing scope or executing a higher Summer Setpoint Temperature (SST) of indoor plan temperature for various time and diverse open-air conditions were created (Raftery et al. 2018). There stand two noteworthy sorts of control strategies been anticipated to accomplish this objective dependent on such circumstances. Different indoor regulator techniques, for example, altering the setback time frame, setback temperature and setpoint temperature are associated with the first category (Moon and Han, 2011; Raftery et al. 2018; Turley et al. 2020). The subsequent sort manages the dynamic control of the setpoint temperature dependent on versatile wellbeing models (Singh et al. 2011; Kramer et al. 2017; Huertas et al. 2019).

Table 3.5: Energy savings synopsis in cooled buildings.

Building	Measure	Outcome	Reference
Museum	Indoor climate conditioning algorithm using SST	Efficient setpoint strategies achieved for reducing museums' energy demand	Kramer et al. (2017)
Office	Simulation-based multi-objective procedure for SST	Annual heating and cooling energy savings of the optimised building amount to 70 %	Senel-Solmaz, (2018)

		and 40 %, respectively	
Public building	Energy consumption simulation analysis method for SST	Decision support for the energy-saving of public building envelopes	Liu et al. (2019)
Office	Different office SST building model parameters using Morris Elementary Effect and Sobol	Annual cooling demand factors for reducing consumption of air-conditioning systems account for 35 %, 33 % and 58 %, respectively	Zeferina et al. (2019)
Museum	Multi-zone thermal model for SST	The indoor relative humidity is ±5% from the set point and decreased energy consumption from 85% to 20%	Ferdyn-Grygierek and Grygierek, (2019)
Residential building	Prediction models using multilayer perceptron are applied based on the SST	Adaptive setpoint temperatures allow such energy consumption to be significantly decreased	Bienvenido-Huertas et al. (2019)

Residential building	Using occupancy prediction model for SST	Thermal comfort and energy savings achieve savings between 1% and 13.3%, respectively.	Turley et al. (2020)

In Table 3.5, a synopsis of a few of the case-based studies including comfort adaptive models in a cooled building is itemised. The consequences of the enumerated examinations demonstrated that energy savings could be accomplished for residential and office structures (Senel-Solmaz, 2018; Bienvenido-Huertas et al. 2019). The outcomes additionally demonstrate that such a control technique is appropriate in a distinctive kind of outside environment (Kramer et al. 2017; Turley et al. 2020). This could have huge energy strategy suggestions as it eases as well as defer the requirement for new power plants to meet the normal rise in energy demand because of the population and economic development.

Therefore, the energy utilisation of air-conditioning can be significantly reduced using utilising a suitable control strategy. This means that, with the implementation of the well-designed indoor smart control system, the indoor temperature and healthy IAQ can be sustained with no further energy consumed. For the aim to improve the IAQ and performance in energy management, a smart control system that is focused on sustainability is required.

3.4 Smart Control for Air-Conditioning

Smart air-conditioning offers a customised mode that can peruse the operator's most preferred and adjusted temperatures and vicissitudes appropriately when the individual goes into the room (Thomas et al. 2012). The system of smart air-conditioning can process image to recognise the individual going into the room and by utilising NNs, the most chosen degree temperature of the objective is distinguished, and it is transformed immediately in relation to the comfort of the consumer (Yu and Lin, 2015). Research studies uncovered that once NN is prepared with enough analogies, it can anticipate the right responses for the new arrangements of information which has not been utilised previously (Virmani and Gite, 2017; Bohr and Memarzadeh, 2020). For example, should an individual need to plan a NN which can perceive written by hand numbers, a study by Virmani and Gite (2017) proposed it is carried out by feeding an enormous arrangement of manually written numbers to it and that aides in building up a system which perceives numbers from prepared set input. The precision of the NN can be improved by expanding the quantity of preparing set input (Chakraborty, 2012). Neural systems are presently utilised in airports and government workplaces to identify telephone numbers and locations. It has an extensive collection of uses in various fields (Bohr and Memarzadeh, 2020).

To decrease the quantity of energy consumed via air-conditioning, studies uncovered that the environmental temperature can be assessed and therefore relying upon that esteem, it gives pleasing degrees of cooling and in this manner, increases the energy usage (Chen and Lee, 2011; Yu and Lin, 2015), This can be done by utilising fuzzy logic according to Yu and Lin (2015). Fuzzy logic copies human thinking. It looks like the act of deciding by humans, which is unmistakably not the same as the decision making by computers that reinforces binary logic FALSE (0) or TRUE (any value greater than 0 or mostly 1) can adjust to any value amongst (0,1) (Ahmad et al. 2016). The fuzzy rules are created conventionally from human skilled knowledge. It is discovered that fuzzy rules produced from information are much more effective for skilled systems than experiential fuzzy rules (Yu and Lin, 2015).

A study by Artificial Intelligence in Society (2019) recently revealed that the use of intelligent strategies in the building control systems began in the 1930s and the computerised reasoning (man-made intelligence) methods were connected to the control of both bioclimatic and customary structures. Intelligent controllers were improved by the utilisation of algorithms evolutionary and produced for the subsystem's control of a building (Ahmad et al. 2016; Artificial Intelligence in Society, 2019). The collaboration of fuzzy logic, NN innovation, and algorithm evolution brought about the supposed Computational Intelligence (CI) which is currently useful in structures.

3.4.1 The Fuzzy Logic Control

Consequently, it is perceived that the significance of the wellbeing of people has steadily upsurges through innovation developments (Lopez, 2004; Chen et al. 2013; Schweiker et al. 2018). As a result of consistent growth in requesting energy efficiency and inhabitant comfort, the investigations identified with the control and design of surrounding states of buildings have been drawing attention for the last couple of decades (Chen et al. 2013; Siddqui et al. 2015). For instance, the ideal temperatures and air states of workplaces, shopping centres and distinctive use territories in a multipurpose building might be extraordinary. Henceforth, the adaptable structure of air-conditioning systems providing various demands is significant in diminishing both the operational expense and investment cost (Ghadi et al. 2014). Also, the operators' inclinations have been thought about and it drove scientists to create intelligent systems for the management of energy in buildings (Siddqui et al. 2015). The intelligent systems are primarily for enormous buildings like rooms, office buildings, commercial and public buildings, and so on (Ghadi et al. 2014). The control systems are controlled and monitored by the indoor environmental parameters to limit the operational expenses and energy consumption and FLC is the control procedure utilised for this reason.

Research studies by Shepherd and Batty (2003), Liang and Du (2005) and Behrooz et al. (2018) unfolded applications for air-conditioning which have been deliberated for execution enhancement over traditional control. As of late, fuzzy control has been effectively utilised for operating and controlling various physical systems. Through the fuzzy controllers with a gathering of rules, the human decision-making procedure is moulded and then simulated (Ahmad et al. 2016). The membership function selection that produces the most extreme execution as an abstract choice is unequivocally identified with fuzzy control performance (Behrooz et al. 2018). The membership function and fuzzy control rules are normally discovered utilising a testing strategy.

In any case, Issam (2012) and Attia et al. (2015) suggested that various analysts considered the FLC of air-conditioning systems. Consequently, the outcomes were contrasted with PID control; however, FLC was demonstrated to have better outcomes in certain investigations. FLC is widely utilised in procedures where systems either display exceedingly nonlinear characters or are extremely multifaceted (Ghadi et al.

2014). FLC is one of the classifications that can effectively control the plants even though there are troubles in determining numerical models or having performance impediments with traditional direct control techniques (Artificial Intelligence in Society, 2019). The variety of building's orientation and type has dependably traded off the comfort and performance of the customary controllers for air-conditioning as finding a widespread mathematical model utilised for akin application is incredibly problematic (Attia et al. 2015). The intelligent systems that are without model controllers can escape the problems. This reality is a general advancement in the development of programmed control systems. Human involvement is the premise of scheming FLC, and this implies that mathematical models are not obligatory for the entire system control.

Hung et al. (2007) and Luo et al. (2015) suggested that FLC were executed for some engineering applications due to such positive benefits. Numerous complex modern developments and residential apparatuses were effectively controlled utilising FLC control (Ghadi et al. 2014). The first fuzzy logic calculation actualised via Mamdani was intended to produce the language control procedure of an accomplished administrator (Mamdani, 1974). Subsequently, Soyguder et al. (2009) anticipated a technique of fuzzy control for a specialist air-conditioning and the control execution was tried and contrasted with ordinary controllers by utilising Matlab/Simulink. The outcomes demonstrated that the presentation of the adaptive fuzzy controller is superior to the regular controllers, regarding both the settling time and steady-state error. Their controller guaranteed the proficient air-conditioning having the steady-state error and base settlings time. Albeit, the fuzzy logic application has been effectively contrasted with the traditional controllers, utilisations of such control strategies remain restricted through the drawback of relying upon the control involvement of the administrator. MacVicar-Whelan (1976) primarily projected some universal rules used for scheming fuzzy controllers’ structures to maintain a strategic distance from this impediment. Similarly, improved outcomes for a similar system were acquired through utilising FLC as a result of PID control (Tang and Mulholland 1987). Also, strategies and GAs originating from adaptive control theory are utilised for FLC optimisation. FLC has been utilised in another age of furnace controllers that examined heating adaptive control to boost both comfort and energy efficiency in a residential building (Altrock et al. 1994). In like manner, Wang et al. (2012) suggested that a decrease in waste and energy consumption in buildings requires an intelligent control system because energy consumption has been straightforwardly identified with wellbeing and eventually operational expenses. A building's indoor environmental essential wellbeing factors, concerning the purchasers' inclinations, are IAQ, thermal and visual (Siddqui et al. 2015; Ahmad et al. 2016).

Thus, investigations have demonstrated that intelligent FLC produced promising outcomes and is connected to an extensive case in structures while showing a widespread overall decrease in energy consumption as opposed to the present control system and accomplishing the ideal level of comfort (Yu and Lin, 2015; Siddqui et al. 2015; Ahmad et al. 2016).

3.4.2 Pure FLC

Fuzzy logic in closed-loop control utilises numerous diverse approaches. The signal measurement from process control is examined in the modest structure of an FLC as the controller inputs. The FLC output drives the process actuators. The fuzzy P controller is named the pure fuzzy logic system. The fuzzy P controller inputs are outdoor temperature and predicted mean vote. The settings of the outputs controller are ventilation window opening angle, auxiliary cooling and auxiliary heating (Dounis and Manolakis, 2001; Dounis and Caraiscos, 2009).

Besides, deterministic signals of these outputs drive the actuators of a process. Four outputs are accustomed to the global P controller (window opening angle, artificial lighting, shadowing and auxiliary cooling/auxiliary heating), and six inputs (illuminance, daylight glare index, CO_2 concentration change, CO_2 concentration, ambient temperature and predicted mean vote) (Kolokotsa et al. 2005; Daum, 2011). The discourse universe of output-input is protected through the membership functions of trapezoidal and triangular. Precedence is specified in the rule design to attain indoor comfort from passive procedures (Daum, 2011). The fuzzy rules permit normal cooling all through reasonable seasons via openings of the window using natural ventilation to influence thermal comfort (Wang et al. 2012). For the reason to evade thermal losses, windows remain locked all through the summer and winter seasons. To permit passive heating, solar gains discontinue unnecessary heating all through the summer and are controlled all through the winter.

3.4.3 Fuzzy Proportional Integral Derivative Controllers

According to Hu et al. (2001), Kumbasar and Hagras (2015) controllers of fuzzy PID (together with PD and PI) are projected in several categories. The controllers of fuzzy PID are in two key categories with respect to their structures in the current studies:

3.4.3.1 Category of Controllers

As revealed in Figure 3.16, the foremost type of fuzzy PID controllers comprises fuzzy rules set in combination with the conventional PID controllers and a fuzzy reasoning device to tune the gains of the PID online (Esfandyari et al. 2013). Controllers of fuzzy PID are utilised as an alternative for the controller of linear PID in entirely modern or classical control application systems (Esfandyari et al. 2013). The reference and measured variable errors were transformed into commands and are useful to the process actuator. Data around their equal transfer output-input physiognomies is vital in an applied project. Control systems development used for every sort of procedure with advanced productivity of better values and energy conversion of the quality standards control is measured as the exploration key basis.

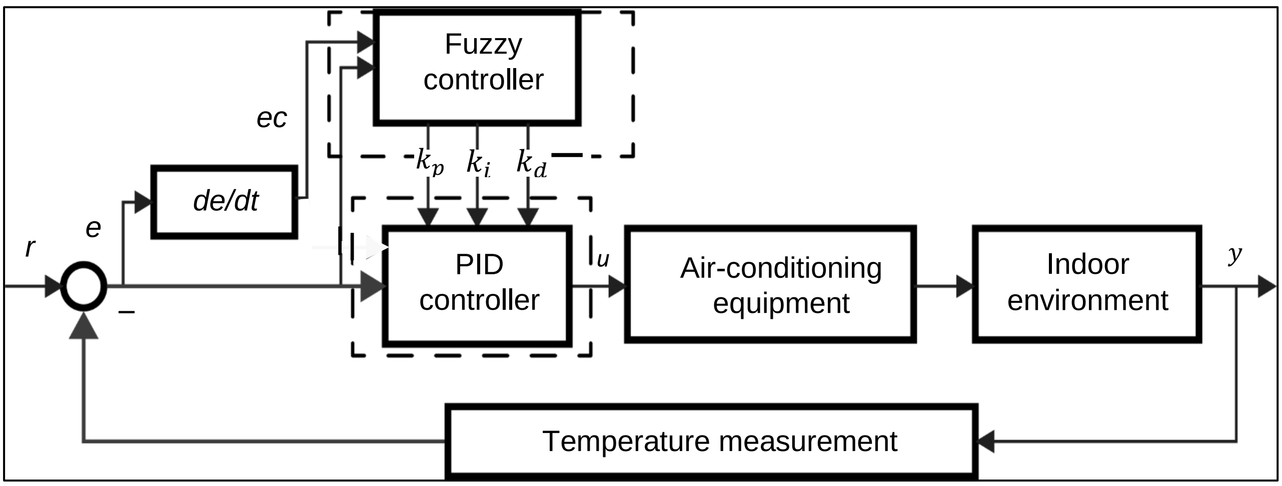

Figure 3.16: Fuzzy PID controller (Esfandyari et al. 2013).

Several explorations associated with the utilisations of fuzzy PID controller technique through different specialists are studied in this segment. The assessment method is utilised to build up philosophy for scientific and ideal fuzzy PID controller (Wang et al. 2008; De-Maity and Mudi, 2015). Moreover, Yame and Takagi-Sugeno (2001) earlier investigated a basic class of Takagi-Sugeno fuzzy PID controllers for the theory of conventional control and a model was introduced to demonstrate a way to deal with the tuning of Takagi-Sugeno fuzzy PID controllers. In this way and the case of a direct plant control process, studies present a tuning strategy dependent on phase and gain margins to decide the coefficients weighting of the fuzzy PID controllers (Duan et al. 2008; Farkh et al. 2015). Mamdani fuzzy PID controllers are examined through numerical simulations (Chao et al. 2017). However, Sugeno is computationally efficient and most appropriate for mathematical analysis whereas, Mamdani demands a considerable burden of computation and is most appropriate for human input (Farkh et al. 2015),

Subsequently, Volosencu (2009) and Cheng et al. (2013) unfolded their system on fuzzy PID controllers tuning in journals and at international conferences. Controllers of this sort can be utilised in fluctuating environments. The primary downside of a control system of this sort is that it is model-subordinate because it necessitates human involvement for plant regulation to characterise the scope of proportional increase.

3.4.3.2 The Fuzzy PID

Typical FLCs are the second class of fuzzy PID controllers and are acknowledged as heuristic set control rules (Piltan et al. 2011). For the reason to be steady with the terminology and to differentiate from the main classification of fuzzy PID controllers; FLC in this classification is termed PID-like such as PD-like or PI-like. Numerous studies on FLC configuration allude to this class (Siddique, 2014; De-Maity and Mudi, 2015).

This sort of controller is alluded to as FLC PID-type because its structures are undifferentiated from that of the traditional PID controller from input to output relationship perspective. The comparability of traditional PD controllers and fuzzy logic PD-type controllers has been set up beneath the extraordinary conditions (Deng et al.

2013). Diverse control tuning systems, for example, optimisation, artificial intelligence, pattern recognition, self-tuning and auto-tuning approaches have earlier been projected (Hung et al. 2007). For coefficients tuning of FLCs PID-type, Guzelkaya offered another technique (Soyguder et al. 2009). Also, the strategy of self-tuning is dependent on the Lyapunov method and is offered by Wei for a category of PID systems control that is nonlinear (Soyguder et al. 2009). The self-organising fuzzy controller has an expansion of the grounded fuzzy controller rule by an extra aptitude learning (De-Maity and Mudi, 2015). Also, the research study offered another structure of fuzzy controller termed type fuzzy controller PID via identifying with the theory of the traditional PID control (Kumbasar, 2014). The tuning of fuzzy PID procedure begins by direct PID controller tuning and at that point, supplanting straight PID controller that is tuned through a direct fuzzy controller and at last, creating the well-tuned and nonlinear fuzzy controller.

Moreover, the significant PID controller benefit is that it does not possess a functioning point. The control methodology assesses the contrast between the setpoint and measured value and assesses the transformation of this alteration to choose whether to reduce or increase the structure control variables. Likewise, FLC can actualise control systems that are nonlinear. The increase will be strong should the comfort condition be cold while paying little respect to its propensity; however, on the off chance that the predicted mean vote mistake is little, the inclination is considered.

3.4.4 Utilisation of Neural Network

According to Liang and Du (2005), and Marvuglia et al. (2014), NN controllers are broadly utilised for temperature and thermal comfort regulators of heating systems (hydronic) – a recognisable proof model of the plant is not obligatory. The NN is deliberated in this section and the air-conditioning control application instance is provided. Artificial Neural Networks (ANNs) are otherwise called NNs – they process information with their strategy simulated through investigations of the capacity of the human cerebrum to gain perceptions and to sum up in the contemplation (Liang and Du, 2005; Colom et al. 2010; Moyo, 2014).

Dependent on the relating information, NNs can be prepared to learn subjective nonlinear connections (De et al. 2007). For the set of rules, control has been utilised in numerous areas, such as control, discourse handling, design acknowledgement, biomedical designing and so forth (Scotton, 2012). Its benefits additionally depicted consideration of specialists with the enthusiasm of control and air-conditioning – ANNs have been practised with air-conditioning issues (Dalipi et al. 2016). Control techniques structured is dependent upon the ANN set of rules that is utilised for monitoring and simulating present-day heating system suburb and brought about exceptional performance (Dalipi et al. 2016). If these models are prepared with legitimate information; they have great precision, respond fast, information-driven and are versatile. Several investigations such as decision-making sustenance for system/plant preservation, training of system/plant machinists, imminent fault, prediction expectation of deprivation, and so forth can be analysed, controlled, monitored and simulated through ANNs (De et al. 2007; Dalipi et al. 2016).

For developed thermal control of system/plant, ANNs have been practised progressively (Moon and Kim, 2010). ANNs use transfer functions and connectivity amongst output, input and hidden neurons, undifferentiated from the learning procedure of the human cerebrum and have been effectively utilised in systems with uncertain elements or non-direct systems (Marvuglia et al. 2014). Specifically, ANNs models are not quite the same as numerical models, for example, PID controllers have flexibility via a process of self-tuning (Marvuglia et al. 2014). This trademark makes ANNs have the option to precisely settle on choices even though there is no external skilled involvement when bizarre annoyances, aggravations, as well as fluctuations in structure foundation conditions happen (Moon and Kim, 2010; Sibo et al. 2013). The control system of ANNs has been demonstrated to have focal points in thermal control as far as the exact control of thermal with diminished overcooling, overheating and enhanced energy productivity (Morel et al. 2001; Marvuglia et al. 2014). A research study by Kalogirou (2006) earlier suggested that heating systems' stop and start times were resolved by utilising artificial NNs models.

Devabhaktuni et al. (2001), Ding et al. (2004) and Chakraborty (2012) uncovered that NN was originally prepared to model the electrical conductivity of active and passive circuits/segments. The NNs that is prepared are regularly alluded to as neural models or principally NN models, which would then be able to be utilised in the design and high-level simulation, giving quick responses to the assignment they have erudite (Scotton, 2012). Modelling techniques and traditional control with significant impediments like observational models, whose precision and range may be restricted or analytical techniques, that may be hard to get for innovative gadgets may be substituted via NNs for better performance or numerical modelling strategies that might be costly through computation (Ahmad et al. 2016). NNs have been utilised in synthesis, measurements, inverse modelling, impedance matching and also, for an extensive collection of air-conditioning applications (Scotton, 2012; Ahmad et al. 2016). As a result of this rising technology, several researchers and engineers of air-conditioning have started captivating serious awareness in this domain.

Also, basic issues of NNs are presented and famously utilised NN multilayer perception is depicted in the following subsection. Air-conditioning application samples outlining the NN utilisation procedures to modelling of components and optimisation of a circuit are shown.

3.4.4.1 Typical Neural Network Structure

There are two sorts of fundamental parts of a NN structure and to be specific: the interconnections between them and processing components. The associations between the neurons are known as connections or neurotransmitters and the processing components are called neurons. Each connection has a comparing parameter weight-related to it.

Neurons that get boosts from different neurons with improved outputs meant for different neurons in the network are identified as hidden neurons. Every neuron gets improvement on different neurons associated with it – they form the data and the output. Improvement neurons on the external network are termed input neurons, even though neurons that the outputs are remotely utilised are termed output neurons. NN structures that are distinctive may be built by utilising various kinds of neurons and by suddenly associating them.

Multilayer perception is a prominently utilised NN structure. The neurons are assembled into layers in the NN multilayer perception. Respectively, the last and first layers are termed output and input layers. Also, hidden layers are termed the remaining layers. Commonly, NN multilayer perception comprises output, input and a single or further hidden layer. For instance, NN multilayer perception with an output, input and single hidden layer is alluded to as multilayer perception three-layer as appeared in Figure 3.17.

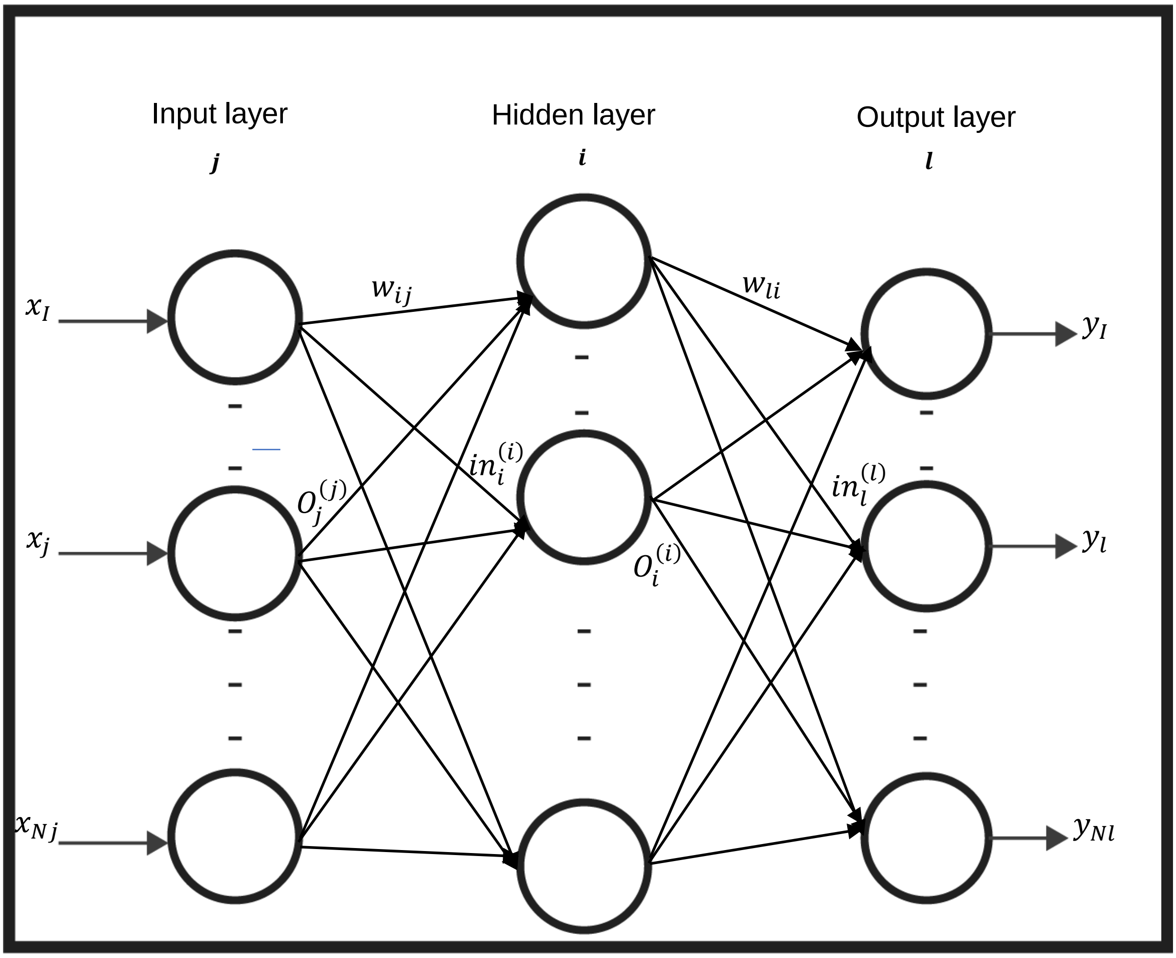

Figure 3.17: The NN structure (Kamar et al. 2013).

For $in_l^{(l)}$signifies the outside input and y_l is the output of lth neuron of the output layer. Also, $in_i^{(i)}$ signifies the ith outside input and $O_i^{(i)}$ is the output of ith hidden layer neuron. x_j is the input and $O_j^{(j)}$ is the output of jth input layer neuron. w_{li} is the connection weight amongst ith hidden layer neuron and the lth $(i = [1,2,3 \ldots\ldots, N_l])$ output layer neuron. w_{ij} is connection weight amongst jth $(j = [1,2,3 \ldots\ldots, N_j])$ input layer neuron and the ith $(i = [1,2,3 \ldots\ldots, N_i])$ hidden layer neuron. Neuron number in the input layer is N_j, the output layer is N_l, and hidden layer is N_i.

Every neuron in the network multilayer perception forms the inputs established from different neurons. The procedure is completed via a capacity in the neuron termed the activation function and the prepared data turns into the neuron output. For instance, each neuron gets upgrades in the hidden layer from input layer neurons. For ith hidden layer, the neuron forms the data in two stages.

Every input is mainly reproduced through the equivalent parameter weight and the outputs are supplementary to yield a sum weight $in_i^{(i)}$ specified as:

$$in_i^{(i)} = \sum_{j-1}^{4} w_{ij}\, O_j^{(j)} \tag{3.14}$$

The sum weight subsequently in equation 3.14 is utilised to dynamic the function of neuron's activation to yield the ultimate neuron output $O_i^{(i)}$ given as:

$$O_i^{(i)} = f\left(in_i^{(i)}\right) \tag{3.15}$$

This yield can thus, convert upgrade to output layer neurons. The greatest generally utilised activation function of hidden neurons is termed sigmoid function since it is a function that is a smooth switch and persistently differentiable, monotonic, continuous and bounded. Additional hyperbolic-tangent circular and arc-tangent function, and so on. It may be utilised as the function of actuation; however, the activation function of hidden neuron that is termed sigmoid function is specified as:

$$f(x) = \frac{1}{(1 + e^{-x})} \tag{3.16}$$

3.4.4.2 Suitable Network Size

Hidden neurons of appropriate numbers are expected to guarantee the NN to be a precise model to become familiar with the focused-on issue. Hidden neurons number rely on the level of nonlinearity of f and the output y and input x dimensionality. Additional neurons are required for the exceptionally nonlinear systems and components even though few are required for smoother items. Besides, the all-inclusive estimate hypothesis does not indicate what ought to be the multilayer perception network size. The exactly hidden layers of neurons and the number of them mandatory for specified task-based modelling stays an open inquiry since the trial-and-error method can be applied to decide hidden neuron numbers. Adaptable procedures which include/erase neurons all through the training period may be utilised to decide suitable neurons number (Devabhaktuni et al. 2001; Alvarez and Salzmann, 2016). The progressive data level in the first modelling issue may stay replicated through multilayer perception layer numbers. As a consequence, applications of air-conditioning generally necessitate a couple of multilayer perceptions hidden layers (such as multilayer perceptions that involve three-or four-layer) (Bonala, 2009).

3.4.5 Techniques of Neuro-Fuzzy

According to Bosque et al. (2014), systems of neuro-fuzzy allude to the systems where the methods of NN were utilised in fuzzy innovation. The hybrid system like ANFIS (Adaptive Neuro-Fuzzy Inference System) has earlier been utilised for the control and forecast of artificial lighting in structures, ensuing diversities of normal lighting (Kurian et al. 2005; Popoola, 2016). Prescient control technique that is well-planned, joined with structure modelling, operators' conduct, and the forecast of climate parameters may keep up the indoor conditions in an ultimate comfort level and also accomplish energy savings (Popoola, 2016). The neural controller that is prepared with the expectational abilities of NNs may be adjusted to solar buildings and the hydronic systems of heating control (Argiriou et al. 2004; Ghadi et al. 2014).

A research study by Argiriou et al. (2004) created and tried a controller for adaptive NN for single-zone control of hydronic systems heating. The controller outputs and inputs are parameters connected with setpoint temperature and device heating. Besides, this control neglects to exhibit phenomenal execution of control as no anticipating of any indoor conditions or climate parameters is engaged with the control procedure. In like manner, Hassan and Kothapalli (2010) suggested a controller of fuzzy-PI that modifies NN. However, it ignores to provide a remarkable development. Notwithstanding, a study by Rami and Al-Jarrah (2013) presents control algorithms for an air-conditioning that joins predictive control, fuzzy systems and NNs. This scheme incorporated the climate parameters forecast and inhabitants' number, and the expectations are then examined to evaluate the performance of the building to accomplish energy-saving and ensure acceptable comfort. This shows that control performance improvement can be accomplished through joining the benefits of advanced and conventional control strategies.

3.4.6 FLC Optimisation

For minimisation of an error (or objective) function as indicated by Ari et al. (2005), the optimisation procedure of the gradient regulates direction to search. This method can be utilised for energy consumption minimisation in circulated environmental systems control while sustain a top inhabitant level of comfort. The most broadly utilised subordinate free procedures are namely, downhill simplex method, random search, simulated annealing and GAs (Jaen-Cuellar et al. 2013). GAs are search-adaptive and algorithm optimisations that work by impersonating normal genetic standards (Jaen-Cuellar et al. 2013). The algorithms are not quite the same as techniques of optimisation and customary search utilised in project engineering matters. Major thoughts are obtained on genetics and are artificially utilised to build algorithms search that is vigorous and necessitate negligible issue correlated data. Besides, a study by Alcala et al. (2003) earlier analysed the utilisation of natural gas to progress FLC that is smartly tuned for air-conditioning, with the end goal of indoor comfort and energy performance enhancement. Moreover, Mossolly et al. (2009) proposed a system with GAs for air-conditioning online control to brand the controller of the air-conditioning as a control system that is self-learning.

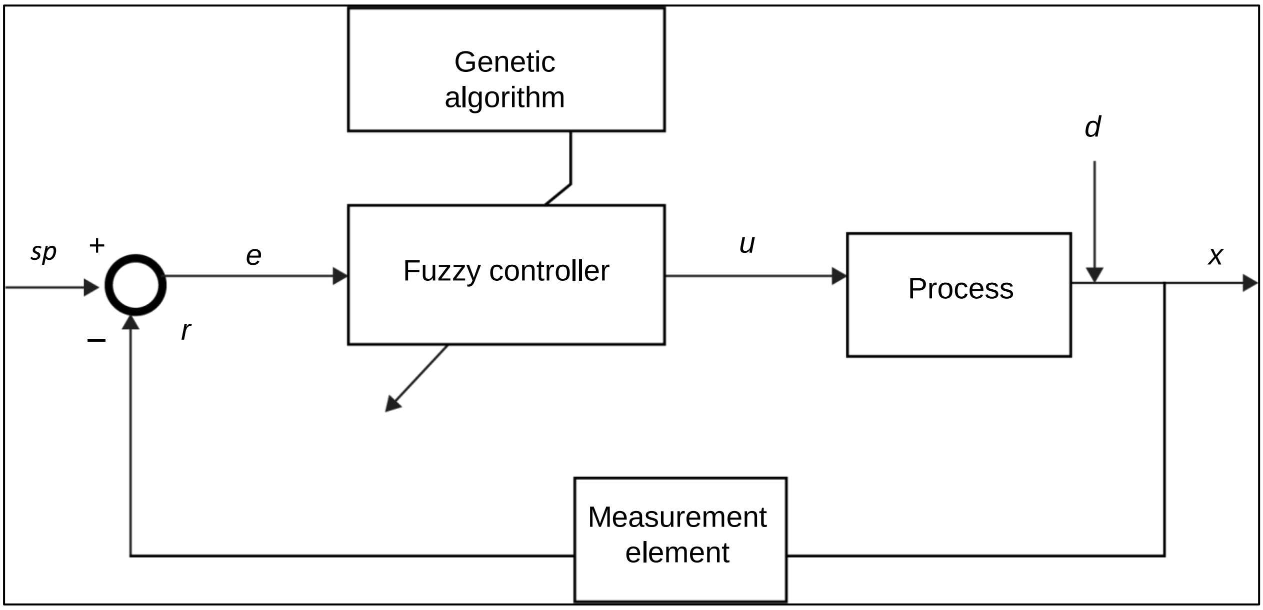

Figure 3.18: Utilising GA and fuzzy controller (Altinten et al. 2006).

Where, d=disturbance; e=error; r=measurement value; u=controller output; x=process output; sp=set point.

A research study by Altinten et al. (2006) anticipated a structured fuzzy control utilising GA as offered in Figure 3.18 for the control of temperature. The function fitness for GA is selected as an absolute integral value error and used to characterise the function of fuzzy membership as specified in Figure 3.19 and Figure 3.20, respectively. Through utilising parameters of fuzzy indicated at steady temperatures, the fuzzy controller efficiency with GA is inspected through experiment and simulation. It is seen in Figure 3.21 that GA can efficiently tune the fuzzy controller for various circumstances and temperature control.

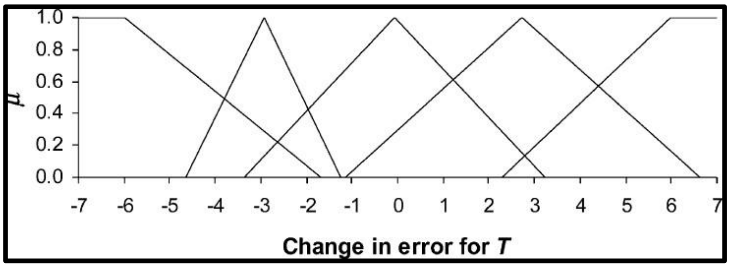

Figure 3.19: Change in error fuzzy membership functions for temperature (Altinten et al. 2006).

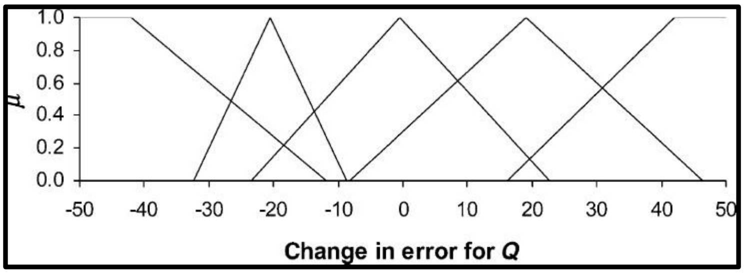

Figure 3.20: Change in error fuzzy membership functions for heat (Altinten et al. 2006).

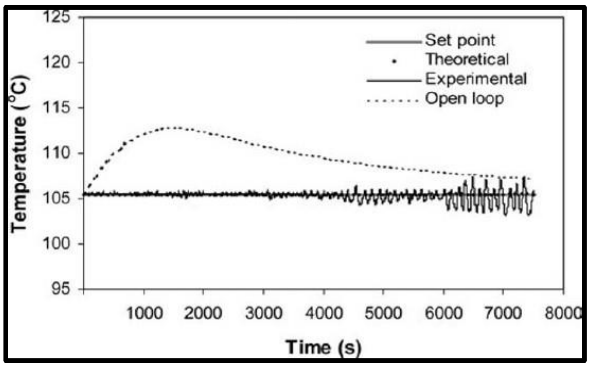

Figure 3.21: Fuzzy genetic control of temperature (Altinten et al. 2006).

For energy saving and built environment control, the illustration and discussion exhibit that smart control systems have been utilised. As indicated by these investigations, the propelled algorithm control can accomplish substantial energy saving contrasted with systems of the traditional control; albeit energy-saving level relies upon the solar power and technology control and likewise, building qualities, climate conditions and preferences of the user. Nevertheless, existing control approaches for air-conditioning can be synopsised in Table 3.6 below:

Table 3.6: The existing control approaches.

Existing Control Approaches		**References**
Customised design	Conventional control methods like PID control should be designed according to the model of the building, and model mismatch will produce poor	De-Maity and Mudi, (2015); Doroshenko, (2017)

	control performance. Even for an adaptive controller, such knowledge is still required to an extent	
Application difficulty	The fuzzy controllers' weak points are due to the difficulty of identifying precise membership functions and the lack of adequate methodical techniques for expert knowledge transformation into the rule base. Besides, parameters tuning takes time. NN can automate the process of tuning parameters, substantially decreasing the time of development and outcomes in improved performance. Nevertheless, in NNs, both knowledge representation and knowledge extraction are challenging	Gomes, (2012); Marvuglia et al. (2014); Moyo, (2014).
Applying advantage controls	Operators having expert knowledge with certain skills are required which restricts the use of such controllers.	Behrooz et al. (2018)
Lag-behind air-conditioning development technologies	Existing control algorithms do not have appropriate control performance and do not offer precise control for this air-conditioning	Behrooz et al. (2018)

In Table 3.7 below, technology control improvement is required in certain domains to address the inadequacies of the air-conditioning existing control technologies. Moreover, this will even unfold a better understanding of control systems associated with renewable-based smart air-conditioning.

Table 3.7: Requirement of technology control improvement.

Improvement of Control Technology	References
For better performance and more efficiency, a new control approach for advanced air-conditioning can be considered	Esfandyari et al. (2013).
For model matching and parameter tuning, model-independent control approaches for general use which can lessen the time of development can be considered. This is important as air-conditioning is broadly applied in buildings	Ghadi et al. (2014: 2018)
Addition of other signals which have a connection with the indoor environment quality in the control process to enhance the control of energy and indoor environment quality performance	Ghadi et al. (2014: 2018)

3.5 Conclusion

In conclusion, there exists some understanding or attempt of sustainability associated with smart techniques and solar air-conditioning. Presenting sustainable developments while focussing attention on solar exhibitions as an underpinning resolution is a requirement. It is of indispensable significance to choose the right devices and components for every approach relying upon the ideal specification performance. Regularly diminishing expenses of system segments associated with effective energy ideas in the domain of solar energy innovation open new prospects for cold and hot systems storage applications in various building areas.

The absorption and adsorption solar systems permitted a considerable energy saving with their design optimisation to the point of utilising refrigerants that is environmentally unfavourable and afterwards capitalising on solar energy that is clean and free to power the system. However, they also fail to recognise the importance of the health and wellbeing of the indoor occupants in their application of sustainability. Previous studies disregard the social aspect of sustainability that is directly connected with the environmental characteristic of the system – the significance of human adaptation of the indoor smart/intelligent systems for optimum thermal and wellbeing comfort.

Accordingly, computational intelligent control unfolds a better approach for indoor environment quality control. For the purpose to accomplish improved execution control, the control elements as well as the air quality and indoor temperature ought to be better known. It is simpler for the design engineers of air-conditioning control system to select a legitimate control technique and to structure the control of improved algorithm since the difficulties associate to such control have been addressed in this study. The following are the indoor environment control problems in the table below:

Indoor Environment Control Problems	
(i)	Difficulty to use suitable ideal guides to pursuit for the best set point(s) and to forecast response of the system.
(ii)	Multifaceted air-conditioning control are tough to be examined.
(iii)	The delay of time
(iv)	In both IAQ and thermal comfort control, disturbances constantly occur in the process control. For example, individuals entering the room can increase the CO_2 concentration while opening door or window might create the variation of indoor temperature.
(v)	The system lag-behind response to the change of indoor environment.
(vi)	One of the main difficulties of IAQ is control signal value of mismeasurement occurrence
(vii)	Since the control signals occasionally relies on one another creates the state of unsteady performance control.

Thus, the performance of present control strategies on various control substances is assessed by a number of investigations and revealed information. The literature uncovered that one controller is problematic to accomplish every control objective and to have exceptional control execution for every control signal. For example, PID may be great for controlling temperature, whereas, it has poor execution control for controlling thermal comfort. In this way, the controller must be structured appropriately depending on sound investigation and comprehension of object control and technological control. The following are the proposed control of indoor environment quality in the table below:

Indoor Environment Control	
(i)	Innovative control methods may combine advanced and conventional control techniques. That is, a technique through which analogies between these are overlapped, and another through which specific merits are merged.
(ii)	Algorithm control which can observe the level of habitation and adjust the change of the air-conditioned area to improve energy efficiency and IAQ.
(iii)	The indoor level of air pollutant must be incorporated in the process of control, which will allow to regulate air changing rate precisely to enhance the system energy efficiency.
(iv)	Smart approach for observing human behaviour, to enable it adapted into the process of control for precise control response for occupant comfort requirement.
(v)	The process of control which does not involve engagement of the operator having certain knowledge or skills.
(vi)	Real-time, closed loop and on-line learning capacity. The performance of indoor environment quality assessment system can be incorporated to make a process of control possess modifying and self-learning capability.

Consequently, this study offers a system for achieving significant energy savings, carbon reductions and achieving environmentally friendly goals. More importantly, there is a significant need towards the advancement of knowledge development, improving the understanding and providing a framework for a future smart renewable-based air-conditioning market. As a result, the next chapter deliberates upon developing conceptual modelling of photovoltaic solar air-conditioning and the indoor environment, that sustainably contributes towards combatting poor IAQ, optimising thermal comfort, achieving significant energy savings and reduction of carbon emissions, vis-à-vis tackling global warming and climate change while enhancing the quality of life in the cities.

Chapter Four

4.0 Modelling of Solar Air-Conditioning and the Smart Indoor Environment

4.1 Introduction

This chapter focusses upon modelling a sustainable solar-based air-conditioning and the indoor environment condition. Conceptual modelling is examined to design and implement the system sustainability of solar photovoltaic and the indoor environment in this study. The conceptual modelling of photovoltaic solar air-conditioning is methodically examined, and each component of the system and their specifications are described. The system components of the solar air-conditioning are studied and used as a basis for the system's description in this chapter. Also, the model of solar air-conditioning, the indoor temperature and IAQ are planned to improve the quality of air in the indoor environment while achieving significant energy savings, carbon reductions and GHG emission reductions, vis-à-vis tackling global warming, climate change and inhabitants' health effect. Upon controlling indoor environment to an optimised level, a healthy and contented indoor environment can be ensured. Likewise, the anticipated controllers of the indoor environment are structured, and the PID control is utilised because of its feasibility. Furthermore, its control execution is mostly founded on parameters of the PID, and inappropriate determination of the parameters will prompt poor control execution. Consequently, intelligent controller is planned to direct the parameters of PID to guarantee output control optimisation. Air pollutant level in the indoor environment is incorporated into control process and this will empower precise control of the air changing rate. Subsequently, an appropriate computation of the controlled object is structured for the control procedure which does not necessitate the operator's intercession possessing explicit knowledge or skills.

In this chapter, the conceptual modelling of photovoltaic solar air conditioning and the indoor environment control are discussed in detail.

4.2 The Modelling Approach

The methods and techniques employed in the modelling process is termed a modelling approach. There are several modelling approaches that can be applied in research studies. However, this study employed conceptual modelling approach which is suitable and fundamentally connected to the scope of this study. The conceptual modelling approach is employed to model the solar air-conditioning and the smart indoor environment. The photovoltaic solar air-conditioning components are systematically described and employed for the sub-system improvement consolidation. For best optimisation possibilities, the indoor environment control procedures are designed to consolidate FLC with the PID for the indoor temperature, and backpropagation NN with the PID for the IAQ. Consequently, the conceptual modelling technique with the justification and basis in existing study is likewise discussed in the subsequent section of this chapter.

4.2.1 Conceptual Modelling and Justification

According to Yilmaz et al. (2015), the conceptual model is a consolidation of all goal-relevant structural and behavioural features of a system that is presented in a predefined format. It provides foundation for the development of the simulation program. However, the term conceptual modelling appears to cause extensive perplexity due to its somewhat various uses in various domains of engineering and science, and in light of the fact that there is no concurred definition inside operational research and simulation (Robinson, 2008). There is a lot of specialised studies in artificial intelligence and software engineering on conceptual modelling that spotlights on demonstrating ontologies and techniques, for example, UML (Unified Modeling Language) for knowledge, ideas and thoughts modelling (Bernald et al. 2012). With regards to operational research ventures, the utilisation is equally more extensive, that in general, allude to the entire exercise (anyway it is done) of choosing what to incorporate into the model (Yilmaz et al. 2015). A typical bit of modelling counsel is to keep the model as simple as could reasonably be expected. Notwithstanding, connecting this back to Occam's or Ockham's razor originating from the 14th century that may be deciphered from the Latin as "elements ought not be duplicated without need". The supplementary expression frequently utilised in studies is LOD which is known as ‘Level of Detail’ with intricacy and LOD giving off an impression of being tantamount much of the time. Different researchers unfolded the advantages of a basic model contrasted with multiplex model together with being more to comprehend, faster to analyse and run, requiring fewer resources and less data, simpler to update and transform and possessing a more noteworthy possibility of acknowledgment (Ward, 1989; Salt, 1993). A straightforward model is recognized as a key factor in operational research accomplishment in the study by Tilanus (1985). In this regard, this study offers a straightforward modelling concept of the system by way of utilising conceptual modelling techniques.

Figure 4.1 demonstrates the main conceptual modelling artefacts adopted for modelling the proposed system in this study. The projectiles in this chart signify progression of data, for example, data about real world provides into the description of the system. The projectiles are not illustrative of sequence stages inside the modelling procedure (Balci, 1994; Willemain, 1995).

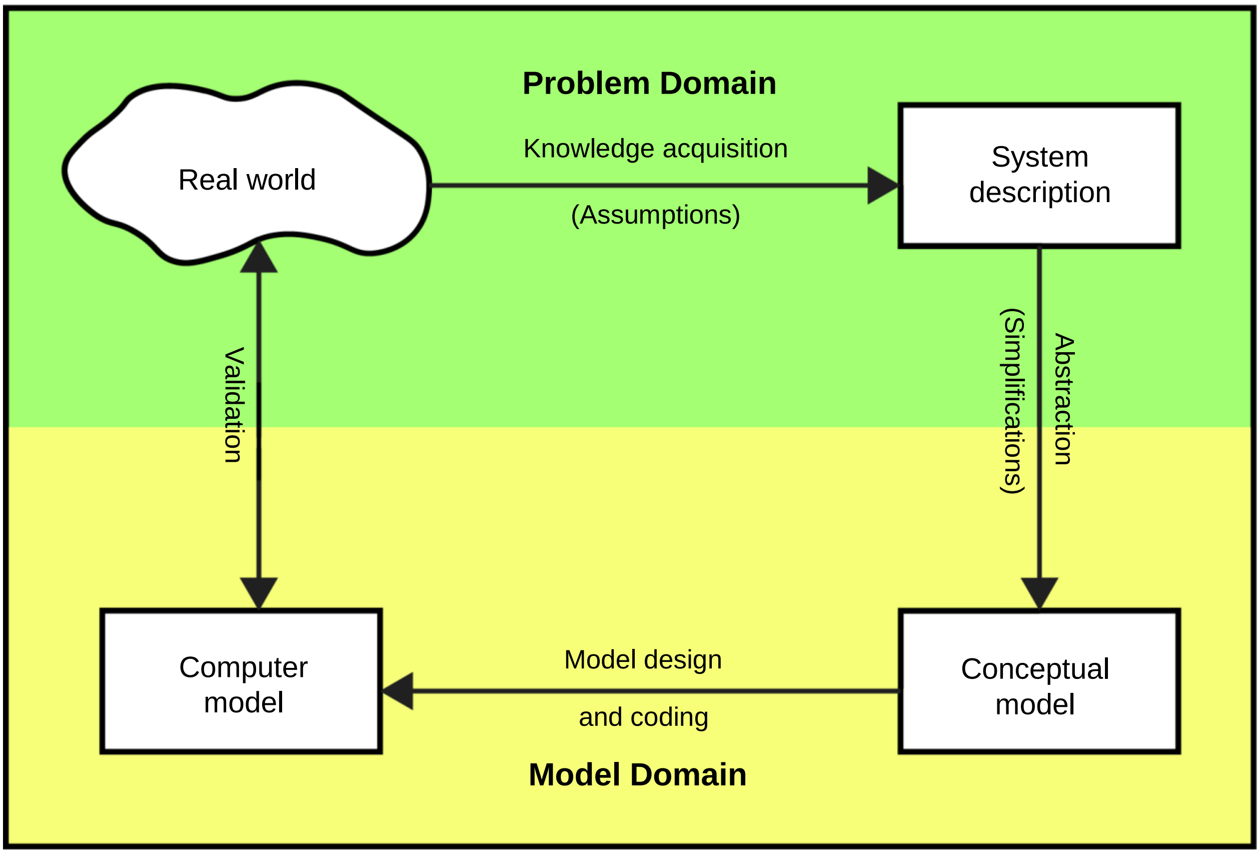

Figure 4.1: Conceptual modelling artefacts (Balci, 1994; Willemain, 1995).

The real world (future or current) as signified by the cloud in Figure 4.1 is where the problem state exists in. Precise artefacts of the conceptual modelling procedure are signified by the three rectangles as presented in Table 4.1.

Table 4.1: The modelling process.

The Modelling Process		**References**
System description	A description of the problem situation and the system in which the problem situation resides	Yilmaz et al. (2015)
Conceptual model	The conceptual model is a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model.	Robinson, (2008)
Computer model	A software specific design and software representation of the conceptual model.	Robinson (2008); Yilmaz et al. (2015)

The artefacts are very isolated. It is not necessarily the case that they are in every case unequivocally communicated, except for the computer model. For example, conceptual model and the description of the system may not be (completely) archived and can stay inside the modeller thoughts and the issue proprietors. It is obviously, frequently great modelling exercise to archive both conceptual model and the description of the system.

As highlighted from the research study by Robinson (2008), the computer model is firmly not the portion of conceptual modelling, however it does, obviously, typify the conceptual model inside model code. For the computer model alongside by model plan, and validation are incorporated into Figure 4.1 for entirety. It is essential to perceive the difference between conceptual model and the description of the system. The description of the system identifies with the issue area otherwise known as the domain of problem – meaning it portrays the issue and this present reality. The conceptual model has a place with the model area that portrays which portion of the system depiction will be incorporated into the model simulation and at which LOD. The researchers' knowledge is that these dual artefacts are regularly confounded and realised as undefined. The definitions at this point are near those utilised via Zeigler (1976). This real world according to studies is typically identical to 'base model' as revealed by Zeigler; the conceptual model directly relates to 'lumped model', the description of the system to the 'experimental frame'.

For the reason that conceptual models are just portrayals of theoretical ideas and their individual connections, the possible advantage of interest of actualising a conceptual model are numerous. However, to a great extent rely upon the technicality and knowledge to devise a solid model and in light of the fact that a conceptual model is so dynamic, and in this way, is just as obliging as the system is devised. There can also be a couple of cautions or disadvantages when executing a conceptual model. Generally, Table 4.2 offers the advantages and disadvantages of conceptual modelling.

Table 4.2: The advantages and disadvantages of conceptual modelling.

Advantages of Conceptual Modelling		References	Disadvantages of Conceptual Modelling		References
Establishes System Concepts	By establishing and defining all the various concepts that are likely to come up throughout the course of a system life cycle, a conceptual model can help ensure that there are fewer system shortcomings, where the system might otherwise have been neglected or forgotten.	Johnson, (2008); Parush, (2015)	Creation Requires Deep Understanding	While conceptual models can (and should) be adaptive, proper creation of a conceptual model requires a fundamental and robust understanding of the system, along with all associated systems.	Thalheim, (2011); Yilmaz et al. (2015; Parush, (2015)
Defines System Scope	A solid conceptual model can be used as a way to define the system scope, which assists with time management and scheduling.	Robinson (2008); Wazlawick; (2014); Yilmaz et al. (2015)	Potential Time Sink	Improper modelling of the system within a conceptual model may lead to massive time waste and potential sunk costs, where development and planning	Bredehoeft, (2005); Tappenden, (2012); Yilmaz et al. (2015)

				have largely gone astray of what was actually necessary in the first place.	
Base Model for Other Models	For most systems, additional, less abstract models will need to be generated beyond the rough concepts defined in the conceptual model. Conceptual models serve as a great start off point from which more other models can be created.	Thalheim, (2011); Yilmaz et al. (2015)	Possible System Clashes	Since conceptual modelling is used to represent such abstract system and their associations, it is possible to create clashes between various components. In this case, a clash simply indicates that one component may conflict with another component, somewhere down the line. This may be seen when design or coding clash with deployment, as the initial assumptions of scaling during design and coding	Geva, (2008); Thalheim, (2011)

				were proven wrong when actual deployment occurred.	
High-Level Understanding	Conceptual models serve as a great tool by providing a high-level understanding of a system throughout the system life cycle. This can be particularly beneficial for researchers and executives, who may not be dealing directly with coding or implementation but require a solid understanding of the system and the relationships therein.	Robinson, (2008); Parush, (2015)	Implementation Challenge Scales with Size	While conceptual models are not inherently ill-suited for large applications, it can be challenging to develop and maintain a proper conceptual model for particularly complex systems, as the number of potential issues, or clashes, will grow exponentially as the system size increases.	Parush, (2015); Becker et al. (2015)

Conceptual model is applied because of the suitability and benefits of the model for solar air-conditioning and smart indoor environment control. Therefore, it is justified for this study as a result of the model-based capacity to describe the objectives, inputs, outputs, content, assumptions and simplifications of the system. Research studies reveal that conceptual model for a system establishes a straightforward consolidated holistic view of what the system is, what it does and the users it will help (Robinson, 2008; Yilmaz et al. 2015; Parush, 2015). The model consolidates the components and mechanisms of photovoltaic solar air-conditioning to reduce the level of energy consumption and rates of carbon emissions. Likewise, the indoor environmental control conceptually consolidates the FLC with PID for the indoor temperature, and backpropagation NN with the PID for the IAQ to maximally optimise the level of thermal comfort within the indoor environment. As a result, conceptual modelling is justified in this study and applied for modelling of the solar air-conditioning and the design of smart indoor environment control.

4.2.2 Conceptual Modelling in Existing Study

Research studies by Hensen (1996), Trcka and Hensen (2010) characterises four classifications of air-conditioning depiction by way of utilising conceptual modelling, extending from absolutely conceptual towards progressively unequivocal. The system of the conceptual modelling technique of the air-conditioning considered illustrative situation where room procedures are examined, while every single different procedure is the idealised secondary and primary system, with an option to force a limit restriction upon them. A model application applies the anticipated peak loads of room heating/cooling to decide the required size of the air-conditioning. Conceptual modelling technique was utilised to model the air-conditioning systems by their classifications (Hensen, 1999; Trcka and Hensen, 2010). According to Paluszczyszyn (2015), a few software programs present certain multifaceted nature by modelling systems utilising conceptual modelling – warm zone connections through algorithm control. In this manner, despite the fact that the system of conceptual modelling is applied, the procedures of the system are not totally overestimated. Their association with the structure is more practically displayed since their attributes can be incorporated into terms of viewpoints, for example, radiant split/convective, time of response, flux limit values and extraction point/heat injection. Conceptual modelling approach was in like manner applied to models of the system of groundwater and system manufacturing (Streams, 1996; Rivulets and Tobias, 1999). This can likewise be a decent procedure in a modelling venture, especially where the primary point is to expand the understanding of what has previously been experienced (Rivulets et al. 2001). Research study by Ghiaus and Hazyuk (2010), also utilised the theorem of superposition for electrical circuits to attain the parameters of model. Their study presumed that the building thermal model is linear, wall thermal capacity and the IAE is lumped and reflected on the time disturbance series, (for example, internal load and weather) and word related projects are recognised in light of the fact that their studies utilised Model Predictive Control (MPC) which projected an unrestrained ideal control calculation to unravel the load approximation issue. Research studies by Ghiaus and Hazyuk (2010) and Felix et al. (2013) have required numerous presumptions to encourage the estimations of heating load, which prompts absence of exactness in the outcomes. Likewise, a single output and single input model type utilised did not appraise the transmission of moisture – a significant component in choosing thermal comfort in the indoor environment. Conceptual modelling is also employed in numerous recent research studies of artificial intelligence and software engineering which focuses on demonstrating ontologies and techniques, for example, UML for knowledge, ideas and thoughts modelling (Abdullah, 2006; Bernald et al. 2012; Kamran and Sheraz, 2018). Methods utilised in distinguishing great model disentanglements in their investigations included optimisation examination and looking at the thorough activities of the model and the outcomes. Moreover, this study exploits recent approach in modelling to perform the system modelling for solar air-conditioning and indoor smart control at runtime.

4.3 Scenario-Based Model of Solar Air-Conditioning

Research by Bronman (1991), Kandpal and Broman (2015) unfolded that a number of computer programs have been recognised well along in equivalent to TRNSYS, furthermost of them with a simple user associate and to some extent lessened functionality. Majority of the program have been successfully applied in solar energy study (for example, Insel, PVSyst, Polysun, T*Sol, commercial, PVGIS, RETscren). Research study by Milrad (2013) likewise revealed that computer programs that is applied in general engineering (for example Matlab, EES, Berkeley Madonna, Stella) are basically less appropriate for the study of solar energy because the programs are extra multi-faceted and possesses absolutely no built-in orientation or references to the systems of renewable energy. As a result, Polysun program is employed for solar air-conditioning and Matlab program is, in turn, employed for smart indoor environment control due to their different suitability purposes.

Study by Mauthner and Weiss (2014) revealed that majority of the solar air-conditionings are situated in specific European districts due to their climatic conditions. The reference location is Rome, but this study also examines the performance of the system in London and Toulouse to analyse the system in different temperate and climatic conditions. According to Henning et al. (2013), $500\ \mathrm{kJ/K}/m^2$ is the heat capacity and $0.5\ \mathrm{W/K} \cdot m^2$ is the building coefficient total heat loss ($U - value$) that basically commensurate with a regular insulated light of building construction. The next section presents the component and layout of the proposed system.

4.3.1 The Component and Layout of the System

The components of photovoltaic solar air-conditioning are the modules of photovoltaic, inverter, system outdoor unit, pumps, system cold storage, brine, indoor cold circulation, system piping, auxiliary heat pump, system heat transfer fluid and domestic hot water tank. Figure 4.2 represents the photovoltaic panel arrangement which is situated on the roof of the building while the layout of the proposed system with the components is presented in Figure 4.3.

Figure 4.2: Scenario-based photovoltaic panel arrangement

This study adopted monocrystalline silicon since research by Thejo et al. 2021 reveal that it has the highest efficiency (beyond 14% conversion efficiency) in comparison to any other type of solar panels. They are space-efficient and require the least amount of space as compared to their counterparts (polycrystalline, amorphous and cadmium telluride) (Bhattacharya and John, 2019). Monocrystalline solar panels have a higher life span and tend to function quite longer than their warranty period (Renewable Energy Hub, 2021). This element is often referred to as single-crystal silicon. It consists of silicon, where the entire solid’s crystal lattice is continuous, unbroken to its edges, and free from grain limits (Thejo et al. 2021). According to Meyer Burger (2019) specification, silicon monocrystalline photovoltaic cells absorb power from the solar and convert it to electrical energy. The cells efficiency is 14.88% and each element size is 1.65 m^2. The photovoltaic frameless elements are protected through solar glass of 5 mm having coating antireflection with the 9 mm overall width. For 14.77 m^2 is the overall zone of the photovoltaic components. Also, 190 kWp is the extreme irradiation of minimal power of individual photovoltaic component, having ±3% error. Likewise, 2.565 kWp is the extreme irradiation of minimal ultimate entire photovoltaic array power. It matches to the 3.5 kW, which is the cooling of extreme electrical power defined below. Likewise, 36.6 V is the current photovoltaic extreme power point component, with 45.2 V as the voltage open circuit. For 5.19 A is the Maximum Power Point (MPP) current of photovoltaic component and subsequently, 5.56 A is the current short-circuit.

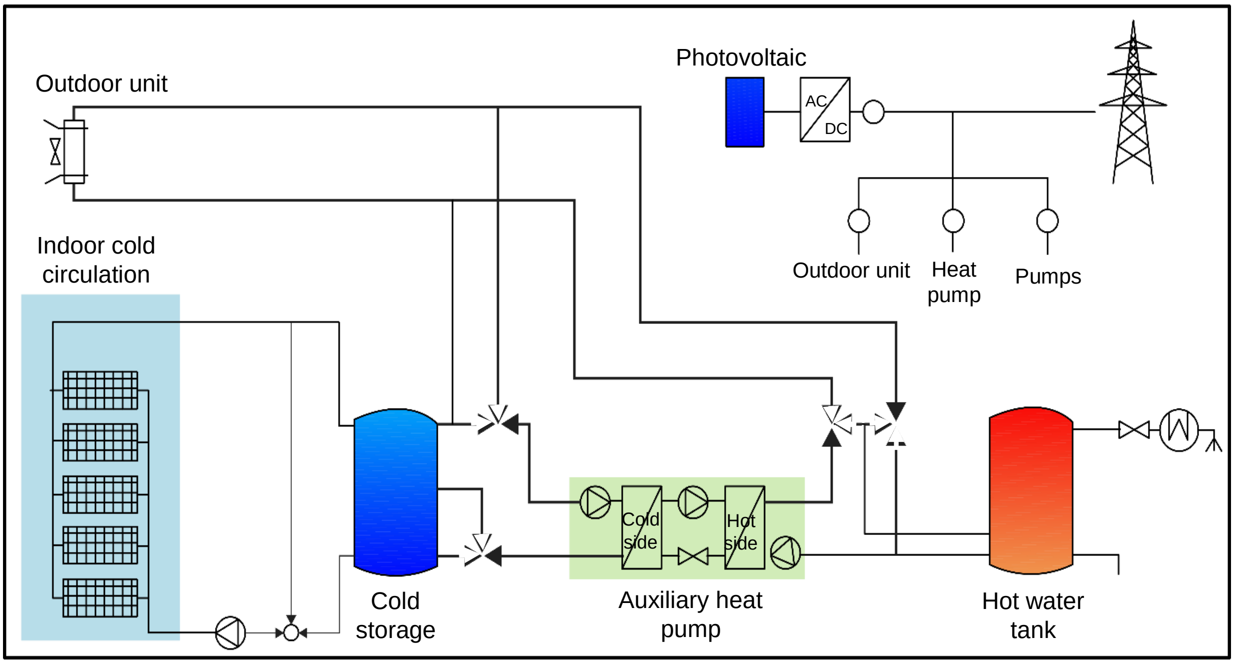

Figure 4.3: Simplified layout of the proposed system using photovoltaic.

In Figure 4.3, the simplified layout of the proposed system with the solar air-conditioning components is presented. The established over-current shield is in-parallel, and the entire photovoltaic components are connected electrically. For 280.8 V is the voltage and 1000 V is the extreme voltage system range. Photovoltaic components connection through the specified recommendation is 60 at serial connection maximum number. There are representative guarantees for the categories of these photovoltaic units; however, a lowest of 90% performance after 10 years of usage and 80% after 25 years. Hence, in the calculations, photovoltaic minimal power reduction with time is considered. Likewise, 0.9% is the yearly efficiency reduction of the preceding annual's rate. Hereafter, the photovoltaic units unframed are aimed to be secured on the proposed building roof. Also, 15° is the inclination to horizon for photovoltaic units to be installed (Henning et al. 2013). There are diverse roof slope and shapes; however, a standard slope number for the reference location is examined in this study. This suffices angle aimed at connection of electric power is beneath the elements. Aluminium is examined for sketching unframed components. The ascending of photovoltaic units deliberated upon is designed in understanding of flexion defence and likely alterations owing to possible enhancement of the thermal. Flexion defence from uppermost and lowermost is planned concerning snow masses and winds respectively. Rubber gaskets between the mounting and photovoltaic elements are examined to permit expansion of the thermal alterations. In the following sections, the description and modelling of the system components are offered in detail.

4.3.2 Scenario-Based Photovoltaic Inverter

Accordingly, arrangement of the photovoltaic produces the direct current, whereas majority of the photovoltaic solar air-conditioning mechanisms which are the heat rejection element, pumps and heat pump are basically premeditated to utilise alternating current. The direct current from photovoltaic arrangement converts the inverter of photovoltaic to the alternating current of grid-compliant and supplies it to the grid of electricity and solar air-conditioning. Consequently, the inverter is selected rendering to photovoltaic arrangement parameters. Similarly, the maximum inverter's direct current, voltage, current and power must be higher than the photovoltaic arrangement minimal standards. Successively, the nominal parameters initial process requires to be at adequate altitude for photovoltaic efficient usage as presented in Table 4.3 – power factor is referred to cos φ.

Table 4.3: Photovoltaic inverter of the direct current input (Alternating Current/Direct Current Inverter Manufactory, 2019).

Maximum DC power at cos φ = 1*	2000 W
Maximum input voltage	750 V
MPP voltage range	180 V to 500 V
Rated input voltage	400 V
Minimum input voltage	125 V
Initial input voltage	150 V
Maximum input current	15 A
Maximum input current per string	15 A
Number of independent MPP inputs	1

Strings per MPP input	2

For the model examined in this investigation, there is 40 m cable length of direct current from the inverter to the photovoltaic cluster. In like manner, there is typically 2.5 mm^2 in the direction of 6 mm^2 cross-areas mandatory cables and, two different three-wire of 1.5 mm^2 cables for the two strings. Likewise, the links are projected to be associated with the divider, even though setting it in the iron chamber with flame safety rules compliance. In this position, a high assurance level inverter is selected. Similarly, establishing power is scrutinised for every single electric piece of the photovoltaic solar air-conditioning. Suitable inverter for the outdoor and indoor usage consumes above the required level and put indoors to guarantee simple association with the information procurement element. The inverter is given modification of electronic solar which keeps electric bends from framing at evacuation connector of direct current. Also, the protection overvoltage through two varistors is given. The inverter is likewise outfitted with a coordinated residual-current all-pole-sensitive checking component. This present system's part can certainly separate amongst ordinary capacitive spillage currents and residual flows, and is outfitted with a defensive conductor observing gadget, which distinguishes the nonappearance of a conductor's defensive association and in this occasion, disengaging the inverter from the framework. An individual examination is scrutinised in the system throughout which the inverter continuously examines undervoltage, overvoltage, most extreme recurrence and the base recurrence reaction time (AC/DC Inverter Manufactory, 2019).

Upon the similarity between the cooling procedures and photovoltaic power generation, research studies proposed that it is an unsolved issue (Guido et al. 2015; Siecker et al. 2017). For the photovoltaic solar air-conditioning model analysed in this investigation – controllable and adaptable photovoltaic inverter is essential. A few working parameters aid to regulate the inverter’s functionality. Grid control capacities is outfitted with the inverter, making it conceivable to enact and design the capacities relying upon the prerequisites of the network administrator or photovoltaic solar air-conditioning control procedure by means of working parameters (for example, responsive power or dynamic power impediment, and so on). For the inverter has an information expression which demonstrates the inverter current working information just as shortcomings and unsettling influences. Subsequently, it is conceivable to see the current, voltage input, control, state, the day-by-day and the aggregate sums of power supplied in, and so forth. The system on the other hand demonstrates the inverter current output and voltage output. Also, it is conceivable to watch the preceding 16 feed-in hours chart of intensity variations, or the output of the energy over the most recent 16 days as indicated by this scenario circumstance.

Table 4.4: Photovoltaic inverter of alternating current output (AC/DC Inverter Manufactory, 2019).

Rated power at 230 V, 50 Hz	2500 W
Maximum apparent AC power cos φ = 1	2500 VA
Rated grid voltage	230 V
AC nominal voltage	220 V / 230 V / 240 V
AC voltage range	180 V to 280 V
Nominal AC current at 230 V	230 V 10.9 A
Maximum output current	12.4 A
Maximum output current in the case of faults	12.4 A
Total harmonic factor of output current at AC total harmonic factor < 2 %	≤ 4 %
AC power > 0.5 nominal AC power	
Rated grid frequency	50 Hz
Operating range at AC grid frequency 50 Hz	45 Hz to 55 Hz
Feed-in phases	1

Sizing domestic scale photovoltaic systems has traditionally been based more on the area available for the photovoltaic installation and the budget of the buyer, than on any economic rationale (Gilbert, 2013). After the electrical demand has been determined, the correct size of the photovoltaic generator needs to be determined. The most sensible procedure to determine the yield of different photovoltaic module types is to base this on their nominal power (Goswami and Kreith, 2016).

In this study, photovoltaic system would be installed on the roof of a building to generate electricity. Therefore, it is important to determine the number of kW_p of DC (Direct Current) at Standard Test Conditions (STC) of panels and the roof area required. The annual energy output (E_{AC}) from the photovoltaic system is provided in equation 4.1 as (Gilbert, 2013):

$$E_{AC} = P_{AC} \; X \; h_{d,ps} \; X \; N_d \tag{4.1}$$

Where, E_{AC} is the annual energy output (kWh), P_{AC} is the AC (Alternating Current) power output (kW), $h_{d,ps}$ is the peak sun hours in a day and N_d is the number of days in a year. Therefore, the annual AC power output (P_{AC}) is calculated from equation 4.1. Taking into account the impacts of inverter efficiency, the DC power under STC ($P_{DC,STC}$) is calculated using equation 4.2 (Gilbert, 2013).

$$P_{DC,STC} = \frac{P_{AC}}{\eta_{inv}} \tag{4.2}$$

Where, η_{inv} is the inverter efficiency.

4.3.3 The Auxiliary Heat Pump of the System

The purpose of solar air-conditioning is the quantitative and qualitative room air cooling (likewise termed heat rejection). For heat cannot impulsively flow from a colder area to a hotter location according to the second law of thermodynamics. As indicated by Renewable Energy Hub (2021), heat pump is much safer and cheaper to run. Also, the system is efficient, requires less maintenance and reduces CO_2 emissions than the electric-driven chiller. Therefore, heat pump is used instead of electric-driven chiller to enable optimum performance of the system. The use of heat pump electricity transmits heat power from cold side (the temperature-low loop) to hot side (the energy-hot loop). Research shows that heat pumps are more sustainable and efficient in winter temperatures unlike gas or electric systems (Renewable Energy Hub, 2021). Hence, heat pump is also used as the auxiliary heating source and serves as a backup system for pumping heat during the winter months. In residential heating the solar system can be used in parallel with a heat pump, which supplies auxiliary energy when the sun is not available (Soteris et al. 2020). Therefore, the total amount of heating energy supplied to the system by the auxiliary heater is given in equation 4.3 (Solar Engineering of Thermal Processes, 2013):

$$Q_{HP} = \ (COP\ X\ W_{HP}) \tag{4.3}$$

Where, Q_{HP} equals the overall heating energy supplied by the heat pump and W_{HP} equals the power consumed by the heat pump's compressor. The performance is dependent on condensing temperature and condenser inlet. In the heating mode, heat pump delivers thermal energy from the condenser for space heating and can be combined with solar heating. In the cooling mode, the evaporator extracts heat from the air to be conditioned and rejects heat from the condenser to the atmosphere with solar energy not contributing to the energy for cooling (Solar Engineering of Thermal Processes, 2013; Soteris et al. 2020).

In this study, the operating principle of the heat pump used with the solar air-conditioning system is based on compression and expansion of a working fluid/refrigerant. According to Solar Engineering of Thermal Processes (2013), heat pump has four main components: evaporator, compressor, condenser and expansion device. The refrigerant is the working fluid that passes through all these components. The evaporator heat is extracted from a waste heat source. In the condenser this heat is delivered to the consumer at a higher temperature level. Electric energy is required to drive the compressor and this energy is added to the heat that is available in the condenser (Liu, 2017). The heat pump operates on the same engineering principle as the air conditioner. It extracts energy from outdoor ambient heat, concentrates it with the aid of a refrigerant in a heat-exchanging coil, and delivers it as processed heat or cooling (Liu, 2017; Grassi, 2018).

Vapor-compression cycle is generally inspected in the machines having heat pump, and moreover, it is analysed in this study for the modelling of photovoltaic solar air-conditioning. Additionally, the vapor-compressor cycle depends upon the rule of turned-around Carnot Cycle. Consequently, the heat pump circle is separated into two sections with an extension valve and vapor compressor. High-weight circle portion is termed heat pump hot-side, and the low-weight circle portion is termed heat pump cold-side. The vapor compressor consumes power for siphoning up refrigerant from cold-side to hot-side heat pump. Two heat exchangers in the vapor-compressor cycle are examined (condenser and evaporator on the hot-side and cold-side respectively, as appeared in Figure 4.4).

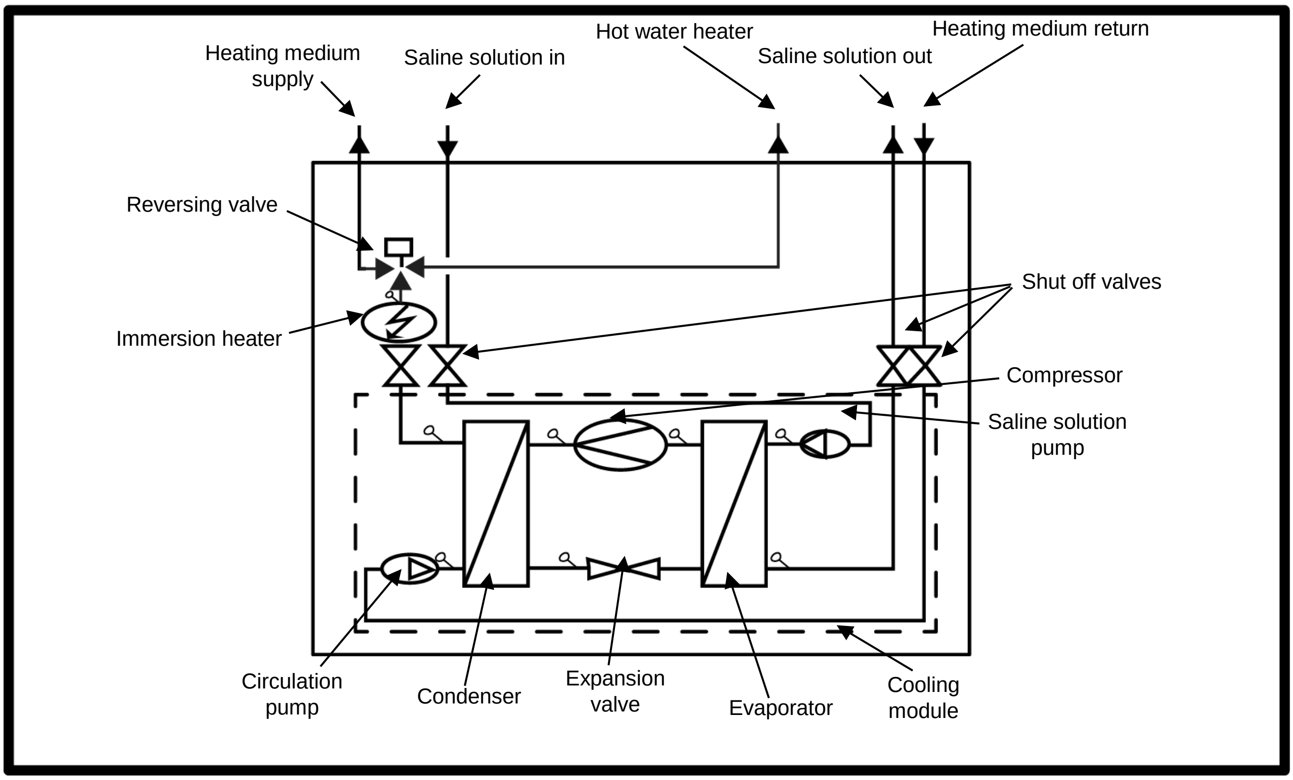

Figure 4.4: Illustration of the auxiliary heat pump (Cooling Machine Manufactory, 2019).

The saline solution discharges its energy to the refrigerant in the evaporator of the heat pump, which is then compressed and vaporised in the compressor. The temperature of refrigerant that is elevated, goes via condenser and it emits its energy to circuit of the heating intermediate and to a certain degree, in the water docked radiator. In the event that there is a more prominent requirement for boiling or heating water than the compressor may give – there is possibly an incorporated drenching radiator (Cooling Machine Manufactory, 2019).

For the photovoltaic solar air-conditioning scenario, highly efficient and small-scale engineering heat pumps are studied. Also, 5 kW cold cooling is the heat pump minimal cooling power (Cooling Machine Manufactory, 2019). Diminishing the utilisation of energy in a long-haul task through utilising of compressor speed-variable which the capacities as indicated via the overarching demand of heating. Compressor speed variety is completed by means of the inverter and the energy-low flexible hoses and circulation pumps are coordinated in the heat pump. Circuits of the liquid saline solution may be on either side through connection. Expansion controllable valve is analysed for refrigerant dosed extension to the low-weight circle. For the heat pump may be determined via utilising AC having 50 Hz normal recurrence (1x230 V, 3x230 V, 3x400 V).

Table 4.5: Heat pump COP together with cold and hot coils two pumps (Cooling Machine Manufactory, 2019).

Cold circuit T/Hot circuit T	0/53	0/45	10/35	10/45
Rated output, kW	3.15	2.87	4.3	3.98
Electrical input, kW	0.67	0.79	0.66	0.83
COP	4.72	3.61	6.49	4.79

Heat pump COP is basically subject to the temperature distinction amongst the cold and hot coils. The temperature likewise influences the productivity of cooling, being founded upon refrigerant physical parameters and explicitly on temperature of the vapor-condensate. Additionally, 1.16 kg requiring R407C refrigerant is utilised by the heat pump (Cooling Machine Manufactory, 2019). Such cold and hot circles heat pumps have inner naturally controlled siphons. The essential functioning speed at the pint when the compressor is running for the siphons is established consequently to acquire the ideal temperature distinction amongst the return and supply lines. This implies the functioning speed redress is to be established toward the start of the procedure cooling.

In like manner, the saline minimal movement at 50 Hz is 0.08 and 0.18 l/s on the hot-side and cold-side, respectively. For the siphons are speed-variable, so the movements amount is from 0.03 l/s in the direction of 0.33 l/s and 0.03 l/s in the direction of 0.52 l/s on the hot side and on cold side respectively. Additionally, the estimations of siphon movements can be diminished with water driven obstruction of photovoltaic solar air-conditioning segments. The exceptionally proficient brackish water siphons are intended for the base utilisation of energy. Consequently, the necessities for weight misfortunes at the rate of minimal flow are ≤64 kPa and ≤69 kPa on hot-side and cold-side, respectively. This establishes the cut-off points for the quantity of estimating components. The water-driven weight misfortunes in conventional systems are not exactly 33% of the most established for the proposed photovoltaic solar air-conditioning operational system, where an array about 10 kPa is established for such misfortunes as well as those from the entirely estimating components. The working weight in hot and cold circles requires to be in the array from 0.05 MPa towards the direction of 0.45 MPa (Cooling Machine Manufactory, 2019).

Correspondingly, 150 kg is the total weight of the heat pump and 90 kg is the module cooling (Cooling Machine Manufactory, 2019). The module cooling comprises of connection pipes, flow sensors, temperature, pumps of cold-side and hot-side, evaporator, expansion valve, condenser and vapour compressor as delineated in Figure 4.4. The heat pump portions excluded in module cooling are the body covering, the armature and control box for association with the structure hydraulic and electrical systems. A 100 L of DHW tank may be alternatively incorporated into heat pump (in any case, it is absent in this examination for the situation-based system). Effectively removable module cooling is the benefit of such heat pump, which lessens the period to be used-up on system repair and modification.

The heat pump under deliberation is produced on a vigorous edge with strong boards and powerful insulator for inhabitant's most ideal comfort. The siphon cooling energy is constrained at 5 kW for diminishing the level of the noise. EN 12102 indicate the yield of the noise via the lateral of 0/35 or after 36 dB in the direction of 43 dB. Also, EN ISO 11203 indicate that the level of pressure sound is determined through the lateral of 0/35 and a separation of 1 m is on or after 21 dB in the direction of 28 dB.

The power of the cooling pump may be expanded in the direction of 6 kW and in this circumstance, the clamour yield will rise near 47 dB (Soteris et al. 2020).

4.3.4 Scenario-Based Cold Circulation of the System

For a cooling ceiling, the heat rejection of the room is reinforced through the panels of radiant ceiling. Besides, a cooling radiant system alludes to a controlled-temperature superficial that cools temperatures of the indoor through expelling reasonable warmth and where the greater part of the heat transfer happens via radiation of the thermal (HVASE, 2008).

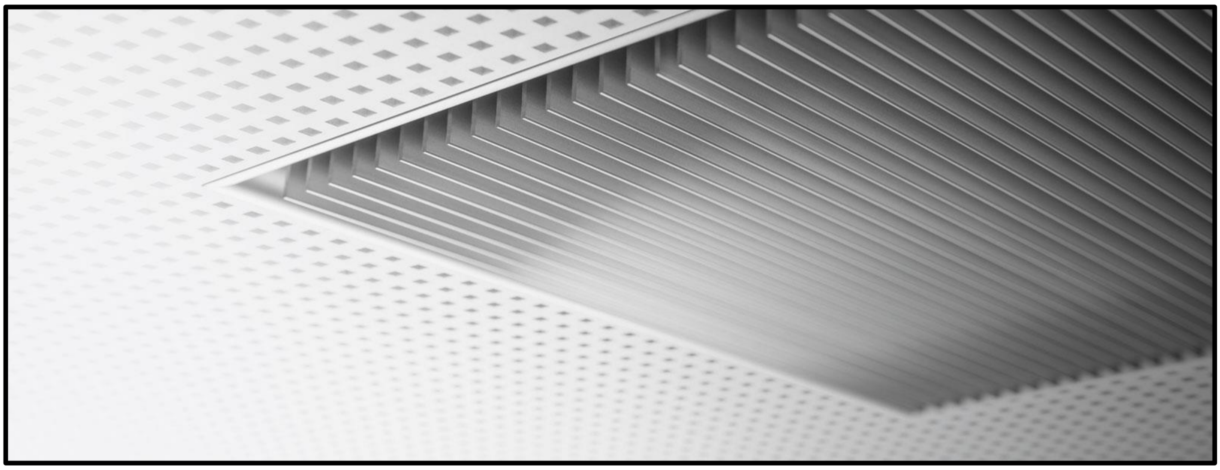

Figure 4.5: The cooling ceiling (Kiefer, 2019)

Likewise, the proposed cooling boards are specified at 0.2 m beneath the roof. The boards utilise no electrical power and are absolutely upkeep free. Subsequently, they do not scatter any residue, they aid counteract colds and any form of sensitive reactions. Steel funnels having 4 lines are specified for cooling roof upper side, to which saline solution is spilling out of the chilly storage. Therefore, brackish water temperature can be measured with dew point apparatus at the blending valve before the bay of roof cooling. A bit of brackish water recycles in cooling roofs, and alternative bit is replaced in the unit of cold storage. Cooling roofs temperature is always kept over the dew point and together with 2°C edge. This is accomplished for defence from the appearance that is basically condensate. The plane surface can possibly be stimulated and furthermore covered with polyester paint that is of high quality.

Figure 4.6: The cold ceiling components hydraulic links (Cooling Ceiling Manufactory, 2019).

Similarly, the proposed bespoke roof cooling comprises of 50 cells as appeared in Figure 4.6. The cells are 0.32 m wide and 3 m long and are entirely connected in series. Ordinarily, cell association have five columns. There are two lines per column and five cells consisting of individual line. The highest point of cooling roof is secured with stone fleece protection. For 11 W/m^2/K is the explicit cooling yield with protection (Cooling Ceiling Manufactory, 2019). Also, 48 m^2 is the all-out area of cooling roofs. Non-secluded pipes likewise take an interest in exchange of heat. The blending valve of these pipelines reach out towards the cooling roofs and amongst them. For 535 W/K is the cooling yield of cooling roof as well as non-protected funnels. Likewise, 95°C is the temperature of utmost activity. There may be brief working period of cooling roof because of its low brackish water mass and inertial low mass. Also, 120 kg is the cooling roof net load with protection and without brackish water. Besides, 0.16 m^3 is the volume of saline solution and 0.5 MPa is the greatest working overpressure (Cooling Ceiling Manufactory, 2019).

4.3.5 The System Outdoor Unit

Subsequently, the greatest piece of hot side heat is rejected to open air. Therefore, the outside unit which is also termed as a heat rejection tower or heat exchanger is analysed for this examination. Also, 5.35 kWh is the minimal outside unit power, and the brine-air heat exchanger is the principle outside unit element (Henning et al. 2013). The heat exchanger receives air from a fan and heat transfer is upgraded to the open air from its outer surface. The rejected heat per 1 K proportion of the contrast amongst the bay brackish water temperature and the open-air temperature is resolved from estimation outcomes. It shows that the rejected heat and the outside weight is ordinarily that of the heat exchanger aluminium possessing outer surfaces of 34.3 m^2. For the three-phase AC; 400 V, 50 Hz is operated by a fan of 200 W while 640 per minute is the ostensible cycles. The fan operation minimal flow of the air is 4100 m^3/h and its distance across is 0.5 m (Henning et al. 2013).

The outdoor unit is proposed to be placed on the south region of the building. Besides, 10 dB – 30 dB is the generated noise at fan activity before outside unit and on the side respectively (Duffie and William, 2012). The outside unit requires a process with saline solution having 20% (C_2H_6O) ethanol and a mixture of water. The flow of the saline solution should be tempestuous to guarantee the subjective transfer of heat from this saltwater to the plates of heat exchanger. For 0.28 l/s is the minimal saline flow via the outside unit which is 150% pump flow of the heat rejection (Henning et al. 2013).

Subsequently, the impact of solar outdoor unit by utilising the effectiveness can be determined as expressed in equation 4.4 (Duffie and William, 2012):

$$\varepsilon = \begin{cases} \frac{1-e^{-NTU(1-C^*)}}{1-C^{*-NTU(1-C^*)}} & if\ C^* \neq 1 \\ \frac{NTU}{1+NTU} & if\ C^* = 1 \end{cases} \tag{4.4}$$

Where, ε is the effectiveness, e is emittance, NTU equals the number of transfer units and it is represented as $\frac{UA}{(mC_P)_{min}}$.

Then, C^* is the capacity rate ratio and is given as:

$$C^* = \frac{({}_mC_P)_{min}}{(mC_P)_{max}} \tag{4.5}$$

Where, $(mC_P)_{min}$ is the minimum heat transfer capacitance (W/K) of the outdoor unit, $(mC_P)_{max}$ is the maximum heat transfer capacitance (W/K) of the outdoor unit and UA is the coefficient area product.

4.3.6 The System Domestic Hot Water

DHW preheating is carried-out by means of heat rejection over the tank. For 200 L is the day-to-day utilisation of DHW, which relates to single-family household utilisation. The inlet chilly water is at the base, streaming through from the network locale drinking water. According to HVASE (2008), utilisation of DHW satisfies the comparing guidelines, being the equivalent consistently. Temperature of the inbound water in summer and in winter is around 15°C and 5°C, respectively. Also, 50°C is the temperature of DHW supply. As specified, the preheating which is dependent upon the system innovation is completed to the best degree, even though succeeding heating is carried out utilising the essential source of heat. The blending valve requires to be situated following the essential source of heat because of wellbeing reasons for consumers of DHW. The hot and cold-water outlet storage is required to be combined because of the temperature level which can be increased over the DHW temperature supply. Akin blending is specified to make the clean threats negligible because it is for the most part of over 50°C temperature.

For 57°C is the most extreme temperature and being constrained because of explicit heat pump and brackish water properties. Also, 52°C is the temperature variance and implies that energy of heat may be put away there up to 27 kWh. Likewise, 8.1 kWh to 10.5 kWh is the amount of day-by-day utilisation of energy for heating DHW that is contingent upon inbound cold-water temperature (Henning et al. 2013).

The hot water storage tank is modelled with the assumption that the hot water is well mixed in the tank and has an even temperature and can be shown by a differential equation in time. The differential equation unfolding the instant energy equilibrium of the storage tank as a time function regrading temperature is provided in equation 4.6 (Solar Engineering of Thermal Processes, 2013):

$$m_1 C_p \frac{dT_s}{dt} = \sum m_2 C_p \left(T_{il} - T_f\right) + Q_{gain} - Q_{Loss} \qquad (4.6)$$

Where, m_1 equals the total mass of fluid in the tank (determined by the volume), C_p equals the heat capacity, m_2 equals the water flow rate into the tank, T_{il} is the initial temperature, T_f is the final temperature, Q_{gain} is the energy gain and Q_{Loss} is the energy loss in the hot water storage tank. The storage tank model balances the temperature with a time variation function of stored energy in the storage tank via heat losses to the environment, transfer of energy via in and out water flows and auxiliary heat input (heat pump).

4.3.7 The System Cold Storage

A cold saltwater buffer is combined as cold storage. This permits the arrangement of the fundamental cold ahead of time. As the temperature of the outside air is diminishing the potential of the heat rejection in the example given; in this way, the COP of the heat pump is increasing. Moreover, this lessens the peak of the cooling power at the most extreme cooling demand. In addition, this permit decreasing the quantity of stop/start heat pump switching and likewise the cold side pump. Hence, the lifetime of the unit increases and the entire system of photovoltaic solar air-conditioning. Also, a 477 L tank is offered via the cold storage and the cold may be kept up to 7 kWh. The tank of the cold storage has no inward heat exchanger, and this possesses a diameter of 0.7 m and a height of 1.92 m, respectively. This possesses a secured envelope having insulation of polyurethane foam. For 0.03 W/(m·k) is the heat conductivity of coefficient insulation cold storage. On the cylinder, it has 50 mm thick insulation with the top having 50 mm and the base having 50 mm. Likewise, 120 kg is the insulation of the weight and 0.3 MPa is the greatest working pressure (HVASE, 2008).

The tank of the specified cold storage is associated with two circles. Firstly, the cold circle between the tank and heat pump. This circle has two contributions at centre levels and cold storage base, even though the yield is on the highest degree of a cold storage tank. The brackish water with a three-way valve which unlocks contribution amongst the tank base and centre degrees; however, making it conceivable to cool just its upper part or entire tank. Secondly, the subsequent circle is that of cooling the roof between the cold storage and the roof. The second circle has one tank top contribution and one base yield. Altogether, the tank has 16 strung gaps. Sensors having 3 temperatures are introduced at the base, top and centre levels. In addition, the ceiling pump cooling is intended for lasting ceiling saltwater flow. The controls of the blending valve of the distribution brackish water and its exchange are in the tank of the cold storage. Thus, the rate of flow is not consistent between the cooling ceiling and cold storage. This sort of association decreases the likelihood of water sledge and its effect.

The cold storage of the solar air-conditioning system is expressed as given in equation 4.7 (Zhai et al. 2013):

$$Ct_{se} = (Tr_{ld} + Pr_{ld} + In_{ld} + Eq_{ld} + If_{ld})\ x\ Sa_f \tag{4.7}$$

Where, Ct_{se} is a total load of cold storage, Tr_{ld} is the storage transmission load, Pr_{ld} is the storage product load, In_{ld} is the storage internal load, Eq_{ld} is the storage equipment load, If_{ld} is the storage infiltration load and Sa_f is the storage safety factor.

4.3.8 The System Heat Transfer Fluid

From investigations, water is supplanted through brackish water to guarantee the operation of the system at the freezing water temperature. For –11°C is the lowest heat pump working temperature and a water-ethanol blend is analysed in the saline solution of photovoltaic solar air-conditioning operation scenario. Also, 16.16 is the mass percentage of ethanol and 20% volume is its substance at the normal encompassing temperature and weight (Haynes and Lide, 1962). The brackish water is specified to possess a colour of transparent blue and the odour of alcohol that permits detecting spillages.

For –10.4°C is the specified temperature of the freezing salt water and 86°C is the temperature of boiling, whereas 977 kg/m^3 at 20°C (Ts) is the density (ρs), and 1191 W/(kg·K) is the capacity of heat (Cs) on a similar temperature (Lange and Dean, 1983). Likewise, Haynes and Lide (1962) suggested that 5.61 mm^2/s is the salt-water viscosity whereas, 87.5°C is the temperature of boiling which is not exactly the system's most investigational most extreme working temperature. Accordingly, the wellbeing high prerequisites are employed. The saline solution density (ρs) and capacity of the heat are relying upon the temperature. These parameters relating to estimations were considered in the energy flow calculations. Saline solution heat capacity of 0°C in the direction of 60°C temperature scope shifts in the array about 2.51%. The heat capacity which is reliance upon the temperature of the saltwater solution is revealed in equation 4.8 (Cooling Machine Manufactory, 2019):

$$Cs = 0.0000280328\,Ts^2 - 0.0015099591\,Ts + 1.20951072 \qquad (4.8)$$

Subsequently, Figure 4.7 exemplifies the assessment of saline solution and water heat capacity. This is grounded upon equation 4.8 and the hypothetical heat capacity requirement of temperature pure water.

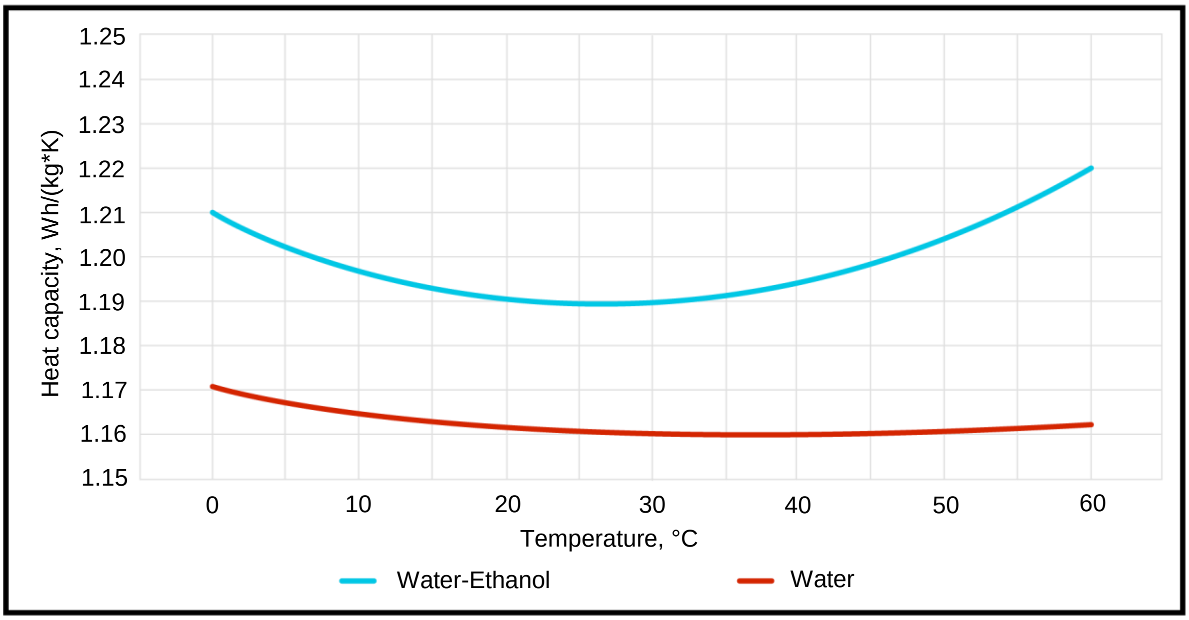

Figure 4.7: The water heat capacity and water-ethanol combination (saline solution) (Cooling Machine Manufactory, 2019).

The saline solution density (rs) is reduced by 2.69% which is the range of temperature of 0°C in the direction of 60°C. The temperature (rTs) of the function density is given in equation 4.9 (Cooling Machine Manufactory, 2019):

$$\rho Ts = -0.000003Ts^2 - 0.00025Ts + 0.98368 \qquad (4.9)$$

Albeit the density contrast of ethanol-water combination (saline solution) and water is shown in Figure 4.8.

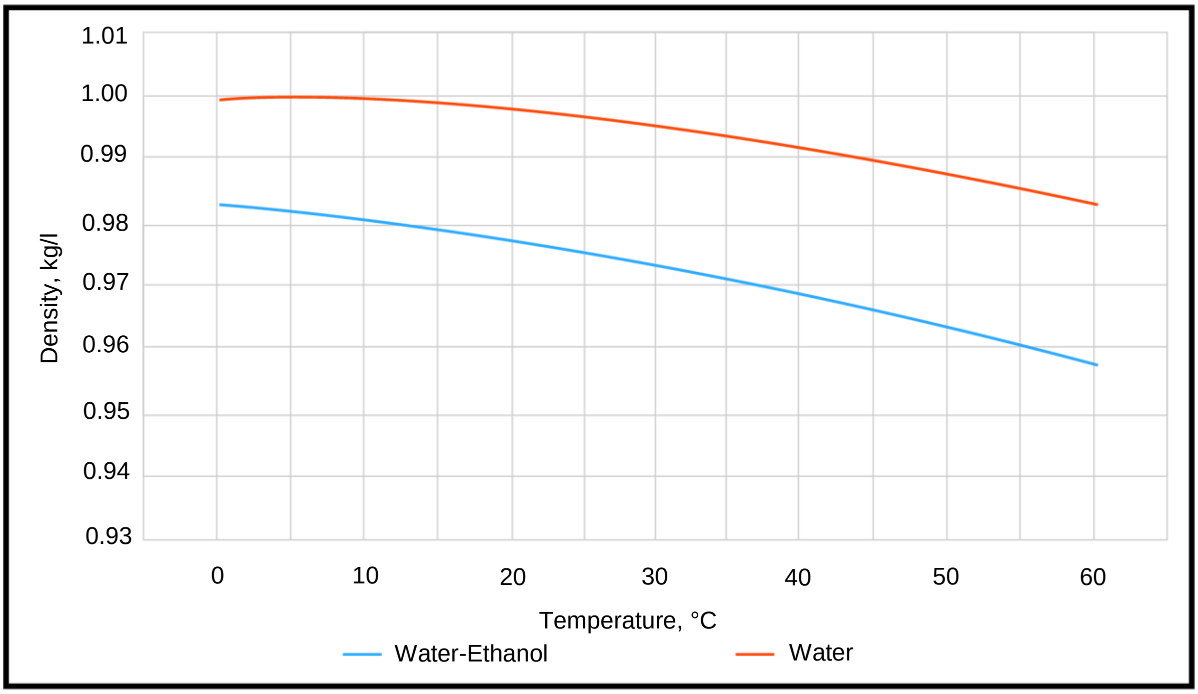

Figure 4.8: Water-ethanol combination and water density (Cooling Machine Manufactory, 2019).

The fundamentals of hydraulic system are typically stainless steel made, whereas several are of copper and aluminium. Therefore, inhibitors are supplemented with the saline solution.

4.3.9 The System Piping

Accordingly, stainless steel pipes of 18 mm in the direction of 28 mm are specified for the proposed photovoltaic solar air-conditioning in this study. For the majority of framework networks and pipe assembly mechanics “press-fit” is utilised. Appropriate and ring-type immobiliser apparel networks are studied to associate the heat pump, outside unit, hot water tank, cold storage, pumps and cold circulation.

The specified pipes are thermally protected or insulated utilising polychloroprene-based manufactured elastic. The insulation is additionally realistic for systems of refrigeration and chilled water. For –50°C temperature is the base administration and 150°C is the limit. The protection secures against cold side losses of thermal, moisture and condensation amassing on pipes. Heat is conductive and ≥ 2 cm is the pipe insulation thickness. Explicit consideration is specified to be given to the powered system's portion insulation having ≥1 cm protection layer of insulation.

4.3.10 The System Dimension and Apparatus

For this study, an exceptionally accurate estimating apparatus is theoretically employed. This apparatus and its position permit inspecting the operational scenario and specific primary parts of photovoltaic solar air-conditioning. The entire estimating strategies analysed for the system model are controlled. For this scenario operation model, it is conceivable to screen and spare the information acquired during the system's activity in the information procurement program. Altogether, the photovoltaic solar air-conditioning system model is anticipated to contain a sensor for CO_2, one sensor for solar irradiation, one sensor for air pressure, four sensors for humidity, and eight for flow counters, six electricity counters and forty sensors for the temperature. Additionally, manual three flow meters, three sensors of manual pressure, and manual eight thermometers are studied for the animate operation of the system's security monitoring. As a consequence, the sensor numbers and their class of accuracy in a standard system must be minimised as a result of simplification cause and economic or commercial basis.

Moreover, electric energy estimations are specified on the sides of DC and AC. The photovoltaic voltage and the forthcoming current are estimated through meters incorporated into the inverter of the photovoltaic. Inverter-delivered parameters of alternating current power are estimated with alternating current, frequency and voltage meters, that are likewise coordinated into the inverter. For 0.01 V is the voltage estimations accuracy and 0.001 A is the estimations on the two sides. Incoming estimations of DC and AC outgoing electrical energy are over with 1 W precision, and 0.01 Hz is the accuracy at estimating recurrence. For the system model, three extra power meters are scrutinised which independently measure the power utilisations of the heat pump, outdoor unit and supplementary pumps. For 1 Wh is the electrical energy accuracy of the entire component estimations. Figure 4.9 presents the positional illustration of the system apparatus in the building.

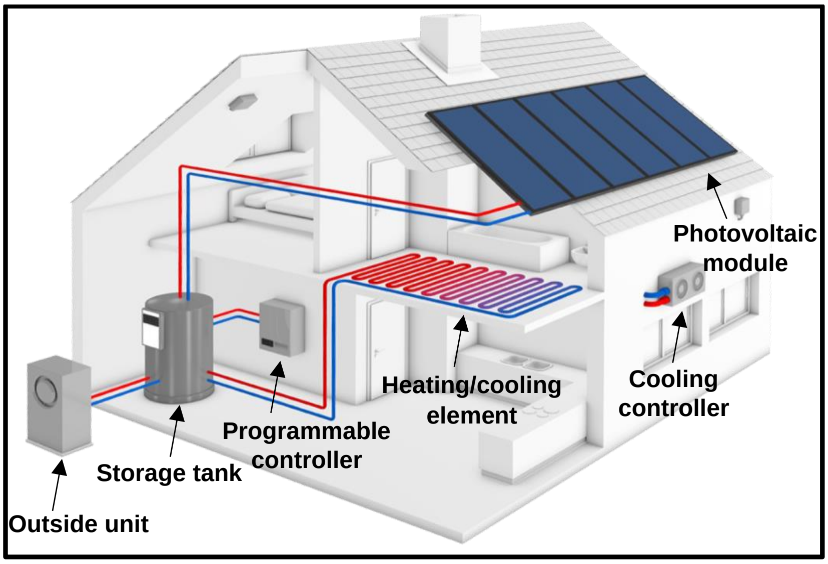

Figure 4.9: Positional illustration of the system apparatus.

The specified dimensions are examined with the flow counters pull-type. Extremely accurate 6 counters of flow are examined for the dimension of current over the key portions of the scenario system. The sensors of temperature typically estimate water, air and saline solution temperatures. Sensors of water temperature and saline solution are projected to be applied in an exceptional metal case inside tanks and pipes whereas, possessing PT100 purpose thermometers resistance of 4 x 0.25 mm^2 wires of class A and having 5 m length of cable. The scope of temperature having PT100 class A is –70 °C in the direction of +550°C and possesses the actual precision after 0.15°C in the direction of 0.27°C, which is basically in the photovoltaic solar air-conditioning temperature array of operation. Temperature and flow counters combination sensors permit thermal energy accounting. In like manner, the heat pump possesses eleven coordinated B class of PT100 thermometers resistance and two flow sensors for checking of energy flow interior control of three current sensors for each stage. The pump likewise possesses switches that are of low and high weight. Likewise, the meteorological station typically makes it conceivable to decide the main parameter of climate conditions for the system model and it can be associated close with the photovoltaic components. The station is specified to incorporate sensors for estimating the temperature of the photovoltaic component, relative humidity of the air, the pressure of air and temperature of the outdoor air. For the system model, the estimation scope apparatus relates to the climate fluctuations. The temperature of the outdoor air of the selected region is examined with 0.2°C accuracies for modelling, whereas having –20°C in the direction of +50°C within the range of specified temperature. 0.1% is the humidity relative to air sensor resolution, albeit it gauges 2% accuracy from 0 to 100% in the entire range. Also, 1.5 hPa is the air weight estimating accuracy from 300 hPa in the direction of 1200 hPa for the entire range. The most noteworthy second-class thermopile pyranometer is examined for estimating the irradiance of the solar power and proposed for shortwave worldwide radiation of solar energy estimations from 300 nm in the direction of 2800 nm within the range which is spectral. The detector thermopile estimates 2000 W/m^2 irradiance whereas, possessing <18s of reaction time and 10 $\mu V/W/m^2$ sensitivity characteristic having –10ºC in the direction of +4ºC that shifts under 5% (Cooling Machine Manufactory, 2019). For <1 W/m^2 is the irradiation of solar accuracy estimation. The temperature component is estimated with the exactness of 1°C from –20°C in the direction of +80°C, in the fundamental range of temperature. The information is obtained by utilising the state-of-the-art meteorological database.

4.3.11 Evaluation of the System Output

To analyse the energy-related performance of the photovoltaic system output, some important component parameters are applied to evaluate the output of the system during simulation in each location. The objective is to evaluate the effect of the main components of the system from the overall performance point of view. The energy performance indices assessed in this study include:

- Photovoltaic yield
- Total electricity consumption
- CO_2 savings of the system
- Energy savings of the system
- Total energy consumption

Photovoltaic Yield

Photovoltaic yield is one of the most important parameters for characterising a photovoltaic system output and it is of great interest to end-users who can be either a homeowner or an investor. The former is concerned about the maximum energy (kWh) produced per kW_p of installed power, while the latter is interested in the maximum possible profit from the system (Mavromatakis et al. 2010; Goswami and Kreith, 2016). The total daily ($E_{AC,d}$) and monthly ($E_{AC,m}$) AC energy generated by the photovoltaic system were obtained as given in equation 4.10 and 4.11 (Mavromatakis et al. 2010):

$$E_{AC,d} = \sum_{t=1}^{t=48} E_{AC,t} \tag{4.10}$$

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,d} \tag{4.11}$$

Where N is the number of days in the month and t is the number of 30-minute time intervals in a day. Similarly, the total daily ($E_{DC,d}$) and monthly ($E_{DC,m}$) DC energy generated by the photovoltaic array were obtained as provided in equation 4.12 and 4.13 (Mavromatakis et al. 2010):

$$E_{DC,d} = \sum_{t=1}^{t=48} E_{DC,t} \tag{4.12}$$

$$E_{DC,m} = \sum_{d=1}^{N} E_{AC,d} \tag{4.13}$$

Total Electricity Consumption

The electric consumption of the system represents the total amount of heating and cooling energy production and the electricity needed for this production. The total electric consumption of the system η_{el} is given in equation 4.14 as (Abumohammad, 2021):

$$\eta_{el} = \mathrm{P}_{PC} + \mathrm{P}_{OS} + \mathrm{P}_{\mathrm{el,CC}} + \mathrm{P}_{\mathrm{el,HP}} + \mathrm{P}_{\mathrm{DHW}} + \mathrm{P}_{HP} \tag{4,14}$$

Where, P_{PC} is the electricity consumed by the pump serving the cold storage [kWh], P_{OS} is the electricity consumed by the pump serving the outdoor system [kWh], $\mathrm{P}_{\mathrm{el,CC}}$ is the electric power of the cooling circulation [kWh], $\mathrm{P}_{\mathrm{el,HP}}$ is the electricity consumed by the heat pump [kWh], P_{DHW} is the electricity consumed by the pump serving the DHW [kWh], P_{HP} is the electricity consumed by the pump serving the heat pump [kWh].

Total Energy Consumption

This is the total energy consumption by the hot water system components, which is the sum of the heating energy consumed by the hot water storage, outdoor unit and the auxiliary energy system provided by the heat pump. The total energy consumption, Q_{TEC}, is presented in equation 4.15 as (Duffie and William, 2012):

$$Q_{TEC} = Q_{HW} + Q_{OU} + Q_{AHP} \tag{4.15}$$

Where, Q_{TEC} is the total energy consumption and, Q_{HW}, Q_{OU} and Q_{AHP} are heating energy (kWh) consumed from the hot water storage, the outdoor unit, and the auxiliary heat pump, respectively.

Energy Savings of the System

The $PE_{savings}$ is the amount of primary energy of the system saved from the consumption of electricity from the photovoltaic system and the auxiliary heat pump. The higher the output value of the system, the higher performance in terms of renewable energy and hence environmental sustainability. To define this index, it is necessary to evaluate the primary energy consumption of a system as given in equation 4.16 (Goswami and Kreith, 2016):

$$\Delta PE_{save} = \Delta P_{elec} + \Delta P_{HP} \tag{4.16}$$

Where, ΔPE_{save} is the energy savings of the system, ΔP_{elec} is the amount of energy saved from the consumption of the photovoltaic system and ΔP_{HP} is the amount of energy saved from the use of an auxiliary heat pump.

CO_2 Savings of the System

CO_2 quantifies the entire emitted CO_2 (kg), produced directly from the system. This quantity can be calculated as given in equation 4.17 (Duffie and William, 2012):

$$CO_2 = ICO_2 . W_e \tag{4.17}$$

Where, ICO_2 represents the CO_2 intensity of the energy source and W_e is the daily consumed energy, kWh.

When the system's energy is electricity, the unit of this conversion coefficient is $kgCO_2/kWh$, and the value is 0.52 (Duffie and William, 2012). The CO_2 emission is an important indicator to determine if a specific technology has environmental benefits and to put a value on them.

The CO_2 savings of the system is the annual reduction of CO_2 emissions. To define this index, it is necessary to evaluate the energy consumption system as expressed in equation 4.18 (Duffie and William, 2012):

$$CO_{2,save} = \frac{\Delta PE_{electrification\ of\ the\ system}}{CO_{2conversion\ elec}} \tag{4.18}$$

Where, $CO_{2,save}$ is the CO_2 saving, $CO_{2conversion\ elec}$ is the emission rate for the production of electricity 0.52 $[kgCO_2/kWh_{PE}]$ and ΔPE is the amount of energy saved in the system, kWh.

4.3.12 The System Process of Operation

The precedence in a cooling season is covering the cooling mandate of the room. The cooling machine to the heat pump is examined to offer heat transfer from an environment of low temperature to an environment of high temperature. The heat pump is power mutable and is regulated through its peculiar regulator box. The heat rejection is measured through the uppermost potential of heat rejection. The temperature of the water at the tank middle level and the internal coil of the coefficient heat transfer are demarcated. Also, the heat transfer rate of the outdoor unit, the air temperature of the outdoor and the consumption of electricity from the fan is reproduced through the main energy factor.

Nevertheless, unrestricted heat rejection is considered during the conceptual modelling of the photovoltaic solar air-conditioning. Unrestricted heat rejection is emanating in the direction of the outside air through the operation of the outside unit and without the operation of a heat pump. There is the consumption of electricity in this procedure with consumers being the hot-side pump and outside fan component.

As a result, the unrestricted heat rejection is detached from the scenario operation of the system in acquiescence with the outcomes of the pre-simulation. The regulator obliges DHW to to preheat in the non-cooling season. In this circumstance, some components of the system operate in the reverse mode, for instance, the outside component is a source of heat, and its interrelation is subsequently substituted for the cold side of the heat pump. The purpose of this regulator is to extremely protect the thermal energy mandate of the DHW. The foremost obstacle at this juncture in the non-cooling season is the low temperature of the outside air. This primarily causes unsafe freezing for the outdoor unit. Also, the low temperature of the outside air subsequently upsurges the difference in temperature in both the hot and cold sides of a heat pump. This expressively reduces the COP of the heat pump and can brand the system less appealing.

For the flow and return of hot side temperatures, a heat pump is regulated through the integral sensors. Temperatures of the brine return may be restricted if needed to the lowest. Also, regulators of the production of heat may be examined in dual conduct. The heating of DHW management is achieved grounded upon the principle of "floating condensing" – meaning the level of temperature required for heating at a precise temperature the outdoor is formed and directed via accumulated values emanating from outside and the flow sensors. The sensor of the room temperature can likewise be examined to reimburse the nonconformity in room temperature (Cooling Machine Manufactory, 2019). The heat pump transports the heat to a secure level of temperature in the other regulator technique and it is recognised as "fixed condensing". The mechanised system of the heating operation is then substituted through the device of an outside regulator unit (Cooling Machine Manufactory, 2019). Consequently, the subsequent sections of this chapter present the modelling of the indoor environment.

4.4 Scenario-Based Modelling of the Indoor Environment

The conceptual modelling consolidates the fuzzy logic with the PID for the indoor temperature, and backpropagation NN with the PID for the IAQ to guarantee output control optimisation. Also, research studies demonstrated that using fuzzy logic via a

Matlab simulation program generates promising results (Yu and Lin, 2015; Shahid et al. 2016). Therefore, the Matlab program is employed for the simulation of the optimised smart indoor environment in chapter five of this study. Moreover, indoor environment scenario-based mathematical modelling is established. 0.3 m is the wall thickness, 4 m is the height, 3.64 m is the width, and 3.64 m is the overall room length. The dimensions of the room are standard dimensions of a medium-sized room (Housing Standards, 2013). The material proposed is sustainable brick harmonising the three bottom-line principles namely, environment, social, and economic influences to meet the goals of today while considering future effects. In essence, the scenario modelling of indoor temperature and IAQ (CO_2) is revealed in the subsequent section of this study.

4.4.1 Scenario Modelling of Indoor Temperature

The temperature of the indoors is influenced via the indoor environment air temperature, loss of heat from the wall, room volume and heater. Therefore, the temperature of the indoor environment can be stated in view of the principle of conservation of energy as follows:

$$\rho_a . C_\rho . V_i . \frac{dT_i}{d\tau} = C - U_w . A_w . (T_i - T_o) \qquad (4.19)$$

Where the time is $\tau(s)$, the temperature of the indoor is T_i(℃), the total wall heat transfer coefficient is $U_w(W/m^2.℃)$, the wall area is $A_w(m^2)$, the temperature of the outdoor is T_o(℃), heater work rate is $U_h(W)$, room volume is $V_i(m^3)$, air heat capacity is $C_p(j/kg.℃)$ and air density is $\rho_a(kg/m^3)$. Accordingly, U_w can subsequently be specified in equation 4,20 as (Heat transfer coefficient, 2019):

$$U_w = \frac{1}{\frac{1}{h_A} + \frac{d_w}{K_b} + \frac{1}{h_B}} \qquad (4.20)$$

The wall thickness is $d_w(m)$ and brick work thermal conductivity is $K_b(W/m\,.℃)$, h_A and $h_B(W/m^3\,.℃)$ is the specific convection fluids transfer of heat coefficients on the wall of each side. Given this scenario, this study considers that h_A=h_B=h_{air} while h_{air} is the air convection transfer of heat coefficients.

Reflecting on equation 4.20, it can be conveyed into:

$$U_w = \frac{1}{\frac{2}{h_{air}} + \frac{d_w}{K_b}} \tag{4.21}$$

By utilising the Laplace transform, equation 4.19 can be expressed as:

$$T_i(s).s = \frac{1}{\rho_a.V_i.C_p}.Q_h(s) - \frac{U_w.A_w}{\rho_a.V_i.C_p}.(T_i(s) - T_o(s)) \tag{4.22}$$

Subsequently, the equation 4.22 can be designated as follows:

$$T_i(s).s + \frac{U_w.A_w}{\rho_a.V_i.C_p}.T_i(s) = \frac{1}{\rho_a.V_i.C_p}.Q_h(s) + T_o(s) \tag{4.23}$$

$$\left(s + \frac{U_w.A_w}{\rho_a.V_i.C_p}\right).T_i(s) = \frac{1}{\rho_a.V_i.C_p}.Q_h(s) + \frac{U_w.A_w}{\rho_a.V_i.C_p}.T_o(s) \tag{4.24}$$

Multiplying the whole equation by $\frac{\rho_a.V_i.C_p}{U_w.A_w}$, it can be expressed as:

$$\left(\frac{\rho_a.V_i.C_p}{U_w.A_w}s + 1\right).T_i(s) = \frac{1}{U_w.A_w}.Q_h(s) + T_o(s) \tag{4.25}$$

Suppose that $\frac{\rho_a.V_i.C_p}{U_w.A_w} = T_{it}$, $\frac{1}{U_w.A_w} = K_{it}$, and $T_o(s) = 0$. Equation 4.24 can be expressed as:

$$(T_{it}s + 1).T_i(s) = K_{it}.Q_h(s) \tag{4.26}$$

By rearranging equation 4.26, the indoor temperature transfer function can be expressed follows:

$$\frac{T_i(s)}{Q_h(s)} = \frac{K_{it}}{T_{it}.s + 1} \tag{4.27}$$

For constant of the time is $T_{it} = \frac{\rho_a.V_i.C_p}{U_w.A_w}$ and the function of transfer gain is $K_{it} = \frac{1}{U_w.A_w}$.

ASHRAE Standard 55-2017 stipulated that indoor temperature can range between approximately 18 – 25℃ depending on several factors such as the season of the year, clothing, level of activity, etc. However, a temperature of around 20℃ is further recommended for standard room size to enable proper functioning of indoor inhabitants. Therefore, the anticipated indoor temperature is assumed to be 20℃. Subsequently, the flow rate volume $f = 0.01m^3/s$ is taken as a constant while $d_w = 0.3m$ is taken as a constant standard depth of the wall. The area of the wall is represented as A_w and is calculated as $A_w = length * width = 3.64 * 3.64 = 13.2496m^2$ and the volume of the room is $V_i = area * height = 13.2496 * 4 = 52.9984\, m^3$. Therefore, scrutinising the table of coefficients via Tools and Basic Information for Design, Engineering and Construction of Technical Applications (2018), this study can obtain: $H = 2538kJ/\, kg$, $h_{air} = 10W/m^2\, .℃$, $K_b = 0.6W/m\, .℃$, $C_p = 1005J/\, kg\, .℃$ and $\rho_a = 1.2kg/m^3$.

Consequently, U_w, T_{it} and K_{it} can be expressed as follows:

$$U_w = \frac{1}{\frac{2}{h_{air}} + \frac{d_w}{K_b}} = 1.43 \tag{4.28}$$

$$T_{it} = \frac{\rho_a\, .\, V_i\, .\, C_p}{U_w\, .\, A_w} = 3373.42 \tag{4.29}$$

$$K_{it} = \frac{1}{U_w\, .\, A_w} = 0.0527 \tag{4.30}$$

By putting the values of constants in the transfer function, the indoor temperature environment transfer function can be conveyed as:

$$\frac{T_i(s)}{Q_h(s)} = \frac{0.0527}{3373.42.\, s + 1} \tag{4.31}$$

4.4.2 Scenario Modelling of Indoor Air Quality (CO_2)

There are diverse kinds of indoor contamination within the indoor environment, and it is unimaginable to expect to control and monitor the entire indoor pollutants. Hence, one predominant contaminant, which necessitates the utmost measure of natural air to weaken such pollutant to an adequate level is chosen in this examination as the control signal for the control methodology. The indicator analysed is indoor CO_2. By way of controlling indoor CO_2 to the ideal levels, the greater part of the other indoor air contaminations may be kept up at adequate levels. The concentration of the indoor CO_2 can be specified as (Lazovic et al. 2015):

$$V_i \frac{dC_{ico_2}}{d\tau} = E_{co_2} - \lambda . V_i . C_{ico_2} - f . \left(C_{ico_2} - C_{oco_2}\right) \tag{4.32}$$

Where, $C_{ico_2}(ppm)$ is the indoor CO_2 concentration, $E_{co_2}(ppm/s)$ is the average CO_2 emanation rate of each person in the indoor environment, $\tau(s)$ is the time, $\lambda(s^{-1})$ is the CO_2 decay constant, $V_i(m^3)$ is the volume of the room, $f(m^3/s)$ is the volume flow rate of the supplied air, $C_{oco_2}(ppm)$ is the outdoor CO_2 concentration.

Taking Laplace transform of the equation 4.32, it can be expressed as:

$$V_i\ s . C_{ico_2} = E_{co_2} - \lambda . V_i . C_{ico_2} - f . C_{ico_2} + f . C_{oco_2} \tag{4.33}$$

Rearranging the above equation, it can be expressed as:

$$V_i\ s . C_{ico_2} + \lambda . V_i . C_{ico_2} + f . C_{ico_2} = E_{co_2} + f . C_{oco_2} \tag{4.34}$$

Taking C_{ico_2} common from the left side and assuming $f . C_{oco_2} = 0$, the transfer function of the indoor CO_2 model can be expressed as:

$$\frac{C_{ico_2}}{E_{co_2}} = \frac{1/\lambda V_i + f}{V_i/\lambda V_i + f\ . s + 1} \tag{4.35}$$

Putting $T_{ico_2} = \frac{V_i}{\lambda . V_i + f}$ which is the system time constant, it can be expressed as:

$$\frac{C_{ico_2}}{E_{co_2}} = \frac{T_{ico_2}/V_i}{T_{ico_2}\ . s + 1} \tag{4.36}$$

By converting the s-domain transfer function to the z-domain and rearranging the transfer function, it can be expressed by dividing the denominator and nominator as follows:

$$\frac{C_{ico_2}}{E_{co_2}} = \frac{1/V_i}{s + 1/T_{ico_2}} \tag{4.37}$$

Since z-transform is as follows:

$$1/s + a = \frac{z}{z - \exp(-at)} \tag{4.38}$$

Hence, the transfer function becomes:

$$\frac{C_{ico_2}}{E_{co_2}}(z) = \frac{(1/V_i)z}{z - \exp(-1/T_{ico_2})} \tag{4.39}$$

4.4.3 The Indoor Temperature and CO_2 Transfer Matrix

The internal CO_2 is reduced using the ventilator. The ventilator is opened or closed based on the control system to reduce the level of CO_2 inside the room. The indoor temperature and level of internal CO_2 are interrelated. So, it is important to study the two variables together and establish a relationship between them using the transfer function. In this study, the variables that are to be controlled are temperature and CO_2 level and these are the outputs of the system. Hence, the system output matrix is $Y = [T_i \quad C_{ico_2}]$, where T_i is the indoor temperature and C_{ico_2} is the indoor CO_2. The heater working power and ventilator working power are controller outputs since these are the parameters supplied by the controller to control the system outputs. Hence, the input matrix is $X = [Q_h \ Q_v]$, where Q_h is the heater working power (indoor temperature output controller), and Q_v is the ventilator working power (indoor CO_2 output controller). The interacting loops are shown below:

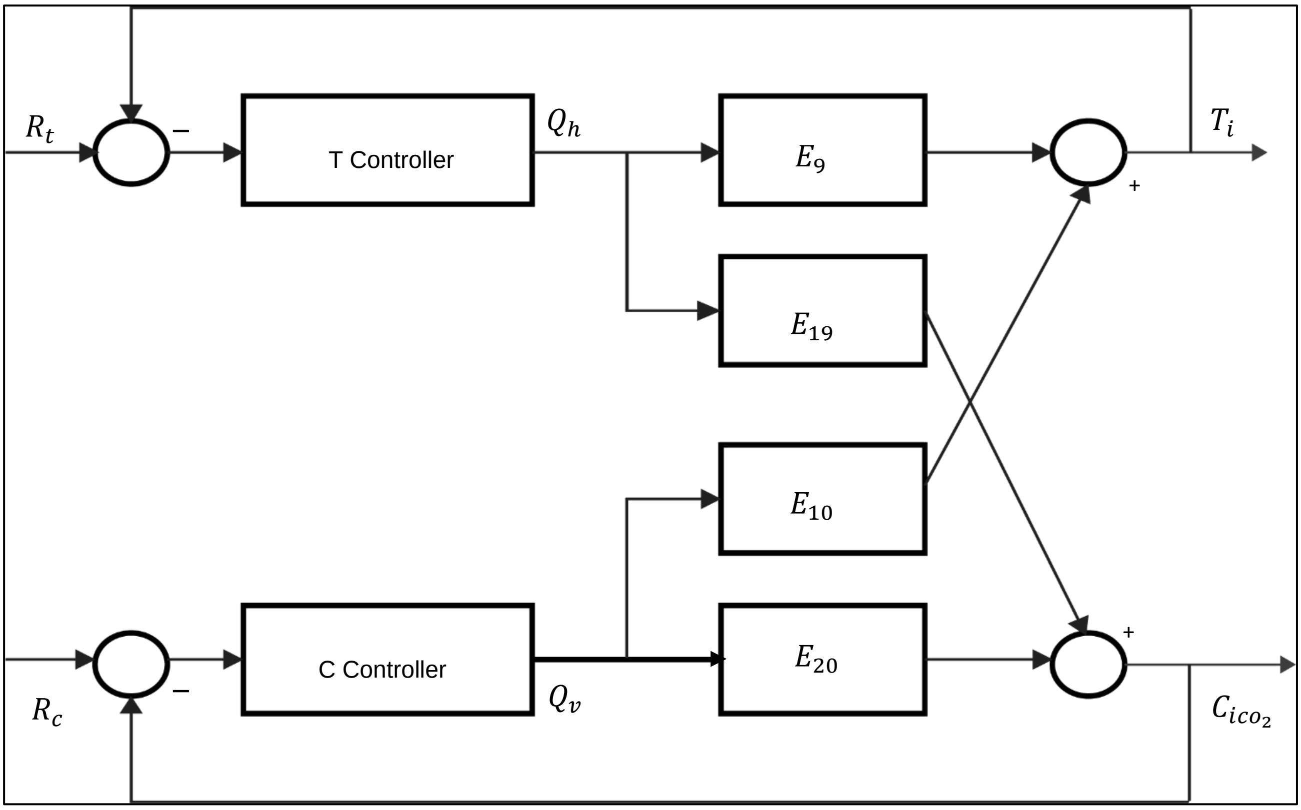

Figure 4.10: Interconnecting loops of indoor temperature and CO_2.

The transfer matrix in the connection between Y and X is expressed as:

$$\begin{bmatrix} T_{ic} \\ C_l \end{bmatrix} = \begin{bmatrix} E_9 & E_{10} \\ E_{19} & E_{20} \end{bmatrix} \begin{bmatrix} Q_h \\ Q_v \end{bmatrix} \tag{4.40}$$

Where R_t is the reference of temperature and R_c is the reference of CO_2 in the room. T_{ic} and C_l are the control variables. T_{ic} is the temperature of the room to be controlled and C_l is the level of CO_2. Also, E_9, E_{10}, E_{19} and E_{20} are transfer function matrix. Since f is a constant value, the CO_2 level is not influenced by the heater's working power but is only influenced by the ventilator's working power. This implies that the indoor CO_2 level is not influenced by the heater's working power. Therefore, $E_{19} = 0$. Equation 4.40 can be expressed as:

$$\begin{bmatrix} T_{ic} \\ C_l \end{bmatrix} = \begin{bmatrix} E_9 & E_{10} \\ 0 & E_{20} \end{bmatrix} \begin{bmatrix} Q_h \\ Q_v \end{bmatrix} \tag{4.41}$$

4.4.4 Approach for Decoupling Indoor Temperature and CO_2.

The temperature and CO_2 are controlled using the heater and ventilator, respectively. As soon as the indoor value of these parameters is changed from the set point, the controller changes the working powers of these systems to reach the reference point.

Indoor temperature and CO_2 are complex systems. The system is associated together as demonstrated in Figure 4.10. It can be observed that once the indoor CO_2 changes, there is a change in the indoor temperature as well. Therefore, the single loop control approach for indoor temperature and CO_2 control cannot meet the requirement of the control system. This will produce inadequate control performance and it is essential to design a decoupling approach to detach the connection between indoor temperature and CO_2. After the indoor temperature and CO_2 are autonomous from one another, the single loop controllers can be employed for controlling the indoor temperature and CO_2. Through this appropriate control technique, an acceptable control performance can be achieved. Nevertheless, the decoupling approach is discussed further in this section.

As shown in Figure 4.11, the variables of a regular two-input two-output system affect each other. The system inputs are R_1 and R_2. The controllers' outputs are X_1 and X_2. The system outputs are Y_1 and Y_2. Also, $X = [Q_h \quad Q_v]$ is the input matrix. where Q_h is the heater working power (indoor temperature controller output) and Q_v is the ventilator working power (indoor CO_2 controller output). Furthermore, $Y = [T_i \quad C_{ico_2}]$, where T_i is the indoor temperature and C_{ico_2} is the indoor CO_2.

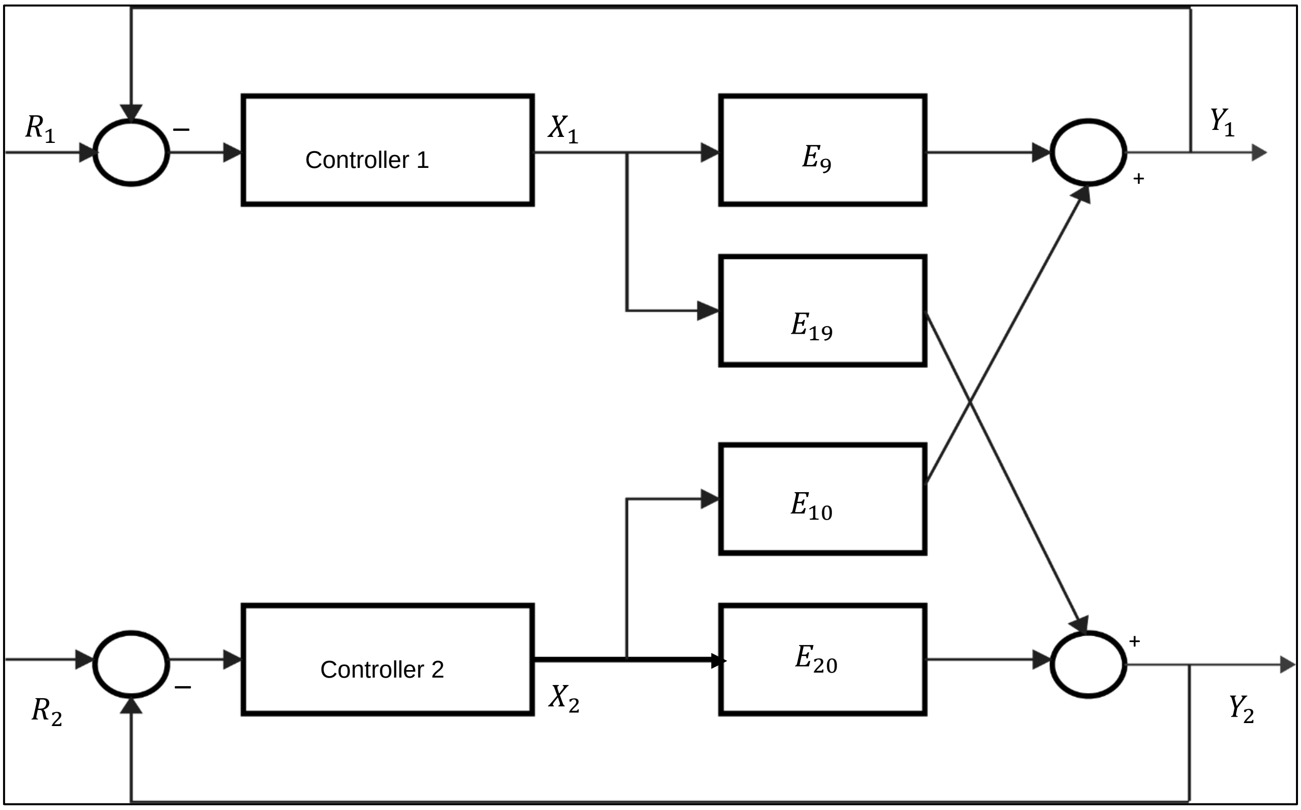

Figure 4.11: Interconnecting loops

For the system output and controller output, the transfer function between them is offered as:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} E_9 & E_{10} \\ E_{19} & E_{20} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \tag{4.42}$$

As revealed in Figure 4.12, B_9, B_{10}, B_{19} and B_{20} decoupling elements can be added between the designed controller and the control object. Therefore, the transfer matrix is expressed as:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} E_9 & E_{10} \\ E_{19} & E_{20} \end{bmatrix} \begin{bmatrix} B_9 & B_{10} \\ B_{19} & B_{20} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \tag{4.43}$$

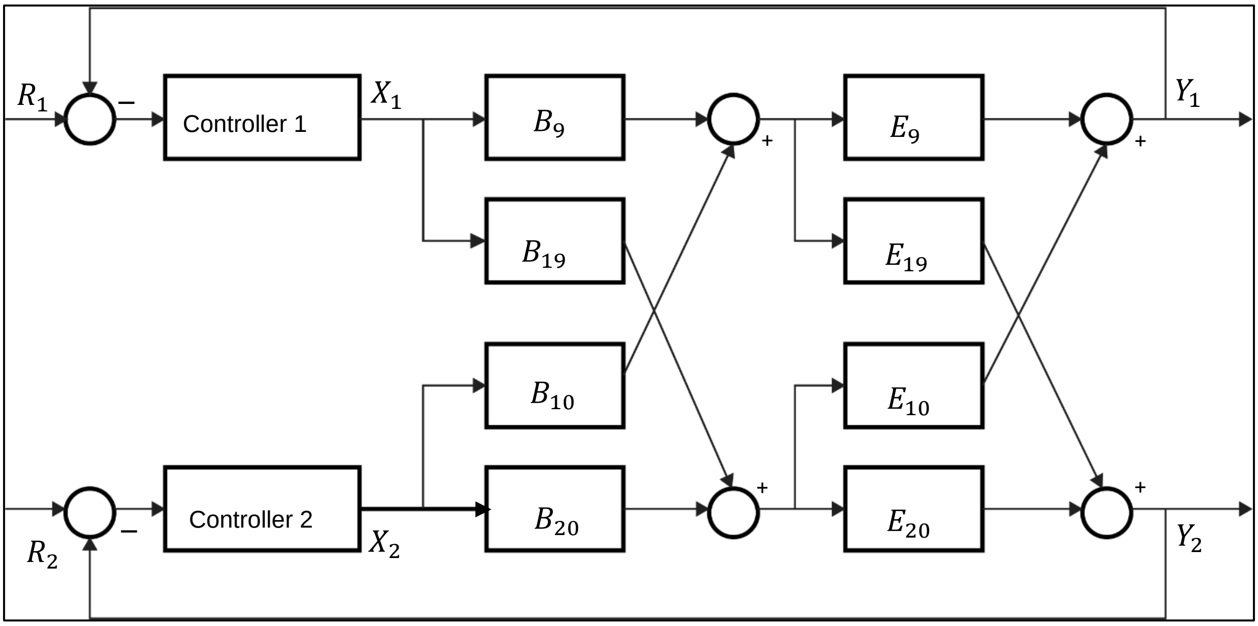

Figure 4.12: Interconnecting loops after adding decoupling elements.

If the following conditions are met for the decoupling matrix:

$$\begin{bmatrix} E_9 & E_{10} \\ E_{19} & E_{20} \end{bmatrix}^{-} = \begin{bmatrix} B_9 & B_{10} \\ B_{19} & B_{20} \end{bmatrix} \tag{4.44}$$

The transfer matrix becomes:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} E_9 & 0 \\ 0 & E_{20} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \tag{4.45}$$

As presented in Figure 4.13, the two single-input single-output systems can be equal to two-input two-output systems. Therefore, the system is independent of each other and the connection between the two variables is detached. For each single-input single-output system, one single control loop can be applied.

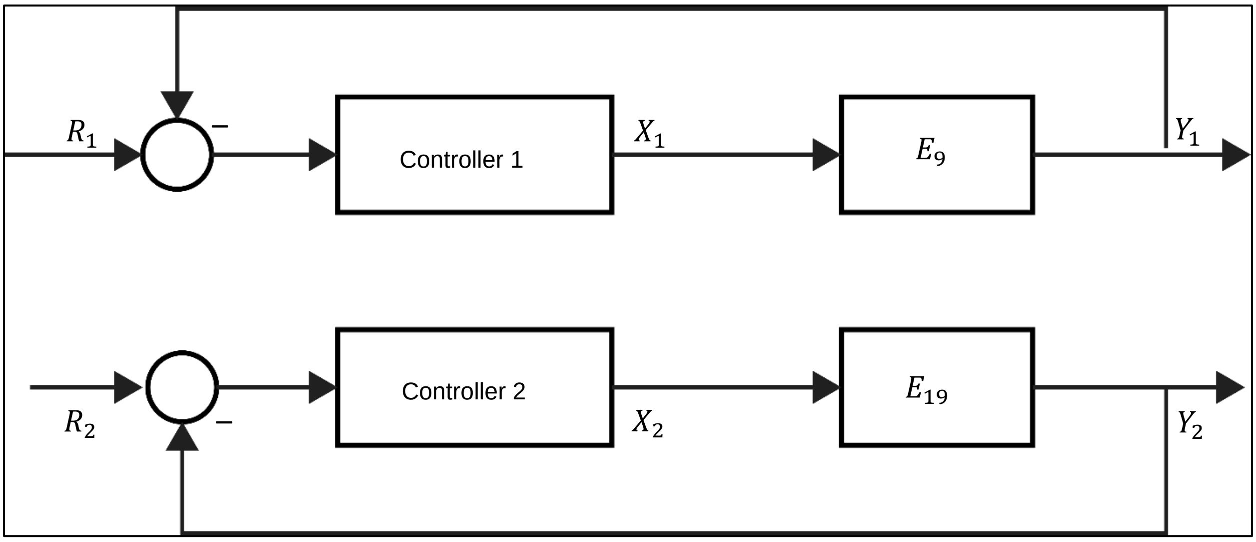

Figure 4.13: Two-input two-output equivalent system

In equation 4.43, the indoor temperature and CO_2 model are offered. It can be noticed that $E_{19} = 0$. Figure 4.14 presents the indoor temperature and indoor CO_2 model flow chat. A temperature control loop and a CO_2 control loop (two control loops model). The indoor CO_2 is only influenced by the ventilator's working power. Nevertheless, the indoor temperature is not only influenced by the working power of the heater but likewise influenced via the working power of the ventilator. This implies that the control approach having single-input single-output cannot control indoor air temperature appropriately if the indoor temperature is influenced by other variables other than the working power of the heater. The goal is to guarantee that indoor temperature only transforms based on the working power of the heater. To make the indoor temperature and CO_2 to be autonomous from one another; it is key to design a decoupling approach to eliminate the influence of E_{19}. Therefore, a decoupling control element in the following equation is designed to achieve the goal.

$$B_{10} = E_{10}/ E_9 \tag{4.46}$$

As indicated in Figure 4.14, the decoupling control element is employed in the system of indoor temperature and CO_2. Between controller 2 and the control objects, a decoupling element is included. This creates a relationship between the two loops of the system.

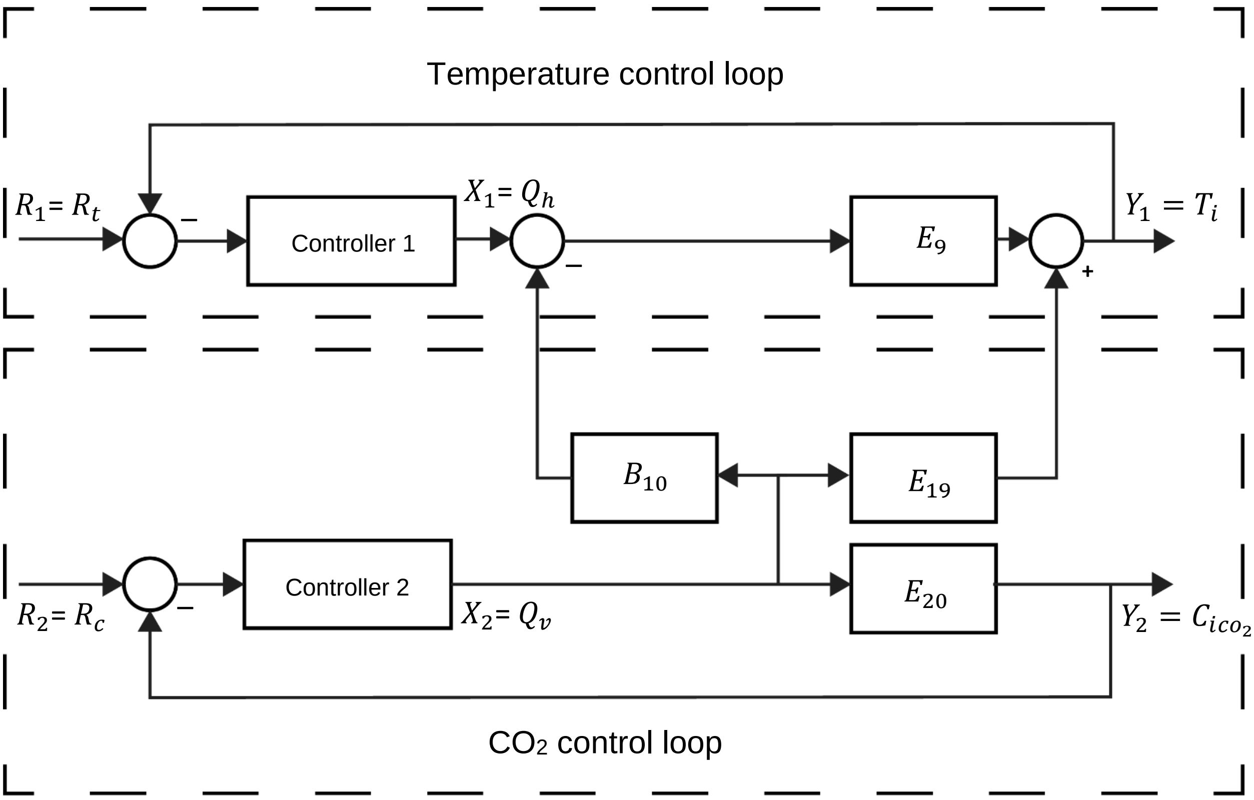

Figure 4.14: System after adding decoupling element

By applying the equation below, the output T_i can be determined. This is based on the indoor temperature and CO_2 system structure offered in Figure 4.14 with a decoupling control approach.

$$T_i = E_9.(Q_h - B_{10}.Q_v) + E_{10}.Q_v = E_9.Q_h \tag{4.47}$$

By applying the indoor temperature transfer function, it is expressed as: $E_9 = \frac{K_{it}}{T_{it}.s+1}$.

The C_{ico_2} output can be calculated as:

$$C_{ico_2} = E_{20}.Q_v \tag{4.48}$$

By applying the indoor CO_2 transfer function, it can be expressed as: $E_{20} = \frac{T_{ico_2}/V_i}{T_{ico_2}.s+1}$.

Therefore, the final transfer matrix becomes:

$$\begin{bmatrix} T_{ic} \\ C_l \end{bmatrix} = \begin{bmatrix} \frac{K_{it}}{T_{it}.s+1} & 0 \\ 0 & \frac{T_{ico_2}/V_i}{T_{ico_2}.s+1} \end{bmatrix} \begin{bmatrix} Q_h \\ Q_v \end{bmatrix} \tag{4.49}$$

The final transfer matrix shows that the system output, the indoor temperature is only influenced via one variable, the working power of the heater. The other system output, indoor CO_2 is only influenced by one variable, the working power of the ventilator. Therefore, this system can be equal to one single-input single-output indoor temperature control loop and one single-input single-output indoor CO_2 control loop. By applying two single loop controllers, the indoor temperature and indoor CO_2 can be possibly controlled.

4.5 Scenario-Based Fuzzy PID Controller

The PID controller which is FLC-dependent is projected for the overall control of the indoor environment quality for the sustainable solar-based air-conditioning in this study. Fuzzy PID controllers can be inspected rather than direct PID controllers in the entire applications of either modern or classical system control. The scheme converts the error amongst the reference and controlled or measured variable into an expected command that is likewise connected to the process actuator. In a reasonable plan, it is imperative to have data about their identical transfer of output-input qualities.

Therefore, this segment presents the guideline and structure of the projected fuzzy PID scheme and subsequently, the processes of control and design controller are typically depicted in detail. The fuzzy PID controller is essentially planned for the temperature and IAQ in this investigation. Thus, the temperature will be scrutinised as the signal control in-order to fundamentally depict the controller in this investigation.

4.5.1 Scenario-Based Structure of Fuzzy PID Controller

The fuzzy PID controller which is self-tuning fundamentally comprises two major divisions:

- FLC as revealed in Figure 4.15 and,

- PID controller

The controller of fuzzy logic is scrutinised for regulating the PID parameters on-line which are the k_p, k_i and k_d through the rules of FLC for improved control performance of the PID in diverse circumstances. Also, the anticipated controller of fuzzy PID is a design-based control auto-adaptive via the means of utilising the controller of incremental fuzzy logic. The controller of the PID is scrutinised for control of the indoor environment.

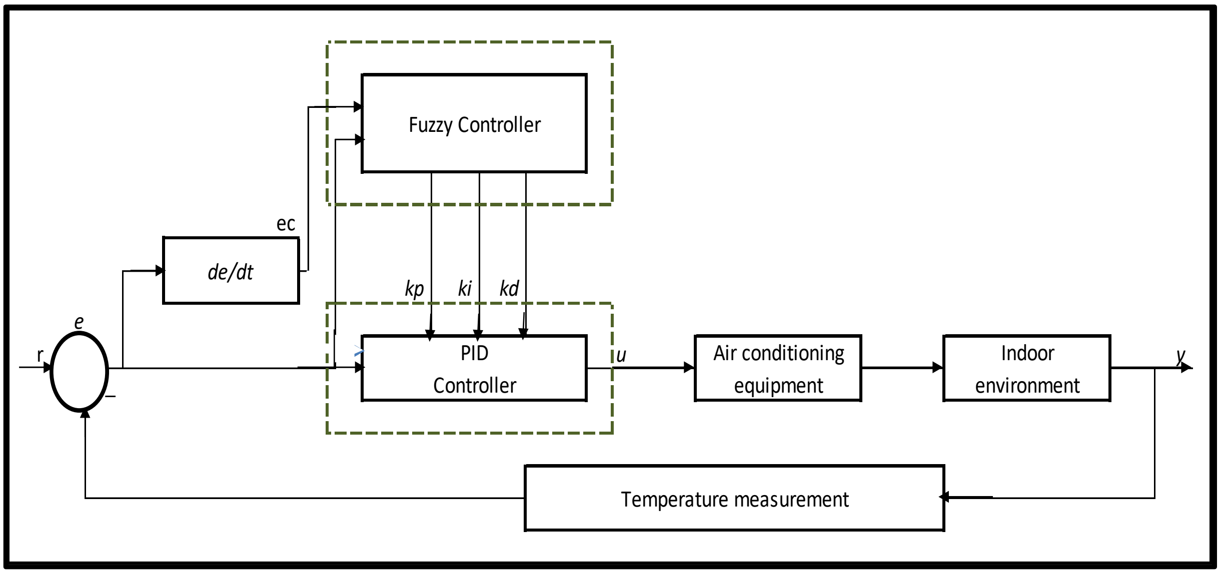

Figure 4.15: Fuzzy-PID controller structure.

Subsequently, the projected fuzzy controller of PID which is self-tuning seeks to advance the control execution generated through the controller of PID. For it retains the basic controller of PID structure and may not compulsorily alter portions of the hardware of the primary control system for execution. In any case, the restraint for conventional algorithm control is substantially unfolded.

4.5.2 PID Control Algorithm

The indoor environment anticipated in this study is controlled through the controller of PID that utilises *e* – error of the system and *ec* – error changing rate, which is specified as the inputs in equation 4.50 and 4.51, respectively. Besides, the error which is specified as *e(k)* amongst the desired output and actual output may be conveyed as:

$$e(k) = r(k) - y(k) \tag{4.50}$$

For $ec(k)$ which is the rate change of $e(k)$ can be specified as:

$$ec(k) = e(k) - e(k-1) \tag{4.51}$$

The PID output is the heater work rate, and the output of the system is the temperature of the indoor air. The algorithm of PID can be given as:

$$u(k) = u(k-1) + k_p\big(e(k) - e(k-1)\big) + k_i e(k) + k_d\big(e(k) - 2e(k-1) + e(k-2)\big) \tag{4.52}$$

The execution of the PID is primarily subject to the collection of k_p, k_i and k_d, which are the parameters of the PID. The PID fuzzy block strategy control is strategised in-order to essentially auto-tune the parameters' values.

4.5.3 The Design of Fuzzy Block

According to Esfandyari et al. (2013), the controller of fuzzy logic function is to fundamentally tune k_p, k_i and k_d, which are the controller of PID parameters online through the rules of FLC, grounded upon *e* and *ec* time-varying as revealed in Figure 4.16.

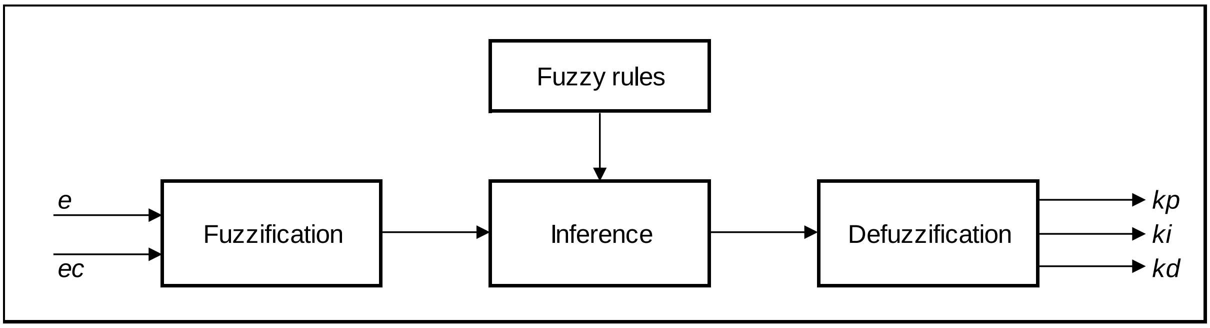

Figure 4.16: The fuzzy block structural outline.

The parameters of PID fuzzy self-tuning are to mainly discover the association of fuzzy amongst three PID parameters and likewise, the *e* and *ec.* Grounded upon output *y* and input *r,* the system output *y* is measured and subsequently, *e* and *ec* are calculated. For the objects that are controlled to accomplish improved dynamic stable execution; the controller of fuzzy logic fundamentally tunes the three parameters (k_p, k_i and k_d) through the rules of fuzzy control online. Therefore, it is required to know individual PID parameters' functions. Subsequently, it is attainable to regulate the connection of *e* and *ec,* which are the fuzzy inputs and k_p, k_i and k_d, which are the fuzzy outputs and lastly, to essentially construct the rule of the fuzzy logic (Wang et al. 1995). In this study, individual PID parameters functions are reflected upon while considering the control execution and the connection to the error of the system is enumerated in Table 4.6.

Table 4.6: The k_p, k_i and k_d tuning effects.

Closed-loop response	Rise time	Settling time	Overshoot	Steady-state error	Stability
Increasing k_p	Decrease	Increase	Small increase	Decrease	Degrade
Increasing k_i	Small decrease	Increase	Increase	Large decrease	Degrade
Increasing k_d	Small decrease	Decrease	Decrease	Minor change	Improve

Table 4.7: k_p fuzzy base rule.

Δk_p / *ec* / *e*	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS

ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Accordingly, the rule of the fuzzy base is defined upon the PID parameters' dialogue as offered in Table 4.6. The rule of the fuzzy base comprises three matrixes through the specific means by which the parameters k_p, k_i and k_d will transform into parameters Δk_p, Δk_i and Δk_d once *e* and *ec* differ. The rule of the fuzzy base is built through utilising numerous statements of if-then, which are the individual statement of fuzzy concepts that is typically consequent and premise. Also, 25 rules as specified in Table 4.7 – Table 4.9 expresses the base rule aimed at the controller of fuzzy PID. The rule base as established by the variables of the fuzzy is Δk_d, Δk_i, Δk_p, *e* and *ec*, which typically equal [PB (Positive Big), PM (Positive Medium), PS (Positive Small), ZO (Zero), NS (Negative Small), NM (Negative Medium) and NB (Negative Big)].

Table 4.8: k_i fuzzy base rule.

Δk_i *e* \ *ec*	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	ND	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 4.9: k_d fuzzy base rule.

Δk_d \ ec / e	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

For Δk_d, Δk_i, Δk_p, *e* and *ec* membership functions are required to be resolved as revealed in Figure 4.17 – Figure 4.21 when the base rule is established. A curve of membership function expresses by what means the input space of an individual point is plotted to a value of membership (on membership degree) amongst values 0 and 1 (Soyguder, 2009). Therefore, the integrated membership functions that are gauss and triangular are applied for the entire variables. Consequently, physical domains for Δk_d are [-4, -3, -2, -1, 0, 1, 2, 3, 4], for Δk_i are [-0.06, -0.04, -0.02, 0, 0.02, 0.04, 0.06], for Δk_p are [-0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3], and for *e* & *ec* are [-3, -2, -1, 0, 1, 2, 3].

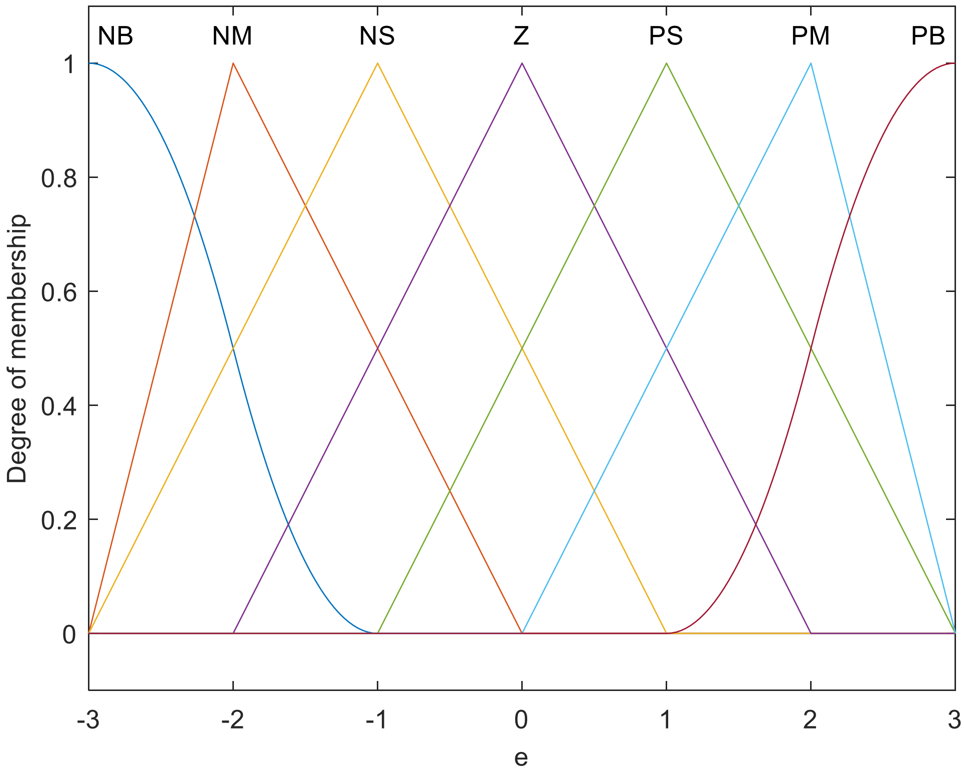

Figure 4.17: The system error membership function.

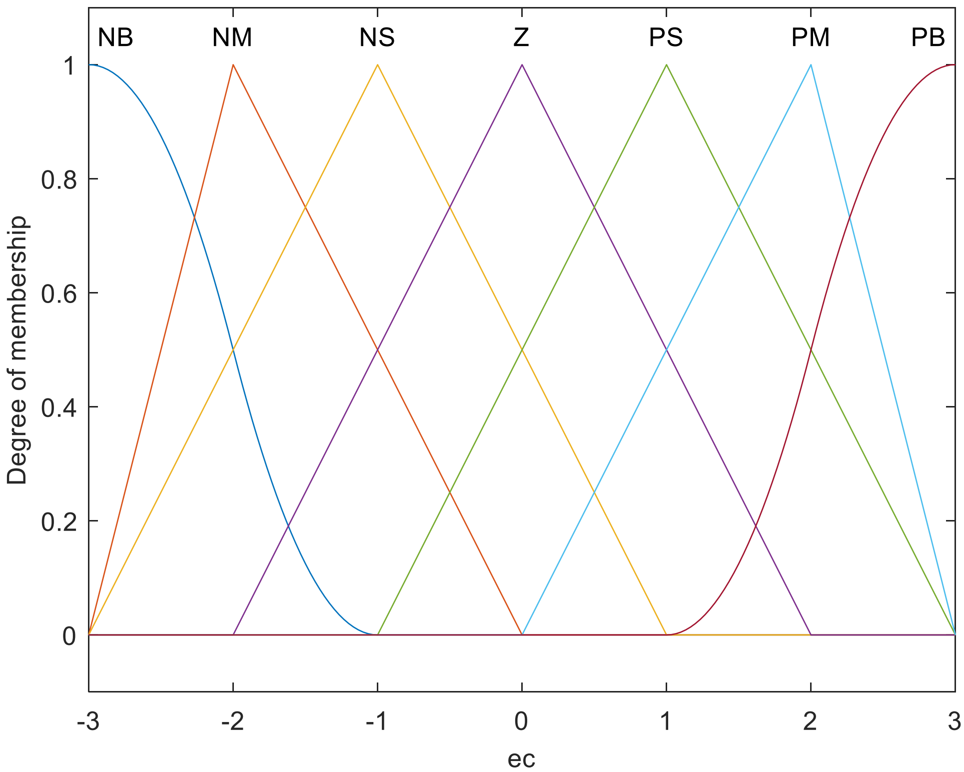

Figure 4.18: The system error changing rate membership function.

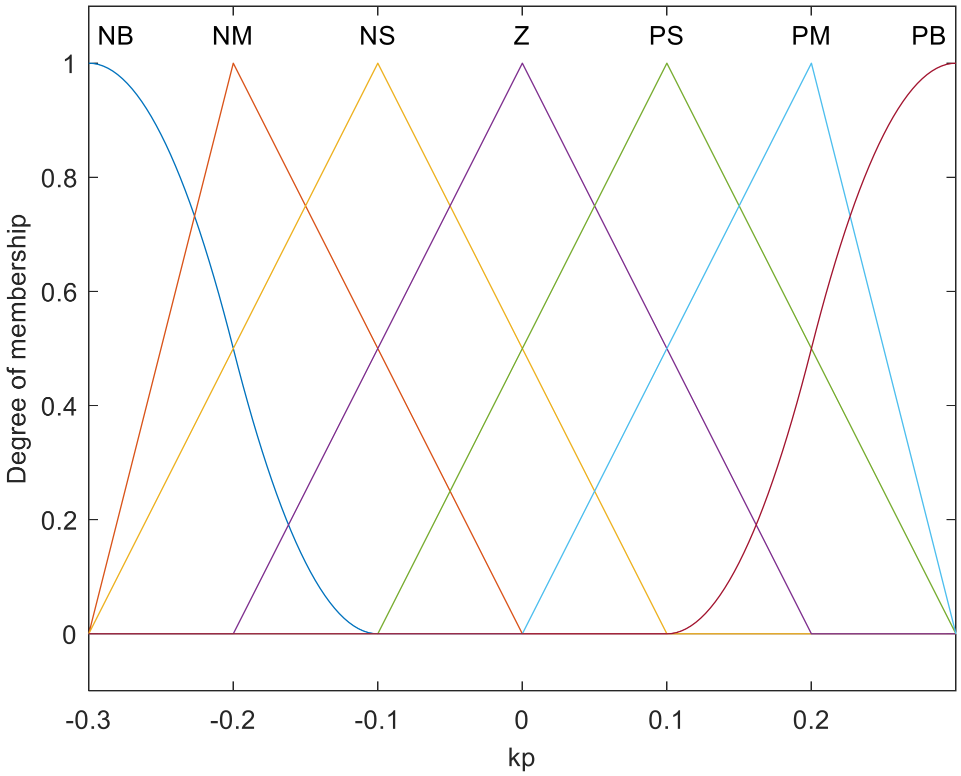

Figure 4.19: The k_p membership function.

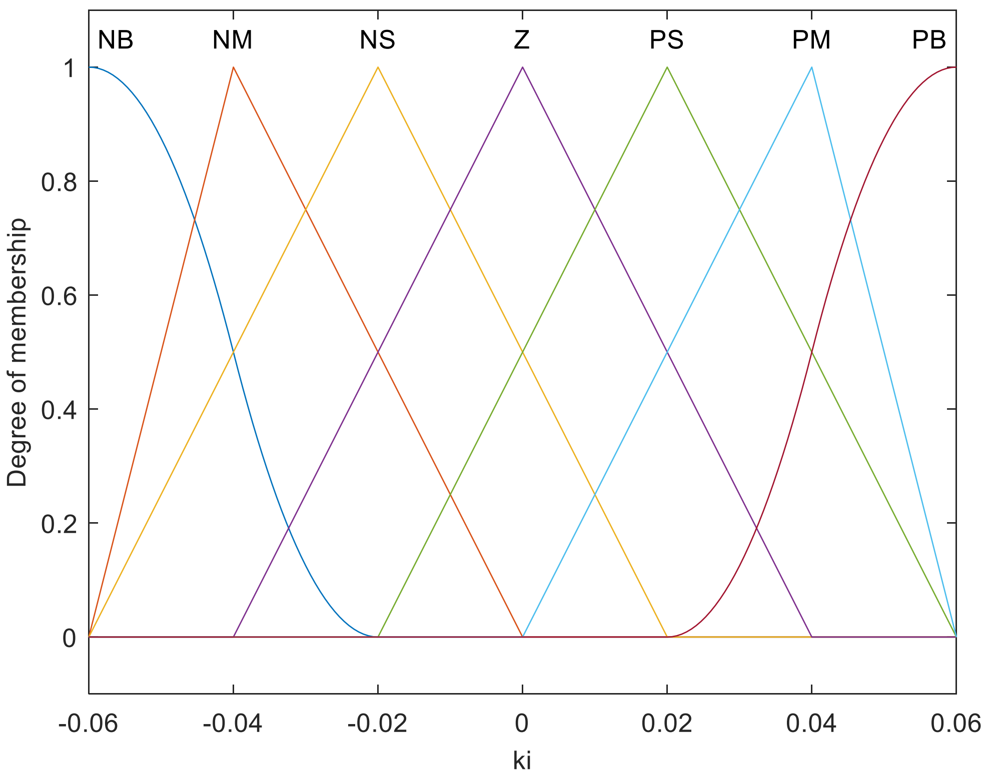

Figure 4.20: The k_i membership function.

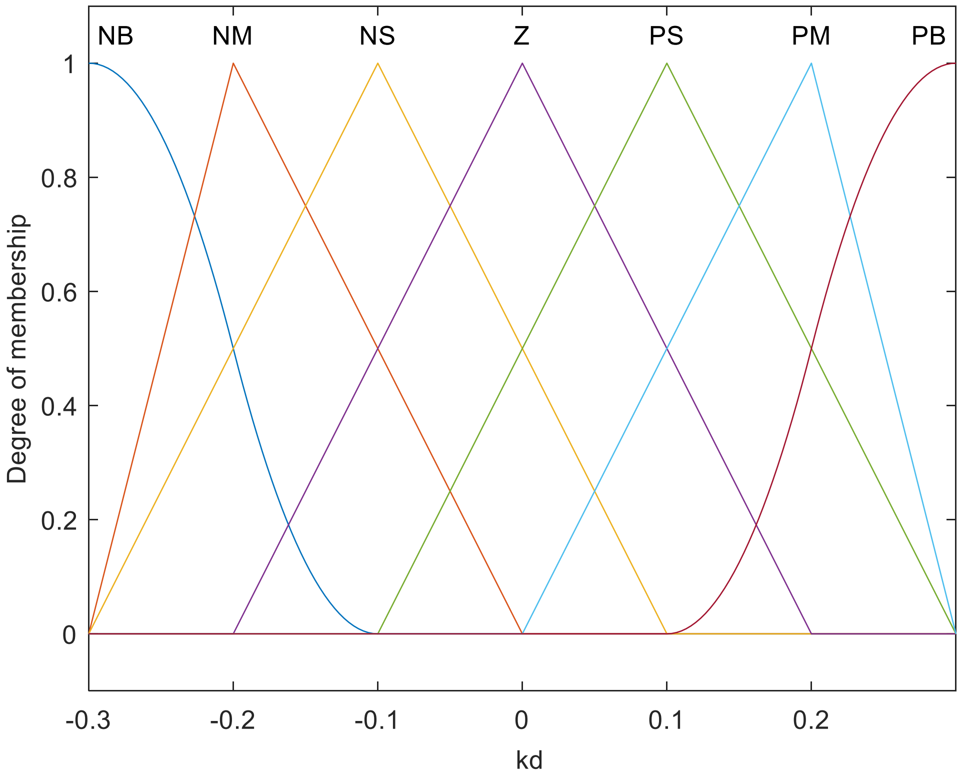

Figure 4.21: The k_d membership function.

Grounded upon the membership function and fuzzy base rule, this study can obtain the values of Δk_p, Δk_i and Δk_d. Through the means of applying the subsequent equations below, the values of k_p, k_i and k_d can be calculated.

$$k_p(k+1) = f_{kp}(e, ec) = k_p^{`}(k) + \Delta k_p(k) \tag{4.53}$$

$$k_i(k+1) = f_{ki}(e, ec) = k_i^{`}(k) + \Delta k_i(k) \tag{4.54}$$

$$k_d(k+1) = f_{kd}(e, ec) = k_d^{`}(k) + \Delta k_d(k) \tag{4.55}$$

Through the means of utilising the controller of fuzzy logic, the anticipated values of k_p, k_i and k_d can be attained and consequently conveyed to the controller of PID to activate the air-conditioning appropriately and acquire the desired indoor environment that is comfortable.

The controller of the fuzzy PID control process is synopsised as revealed in Table 4.10.

Table 4.10: The control process of Fuzzy PID

Fuzzy-PID Control Process	
(i)	At sample step k, assemble control data by employing the measurement apparatus
(ii)	Through employing equations 4.50 and 4.51, analyse the system error and the rate change of system error
(iii)	Employing the membership function for the fuzzification of *e* and *ec*
(iv)	Employing the fuzzy rule to acquire the fuzzy values of Δk_p, Δk_i and Δk_d
(v)	Employing the membership function for defuzzification of Δk_p, Δk_i and Δk_d
(vi)	By employing equations 4.53 – 4.55, analyse k_p, k_i and k_d
(vii)	For the control of indoor temperature, k_p, k_i and k_d are offered to the PID controller.

In the subsequent chapter, the projected fuzzy PID control approach is substantiated through the means of simulation tests by applying the Matlab program.

4.6 Backpropagation Neural Network PID Controller

The concentration of indoor CO_2 analysis and measurement may be beneficial for comprehending ventilation and IAQ efficiency. The IAQ control trouble is the dimension errors and delay of time. Nonetheless, for the goal to attain the system's best performance regarding small overshoot, interference resistance, systemic stability and response speed, a backpropagation NN that is based upon algorithm weight update with PID controller is anticipated.

In this section, the algorithm and structure of the backpropagation NN with the PID controller are presented. The backpropagation NN with PID performance is substantiated through computer simulation by way of applying for the Matlab program as deliberated upon in the subsequent chapter

4.6.1 Backpropagation Neural Network PID Controller Structure

In this study, Figure 4.22 offers the intelligent PID controller structure which is grounded upon the learning algorithm of backpropagation NN. For it comprises two divisions:

- backpropagation NN and,
- typical PID controller

The PID controller is scrutinised to control the entity of the environment IAQ. The performance control is contingent upon the parameters, k_p, k_i and k_d setting of the PID control that can be auto-tuned through backpropagation NN. The backpropagation NN utilises an algorithm of online training, grounded upon the approach of descent gradient to update weights of the network and guarantees that the NN which is designed can calculate the required parameters of PID control for the PID controller. By connecting the intelligent backpropagation NN with the typical PID in this method, the chosen system output can be pursued with a definite constancy.

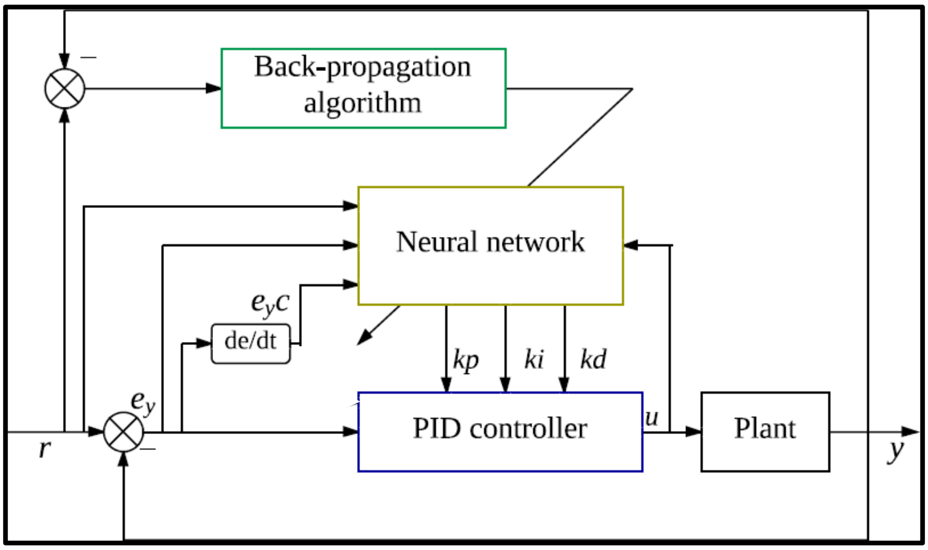

Figure 4.22: Structure of backpropagation NN based on PID control.

4.6.2 Algorithm of PID Control

The gradational digital control algorithm of PID can be conveyed as:

$$u(k) = u(k-1) + k_p\{e_y(k) - e_y(k-1)\} + k_i e_y(k) \\ + k_d\{e_y(k) - 2e_y(k-1) + e_y(k-2)\} \quad (4.56)$$

Thus, k_d is a term of the derivative, k_i is a term of the integral, k_p is a term of the proportion, u is the output of the PID controller and e_y is an error of the system. This can be conveyed in equation 4.57, while r is the actual system output and y is the targeted system output.

$$e_y(k) = r(k) - y(k) \quad (4.57)$$

4.6.3 Algorithm of Backpropagation Neural Network

Therefore, whether the NN possess enough neurons, it can estimate a single hidden layer of whichever incessant function (Ken-Ichi, 1989; Hui et al. 2006). Hence, a single hidden layer of NN is depicted. For the anticipated strategy having four-input-three-output revealed in Figure 4.23 is the backpropagation NN possessing triple layers such as the output layer, input layer and single hidden layer. Nevertheless, the adjustment weights rule of backpropagation and the progressive feed algorithm is deliberated thoroughly in this section.

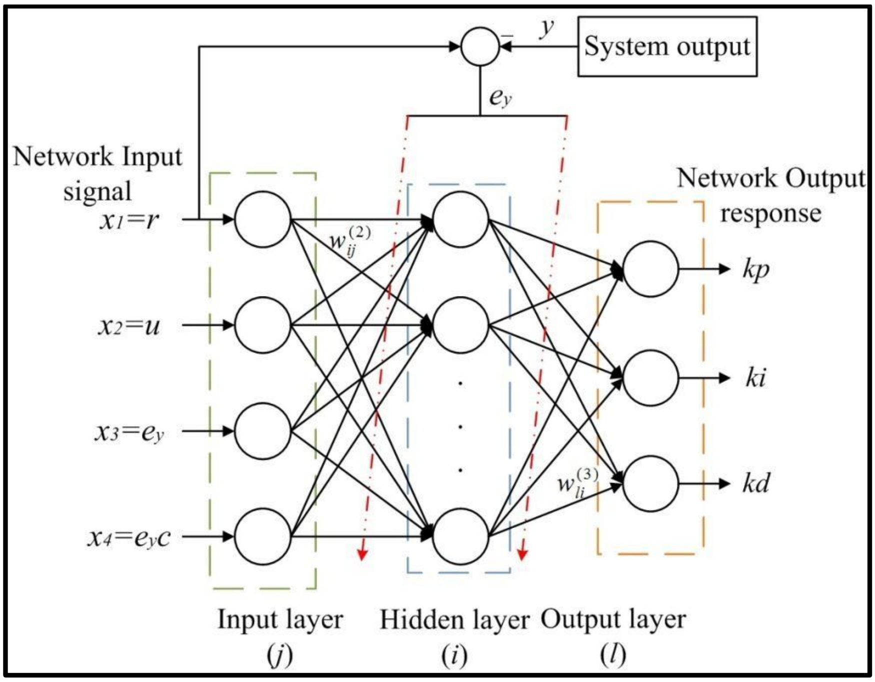

Figure 4.23: Algorithm structure of backpropagation NN.

4.6.3.1 Scenario Control-Based Feed Forward

As shown in both Figure 4.22 and Figure 4.23, the NN that is designed possesses four inputs as conveyed below in equation 4.58:

$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{Bmatrix} = \begin{Bmatrix} r \\ u \\ e_y \\ e_y c \end{Bmatrix} \tag{4.58}$$

Thus, u, e_y and r are explained in equations 4.56 and 4.57, respectively; whereas $e_y c$ is the system error changing rate e_y which is conveyed as:

$$e_y c(k) = e_y(k) - e_y(k-1) \tag{4.59}$$

In the input layer, individually neuron output is conveyed as follows:

$$O_j^{(1)} = x(j) \qquad \{j = 1,2,3,4\} \tag{4.60}$$

The superscript one which is illustrated in equation 4.60 as (^{1}) is specifically positioned for the input layer in the algorithm that is designed. Also, the hidden layer NN of individually neuron input can be calculated grounded upon the input layer output. This is conveyed in equation 4.61 below:

$$in_i^{(2)}(k) = \sum_{j=1}^{4} w_{ij}^{(2)} O_j^{(1)} \qquad \{i = 1,2, \dots, N\} \tag{4.61}$$

The superscript two which is illustrated in equation 4.61 as (^{2}) is subsequently positioned for the hidden layer whereas, the weight linking the neurons hidden layer to the neurons' input layer is $w_{ij}^{(2)}$ and neurons number within hidden layer is N. Therefore, individually neuron output within hidden layer NN can be conveyed as:

$$O_i^{(2)}(k) = f\left(in_i^{(2)}(k)\right) \tag{4.62}$$

In the hidden layer, the function of activation is $f(x)$ and it subsequently offers the association between individually output and input neurons. In any case, the function of the symmetrical sigmoid is utilised consequently as the function of activation and conveyed in equation 4.63 as:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{4.63}$$

When individually neuron output in the hidden layer is designed, individually neuron input within the output layer can be specified in the equation 4.64 as follows:

$$in_l^{(3)}(k) = \sum_{i=1}^{N} w_{li}^{(3)} O_j^{(2)}(k) \qquad \{l = 1,2,3\} \tag{4.64}$$

Thus, the superscript three which is illustrated in equation 4.65 as (^{3}) is positioned for the output layer whereas, the weight linking the neuron's output layer to the neurons' hidden layer is $w_{li}^{(3)}$. The output layer neurons number is three and the outputs of the neurons are the parameters of PID. Individually neuron output within the output layer is specified via the subsequent equations below:

$$O_l^{(3)}(k) = g\left(in_l^{(3)}(k)\right) \tag{4.65}$$

$$O_l^{(3)}(k) = k_p \tag{4.66}$$

$$O_2^{(3)}(k) = k_i \tag{4.67}$$

$$O_3^{(3)}(k) = k_d \tag{4.68}$$

Thus, the function of activation which offers the association between individually neuron output and input within the output layer is $g(x)$. The output layer yields are the k_p, k_i and k_d which are the parameters of PID. Since the values cannot be negative, the function of the sigmoid that is non-negative is scrutinised as the function of activation within the output layer. This is specified as follows in equation 4.69:

$$g(x) = \frac{1}{2}(1 + \tanh(x)) = \frac{e^x}{e^x + e^{-x}} \tag{4.69}$$

Accordingly, the projected NN can automatically tune the parameters of PID, and this can assist engineers through the means of lessening the cost of time for system control process planning. Albeit, in-process control that is model-based, modelling errors occur frequently and intensely enlarge the problem to precisely regulate the procedure. So, an algorithm of online training is utilised to regulate the weights of the network for lessening error e_y of the system within back-propagation NN controller design.

4.6.3.2 Scenario-Based Weight Update

The error output system function in this algorithm is demarcated through the specified equation 4.70 as follows:

$$E_y(k) = \frac{1}{2}(r(k) - y(k))^2 = \frac{1}{2}e_y^2 \tag{4.70}$$

The model of the NN training process should be implemented hitherto it can be set into usage. This process of training is recurrently pending the training data mean-square-error extend to the anticipated lower limit. The process of training in the existing work is grounded upon the back propagation. The back propagation elementary knowledge is to regulate the weights of the neuron by means of utilising the algorithm of gradient descent on the function error in the process of iteration.

Usually, individually weight adjustment as of the hidden layer in the direction of the output layer can be conveyed in equation 4.71 as:

$$\Delta w_{li}^{(3)}(k) = -\eta \frac{\partial E_y(k)}{\partial w_{li}^{(3)}} \tag{4.71}$$

A term of momentum is supplemented to the change of weight in the anticipated algorithm for the reason to evade the local minima, which is typically the recognised issue connected by the algorithm of backpropagation. This buttresses that the weight transforms the process of iteration and is even contingent not precisely upon the existing error; however, upon hitherto transformations. As revealed in Figure 4.24, individually weight adjustment as of the hidden layer, in the direction of the output layer is altered grounded upon the function of the output error system.

$$\Delta w_{li}^{(3)}(k) = -\eta \frac{\partial E_y(k)}{\partial w_{li}^{(3)}} + \alpha \Delta w_{li}^{(3)}(k-1) \tag{4.72}$$

For α is the factor of momentum and η is the rate of learning.

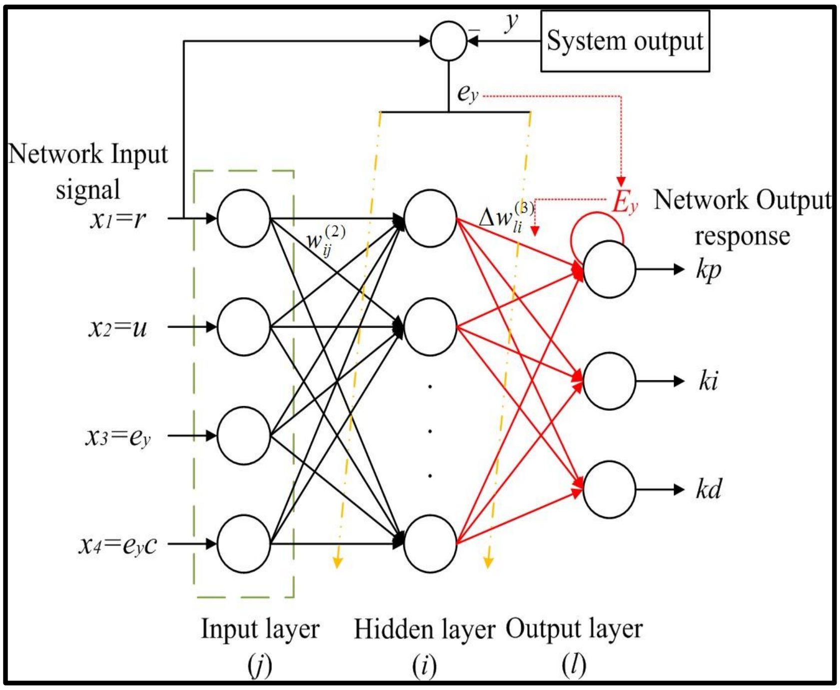

Figure 4.24: The hidden layer to output layer weight adjustment.

Subsequently,

$$\frac{\partial E_y(k)}{\partial w_{li}^{(3)}(k)} = \frac{\partial E_y(k)}{\partial y(k)} \cdot \frac{\partial y(k)}{\partial u(k)} \cdot \frac{\partial u(k)}{\partial O_l^{(3)}(k)} \cdot \frac{O_l^{(3)}(k)}{\partial in_l^{(3)}(k)} \cdot \frac{\partial in_l^{(3)}(k)}{\partial w_{li}^{(3)}(k)} \tag{4.73}$$

$$\frac{\partial in_l^{(3)}(k)}{\partial w_{li}^{(3)}(k)} = O_l^{(2)}(k) \tag{4.74}$$

The subsequent equations are calculated by focussing on equations 4.56, 4.66, 4.67 and 4.68, respectively:

$$\frac{\partial u(k)}{\partial O_l^{(3)}(k)} = e_y(k) - e_y(k-1) \tag{4.75}$$

$$\frac{\partial u(k)}{\partial O_2^{(3)}} = e_y(k) \tag{4.76}$$

$$\frac{\partial u(k)}{\partial O_3^{(3)}} = e_y(k) - 2e_y(k-1) + e_y(k-2) \tag{4.77}$$

In the output layer, the weight update of the learning algorithm can be conveyed as:

$$w_{li}^{(3)}(k+1) = w_{li}^{(3)}(k) + \Delta w_{li}^{(3)}(k) \tag{4.78}$$

$$\Delta w_{li}^{(3)}(k) = \alpha \Delta w_{li}^{(3)}(k-1) + \ \eta \delta_l^{(3)} O_i^{(2)}(k) \tag{4.79}$$

As shown in Figure 4.25, $\delta_l^{(3)}$is the function error of the hidden-layer network, which is required for weights adjustment of the input layer, in the direction of the hidden layer.

Thus, $\delta_l^{(3)}$ is conveyed as:

$$\delta_l^{(3)} = e_y(k) . \frac{\partial y(k)}{\partial u(k)} \cdot \frac{\partial u(k)}{\partial O_l^{(3)}(k)} \cdot g'\left(in_l^{(3)}(k)\right) \tag{4.80}$$

For $g(x)$, which is the first derivative is specified as follows:

$$g'(x) = g(x)\big(1 - g(x)\big) \tag{4.81}$$

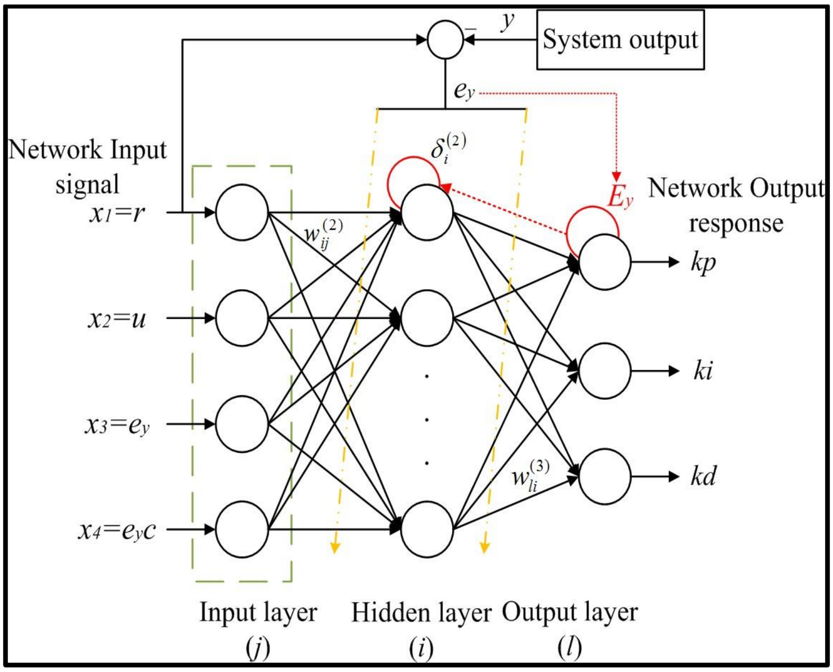

Figure 4.25: The hidden layer network error function.

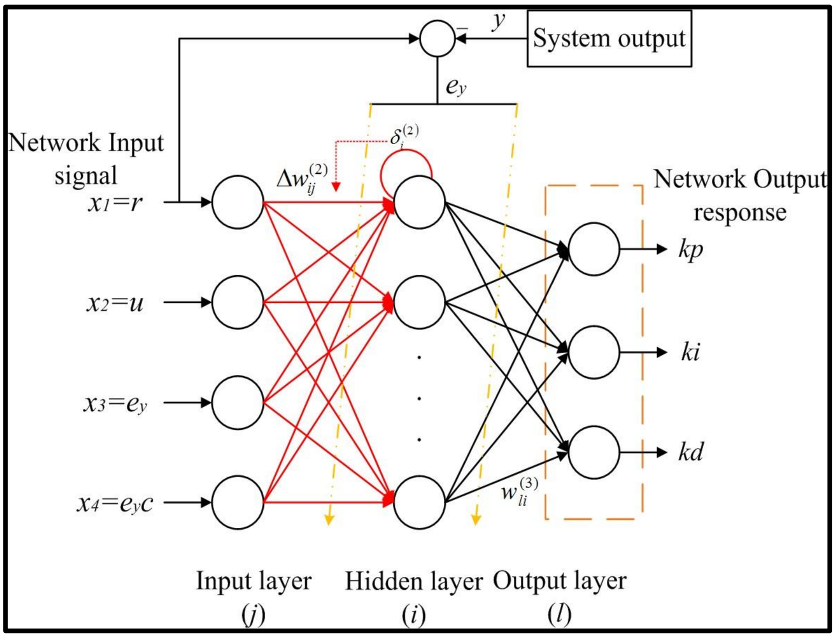

Figure 4.26: The input layer to hidden layer weight adjustment.

By way of utilising similar calculations and the hidden layer weight update – it is typically calculated grounded upon the algorithm of gradient descent and the function of hidden layer error as illustrated in Figure 4.26. As follows, an algorithm of learning can be conveyed as:

$$w_{ij}^{(2)}(k+1) = w_{ij}^{(2)}(k) + \Delta w_{ij}^{(2)}(k) \tag{4.82}$$

$$\Delta w_{ij}^{(2)}(k) = \alpha \Delta w_{ij}^{(2)}(k-1) + \eta \delta_i^{(2)} O_j^{(1)}(k) \tag{4.83}$$

$$\delta_l^{(2)} = f'\left(in_i^{(2)}(k)\right) . \sum_{i=1}^{3} \delta_l^{(3)} w_{li}^{(3)}(k) \tag{4.84}$$

For $f(x)$, which is the first derivative is specified as follows:

$$f'(x) = \frac{\left(1 - f^2(x)\right)}{2} \tag{4.85}$$

Consequently, the NN weights are trained in the control process via the weights of backpropagation rule adjustment for the reason to acquire the optimum k_p, k_i and k_d, which are the parameters of PID for the controller of PID. Thus, a suitable IAQ can be given through the designed system control. The backpropagation NN algorithm control process grounded upon PID can be synopsised in Table 4.11.

Table 4.11: Control process of backpropagation NN-PID.

Backpropagation NN – PID Process	
(i)	Adjust the momentum factor α despite *k*=1, learning rate η and individual weight in the NN $w_{ij}^{(2)}(k)$ and $w_{li}^{(3)}(k)$
(ii)	Assemble data *r*(*k*) and *y*(*k*), and analyse the e_y system error
(iii)	Analyse each neuron's input and output and obtain the k_p, k_i and k_d parameters of PID
(iv)	Analyse the output of the PID controller
(v)	Regulate individual neuron weight in the NN with the learning algorithm of

	backpropagation to apprehend the parameters k_p, k_i and k_d of PID self-adaptive regulation

The control execution of the anticipated backpropagation NN that is based upon the PID control approach for IAQ is substantiated through simulating tests by means of utilising the Matlab program in the subsequent chapter.

4.7 Conclusion

The modelling of photovoltaic solar air-conditioning and the indoor environment has been applied in this chapter. The conceptual modelling is justified in the existing study and the modelling approach employed has proved to be suitable for the scope of this study. The modelling of photovoltaic solar air-conditioning examined can give the anticipated power to an electrically controlled cooling and the components of the system are systematically described. In line with the basis of system modelling, the solar air-conditioning is simulated in the next chapter by using the Polysun program. The modelling offers to provide the energy efficiency and the CO_2 savings which is, in turn, an absolute necessity in each structure to accomplish a decent level of appropriate indoor comfort within the structure, vis-à-vis improving human adaptation in the indoor environment. Also, indoor environment quality has fundamentally influenced inhabitants' wellbeing, individuals' efficiency and comfort feelings. Thus, significant factors, for example, the indoor temperature and IAQ are examined and must be properly controlled for the growing demand expectation for everyday comforts. In any case, significant troubles exist as presented in the table below that cut off the control innovations development for the control of indoor environment quality.

Control Technology Restriction	
(i)	Difficulty to use suitable ideal guides to pursue the best set point(s) and to forecast the response of the system.

(ii)	Multifaceted air-conditioning control is tough to be examined.
(iii)	The delay in time
(iv)	In both IAQ and thermal comfort control, disturbances constantly occur in the process control. For example, individuals entering the room can increase the CO_2 concentration while opening a door or window might create a variation in indoor temperature.
(v)	The system lag-behind response to the change of the indoor environment.
(vi)	One of the main difficulties of IAQ is controlling the signal value of mismeasurement occurrence
(vii)	Since the control signals occasionally rely on one another, it can create a state of unsteady performance control.

Upon the purpose to resolve these difficulties, this chapter designed and consolidated smart/intelligent controllers (fuzzy PID controller and backpropagation NN-PID) for controlling indoor temperature and IAQ (CO_2), respectively. The controller designs which incorporate the algorithms and structures control are thoroughly examined. For it synopsises the individual controller design and hypothetically examines their possible control benefits.

In the literature, the indoor temperature control problems are described, and a fuzzy PID controller is designed in this chapter to resolve the difficulties, vis-à-vis to attain the purpose of sustaining the anticipated indoor environment quality. This controller structure comprises two key portions which are the PID control for indoor air temperature control and FLC for adjusting the PID controller parameters as stated by the existing conditions of the indoor environment. The indoor environmental quality can be well-controlled grounded upon the theoretical dialogue of the algorithm of the projected fuzzy PID controller as-long-as:

- selection of better parameters of PID can guarantee the required output of the system;
- ensuring the controller of the PID is appropriate for the control object;
- the control of fuzzy logic for optimal parameters of PID regulation to guarantee compliance to diverse conditions.

Subsequently, the indoor environment control has several problems as described in the literature and backpropagation NN based upon PID is designed in this study to resolve the problems. The IAQ control difficulties can be finalised as follows:

- occurrence of mismeasurement;
- delay of time;
- lag-behind system response: the change of indoor environment.

To attain and sustain the appropriate level of IAQ (CO_2), backpropagation NN based upon PID is designed in this study. The anticipated backpropagation NN based upon the PID controller integrates the PID controller and a NN which is applied to the algorithm of back-propagation. This controller structure comprises two key portions which are the PID control for IAQ and backpropagation NN for adjusting the PID controller parameters as stated by the existing conditions of the indoor environment. The IAQ can be well-controlled grounded upon the theoretical dialogue of the algorithm of the backpropagation NN which is based upon a PID controller that possesses the subsequent capacities:

- NN for ideal parameters of PID regulation to guarantee rapid disturbance recovery;
- algorithm of backpropagation for weights adjustment in NN to guarantee the system rapidly answers to changes in the indoor environment;
- PID controller is appropriate for several object control as well as IAQ.

In light of this, fuzzy PID controller and backpropagation NN-PID unfolded the human adaptation of social sustainability of the wellbeing and comfort of inhabitants (measured through controllers' performance indexes in the next chapter) which is, in turn, technically influenced by the environmental sustainability of the system. Nevertheless, the next chapter of this study focuses on the simulation results of the proposed photovoltaic solar air-conditioning and the smart indoor environment by means of using a computer model (Polysun and Matlab program) to analyse the effectiveness and efficiency of the projected scenario system which, in turn, contribute towards achieving better energy savings and reduced carbon emissions while combatting climate change and health effects of inhabitants, vis-à-vis environmentally friendly system to enhance the quality of life in the municipalities.

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Chapter Five

5.0 Simulation of Solar Air-Conditioning and the Smart Indoor Environment

5.1 Introduction

The preceding chapter unfolded the detailed designs of the proposed solar air-conditioning and the smart system controllers. Given the reason to accomplish the strong sustainability goal of the system; the solar air-conditioning and the smart controller of the indoor environment must reflect the three pillars of sustainability. Hence, the proposed photovoltaic solar air-conditioning and the two system controllers namely, fuzzy PID controller and backpropagation NN grounded upon PID controller must be environmentally friendly and able in that sense to accomplish a comfortable and healthy indoor environmental quality while reducing the rate of energy consumption and carbon emissions.

Therefore, the performance of the proposed photovoltaic solar air-conditioning and the controllers of the indoor temperature and IAQ (CO_2) are presented in this chapter. The simulating tests of photovoltaic solar air-conditioning and the smart controller of the system are theoretically grounded upon the conceptual modelling of photovoltaic solar air-conditioning and the indoor environment that are deliberated upon in the previous chapter. The simulations have been taken on the platform of Polysun and Matlab programs, respectively. The components of the photovoltaic solar air-conditioning were simulated using the Polysun program. Also, the simulation of the smart indoor environment using the Matlab program is systematically performed while carefully taking into account the performance of system controllers such as the stability, adaptability, speed response and overshoot. Correspondingly, the proposed photovoltaic solar air-conditioning and the performance of the smart indoor controllers are analysed.

5.2 Simulation of Solar Air-Conditioning

The simulation of photovoltaic solar air-conditioning is actualised by way of utilising the state-of-the-art Polysun designer version. The modelling and the descriptive fundamental mechanisms of the solar air-conditioning are offered in chapter four. Therefore, the simplified representation of the proposed system is revealed below in Figure 5.1. The window glazing ratio towards the area of the building wall is typically constant for the entire structure margins and the infiltration and exchange rate are produced by natural ventilation. The reference location is Rome, but this study also analyses the system in London and Toulouse as earlier mentioned in the preceding chapter. This is to examine the performance of the system in different regions and climatic conditions as presented in sections 5.2.2 and 5.2.3, respectively. In Rome, the tilted angle of the photovoltaic module is 45°, while the normal direct irradiation and global irradiation annual sum are 1587 kWh/m^2 and 1530 kWh/m^2, respectively. Moreover, the specific annual yield is 1281 kWh while the annual photovoltaic energy production DC is 7590.4 kWh, and the energy production AC is 6917.6 kWh. The system accounted for 38% of the average annual energy savings in Rome.

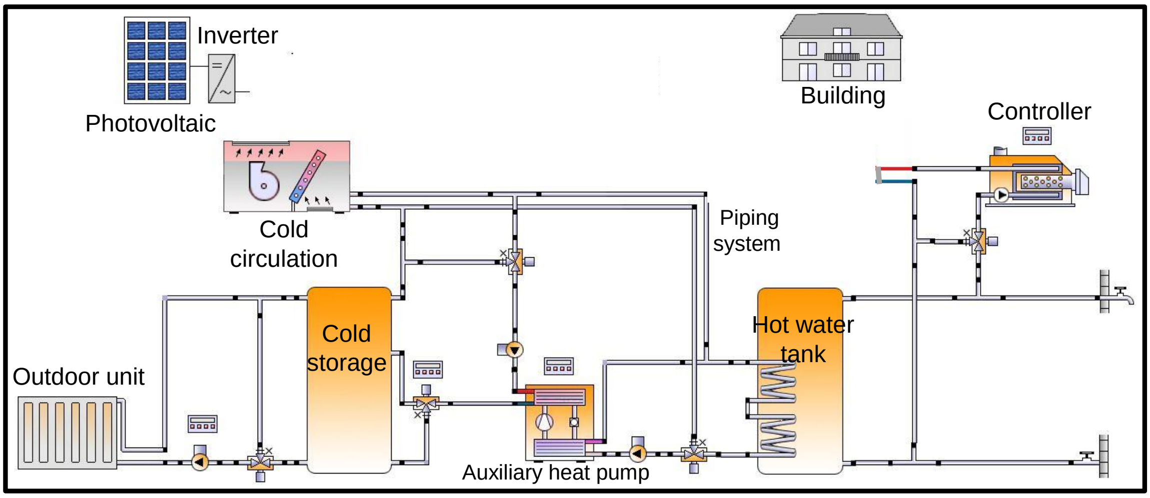

Figure 5.1: Simplified representation of the solar air-conditioning.

5.2.1 Performance Analysis of the Reference Location

In a cooling season, the photovoltaic electricity is produced with the total efficiency of the inverter all through the year. Albeit middle May is the period of cooling up to the time of October for the precise cooling energy mandate. There is heat gain of the building in the cooling season, where there is solar gain via the windows, including stemming after the flow of heat via the envelope of the structure. For the infiltration, natural ventilation, and the remaining inside heat gain is attained in the building. Once the outside temperature is lesser than the inside temperature, an increased percentage of the heat gain is rejected through the envelope of the structure, infiltration and natural ventilation.

Consequently, Figure 5.2 unfolds the outcome of the energy production of photovoltaic AC. For the room, the air stays in the range of comfort temperature at photovoltaic solar air-conditioning performance. The excess air temperature over the conditioning set temperature is decreased during the operation of the system. Correspondingly, the required power is used up to operate the fluid pumps, outdoor unit and auxiliary heat pump. The photovoltaic solar air-conditioning system produces electricity with the photovoltaic array, and the electricity is consumed by all system’s components in the cooling season. An average of 55% of the photovoltaic produced electricity is used by the heat pump for cold production. As a result, the photovoltaic solar air-conditioning can completely provide power independently with overall annual photovoltaic CO_2 savings of 3711 kg as presented in Figure 5.3. The simulation has shown that a solar photovoltaic combined with air-conditioning component can not only yield high energy savings but can also achieve a significant annual reduction of CO_2 emissions. This signifies that the energy usage is efficient which enhances the performance of the overall system by making sure the system only uses the required electricity needed for the air-conditioning. It indicates the amount of the CO_2 saved is high in comparison to a conventional system where the same power consumptions have to be covered and no renewable energy sources are used.

Research by EPA (2020) indicated that 20% of generated electricity can be stored in reserves. For instance, electricity generated during the day by solar photovoltaic panels can be stored in an electric battery to be used for boiling the kettle or watching television when solar photovoltaic panels are no longer generating electricity. This implies that a high potential for optimisation is hidden in the availability of the photovoltaic array electricity for electric energy consumption and cold production.

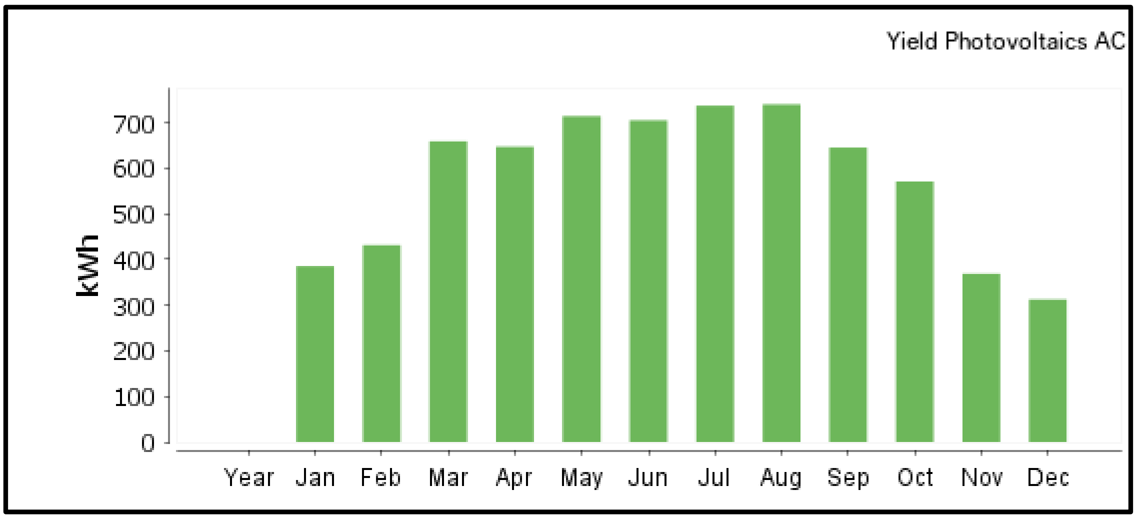

Figure 5.2: Photovoltaic yield of the system.

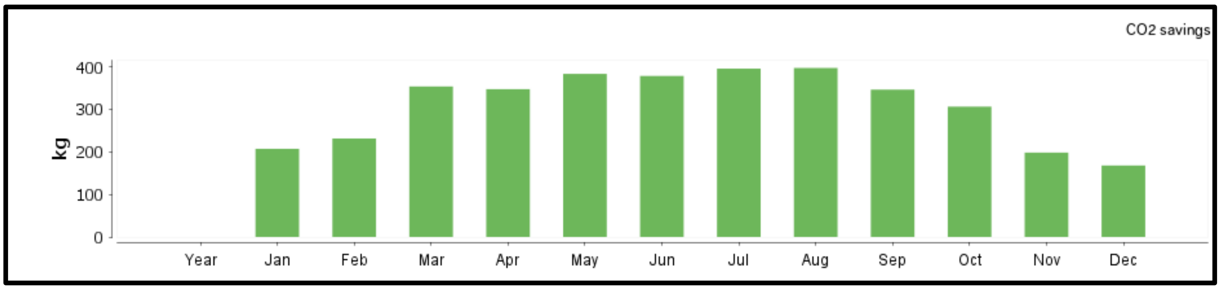

Figure 5.3: CO_2 savings of the system.

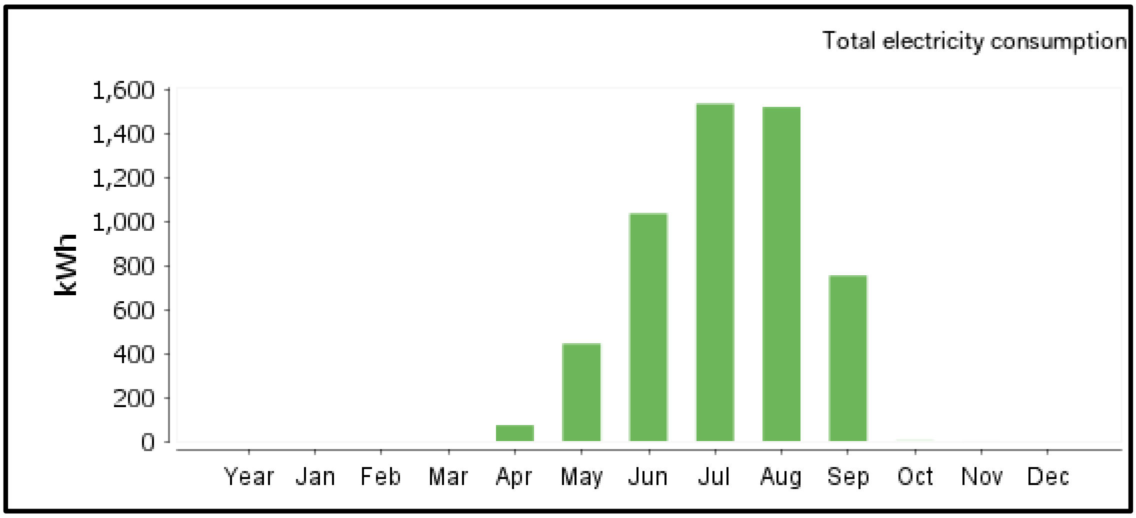

Figure 5.4: Total electricity consumption of the system.

The total electricity consumption of the system in Figure 5.4 represents the amount of electrical energy that has been consumed over a specific time in the cooling season.

It is the sum of own electricity consumption from the consumption profiles and the electricity consumption of the thermal components (the electricity consumed by the pump serving the cold storage, electricity consumed by the pump serving the outdoor system, the electric power of the cooling circulation, the electricity consumed by heat pump, the electricity consumed by the pump serving the DHW and the electricity consumed by the pump serving the heat pump). Total electricity consumption is the form of energy consumption that uses electric energy. It is the actual energy demand made on the existing electricity supply during the period of April to September. In the cooling season and non-cooling season, the system accounted for 45% and 18% of energy savings in Rome, respectively. The total average annual savings of the system is accounted for 38%. Also, Figure 5.5 shows that there is significant energy savings of the heat pump which saves 22% of the total average annual energy savings. This is because the solar photovoltaic will provide more energy for set conditioning during the summer than during the winter. It means that an auxiliary heat source will still be required for heating during the winter months. However, the solar photovoltaic system is still able to save energy that would have been required annually for heating using conventional energy sources.

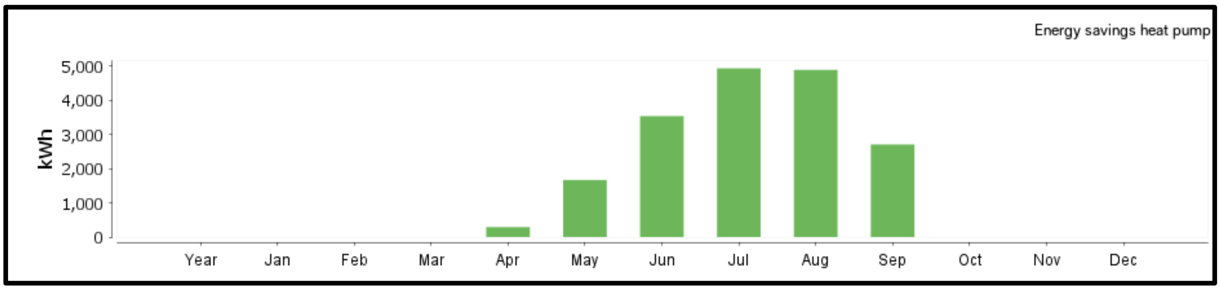

Figure 5.5: Energy savings heat pump of the system.

Similarly, during the winter months, the solar photovoltaic energy is not able to completely cover the system i.e., the total energy consumption of the system and DHW loads of the heating. So, there is a necessity for an auxiliary heat basis. The heat pump which serves as the auxiliary heater is utilised in this situation for heating whenever the system is unable to meet up the set conditioning temperature required. The auxiliary heat provided by the heating system is transmitted for preheating of DHW. This operation makes energy usage to be efficient and subsequently enhances the performance of the overall system as well by making sure the system only uses the required energy needed by the system.

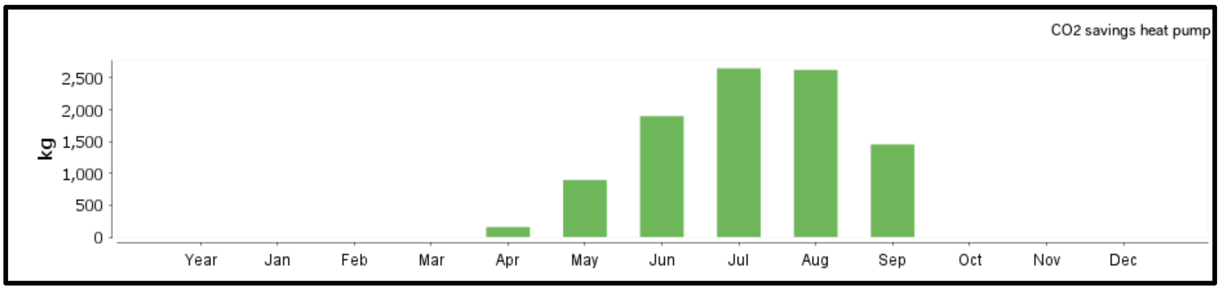

Figure 5.6: CO_2 savings heat pump of the system.

In Figure 5.6, it can be observed that the heat pump applies to the system for the cooling season. This means that the heat pump which serves as the auxiliary heat source is optimised to increase the system efficiency of operation and to save a significant amount of CO_2 during the system operation especially during the summer months (April – September). The simulation has demonstrated that solar photovoltaic power coupled with integrated air-conditioning components can not only yield high energy savings but can also achieve an appreciable annual reduction of CO_2 emissions.

The energy balance is negative during the winter months due to energy lost to the environment. As a result, energy is added by the auxiliary heater to supply energy through the outdoor unit. During this time, little energy storage occurs. In contrast, during the summer months, more energy is being delivered to the system for the required set conditioning by solar power. During this period, the auxiliary heating is at a minimum. Also, additional energy savings are expected since the system component has low electricity consumption. Energy savings related to the solar photovoltaic power contribution are observed since heat energy is driven by the auxiliary heat source when heating power is required by the system component and the solar radiation is not enough. Therefore, the electricity consumption through cooling and heat pump is covered by photovoltaic electricity.

In a non-cooling season, the photovoltaic power that is generated may be utilised for heating. The auxiliary heat pump is utilised in this situation for heat up where heating of the room possesses the foremost, even though the DHW heat the second precedence. Albeit elevated temperatures of DHW makes this procedure less efficient.

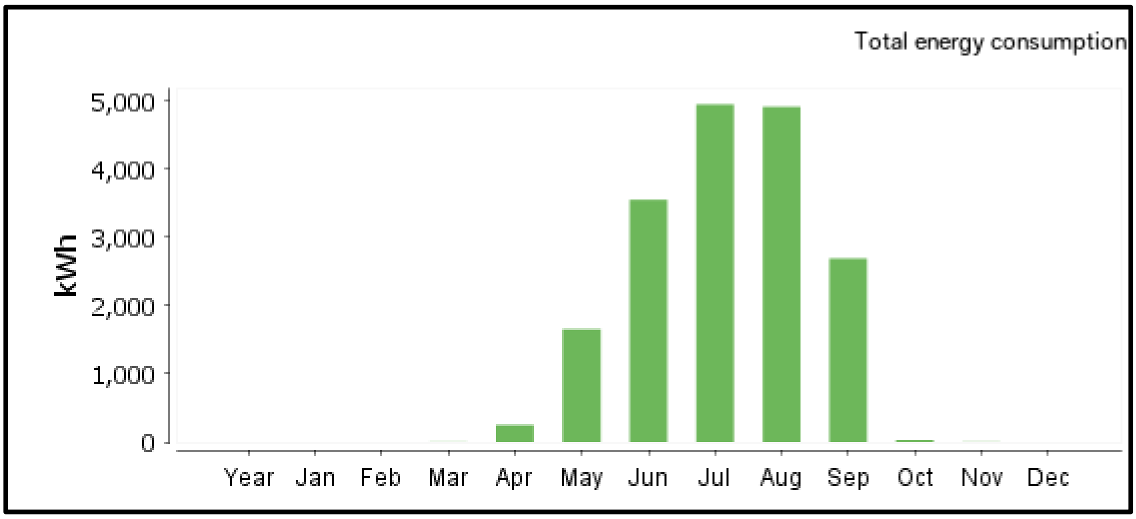

Figure 5.7: Total energy consumption of the system.

The total energy consumption throughout the year is offered in Figure 5.7. The solar photovoltaic energy is not able to completely cover the DHW heating and room heating during the winter months. Therefore, there is a necessity for an auxiliary heat source. The heat pump operates as the auxiliary source of heat during the period of October to March. As indicated by NHBC (2016), the heat pump can serve as an auxiliary heat source to a photovoltaic system regardless of how the heat is generated or delivered. Decreased averaged temperature difference between the hot and the cold side of the heat pump significantly affects its COP. The heat production efficiency for DHW is almost two times less than for low-temperature heating. Hence, the production of heat for DHW needs is a second priority. The auxiliary heat pump operates on the absorbed heat and consumed electricity after deduction of heat losses.

The device, apart from the outdoor unit, is established and the relevant heat losses should not affect the cooling or heating demands of the cooled/heated room. It may be possible to equalise the energy balance by adding the heat rejection energy flows through the outdoor unit and by excluding the photovoltaic influence. In the cooling season, the amount of heat rejected exceeds the demand of DHW. As previously mentioned, the rejected heat is diverted to the DHW heating. Thus, the greater part of the rejected heat is dismissed by the surrounding. This heat may be utilised for swimming pools, which will lessen the temperature of the high-temperature liquid circle, in this way, improving the system efficiency.

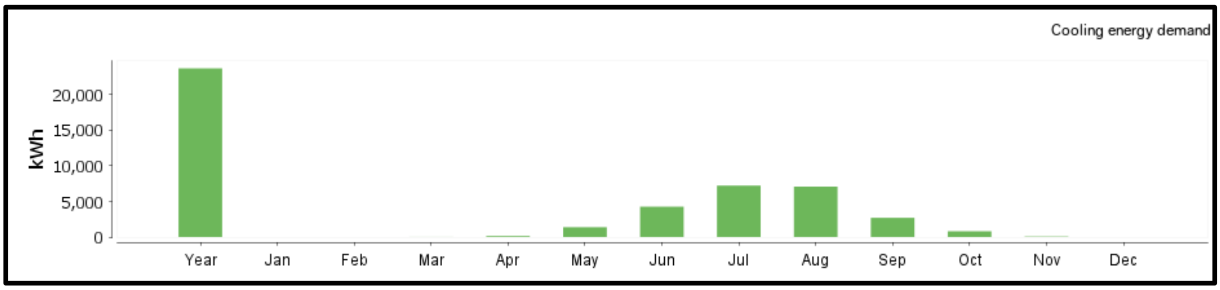

Figure 5.8: The cooling energy demand of the system.

In Figure 5.8, it can be observed that there is more cooling demand between May – September, in comparison to other months of the year. This is because, in the cooling season the hot weather conditions necessitate for more cooling demand. Furthermore, the utilisation of outdoor air heat is constrained because of the protection from freezing on the outside low temperature and high conditions of humidity. From November to March, heating and preheating of DHW are diminished. This is the fundamental drawback of the photovoltaic solar air-conditioning innovation. In like manner, the low use of free cooling toward the start and the close of the cooling season is because of low cooling utilisation. Cold storage discharge is slower than its reviving through the cooling circulation. This is particularly recognisable in the season of high photovoltaic production. However, there is no requirement for free cooling in the season of low solar irradiation, and the photovoltaics in that time produced power supplies into the network. The cooling energy demand of the system is uncovered in Figure 5.8 and the information shows that photovoltaic solar air-conditioning lessens the peak of power utilisation from the grid for cold production.

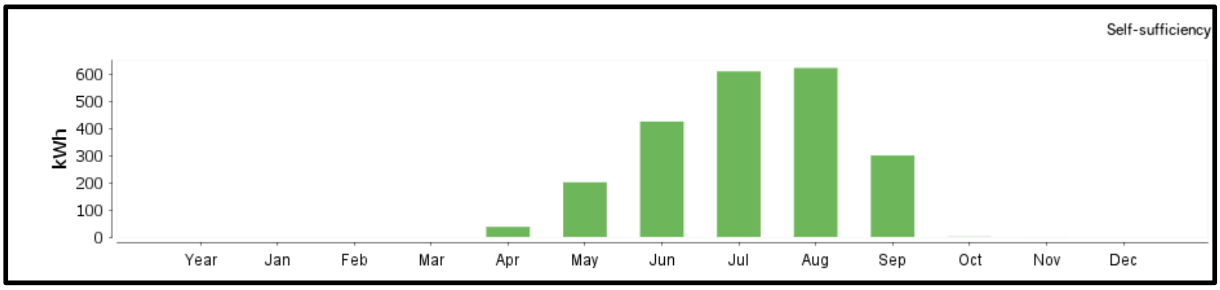

Figure 5.9: Self-sufficiency of the system

Self-sufficiency implies that the photovoltaic energy is sufficient to completely power the system in the cooling season. In Figure 5.9, it can be observed that the self-sufficiently applies to the photovoltaic energy for the cooling season (April to

September). This means that the photovoltaic can produce the required energy to power the system during the cooling season. Although in the non-cooling season, the system is less self-sufficient due to the requirements of the space heating and DHW system. During this period, the efficiency of air-conditioning is reduced since heating is mostly required during the winter months. It affirms that significant cooling utilisation happens from April to September. Thus, the cold storage requires recharging towards the start of the day. In this way, the power used up through the cooling surpasses the photovoltaic electricity produced in the first part of the daytime. Moreover, in the afternoon, traditional air-conditionings have everyday power utilisation peaks, but the photovoltaic solar air-conditioning delivers a surplus of electricity. Figure 5.10 and Figure 5.11 show the graphical evaluation of the cooling energy demand and photovoltaic CO_2 savings for the district of Rome.

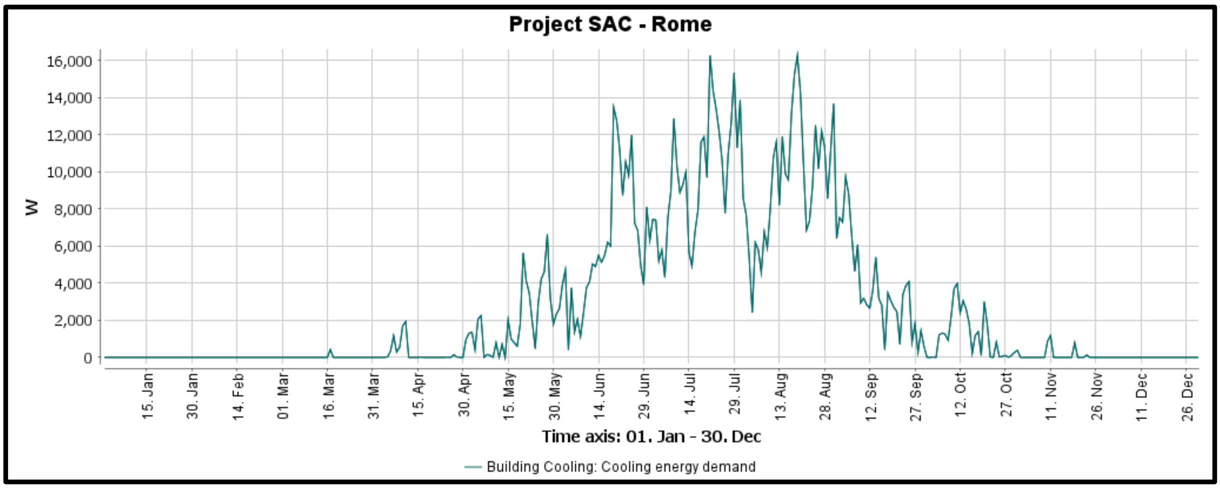

Figure 5.10: Graphical evaluation of the cooling energy demand

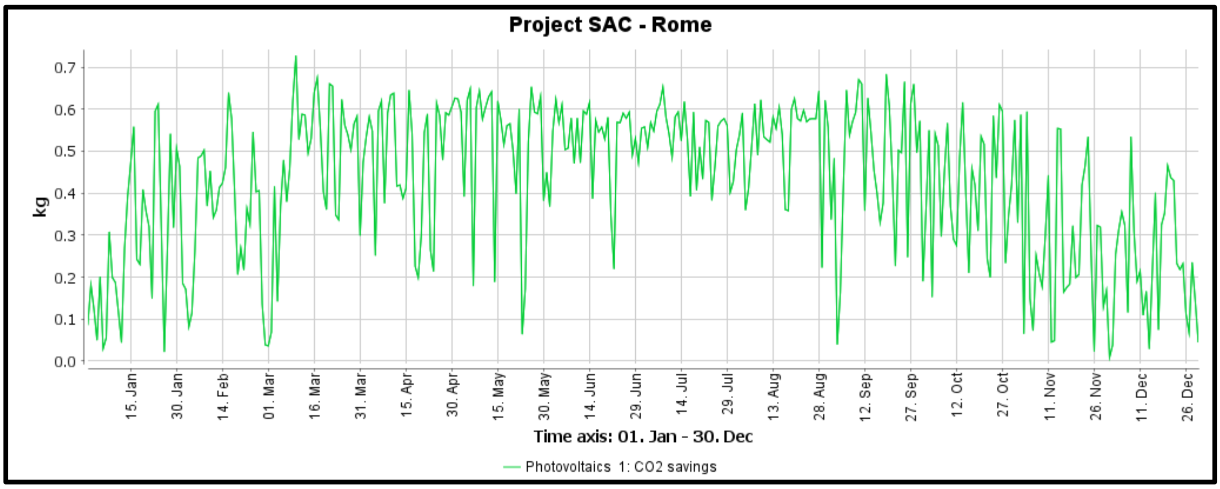

Figure 5.11: Graphical evaluation of the photovoltaic CO_2 savings

The greater part of the power overproduction transpires all through transitional times of cooling-to-warming seasons. During this time, the energy of air-conditioning and heating; for example, power requirements are low. However, a positive outside climate conditions decline the temperature contrast amongst the sub-systems of heat rejection and thus is helpful for the cooling system efficiency in the heating of DHW. In springtime, power overproduction is particularly recognisable, and the photovoltaic power production is higher during the springtime than in autumn – this is as a result of reduced outdoor air-temperature in the spring season, which therefore expands the effectiveness of photovoltaic units.

Photovoltaic yield – The result shows that the total annual energy supplied to the air-conditioning system is 6917.6 kWh. The energy supplied during the winter months is low. This means the auxiliary heating system works more during winter. Consequently, the auxiliary heating system is optimised to increase the efficiency of operation and to save a significant amount of energy especially during the summer months. In the spring to the summer season (April – October), enough useful energy is supplied to the air-conditioning system with little auxiliary heating from the heat pump for energy demand to be covered.

Total energy consumption of the system – The result shows that the total annual energy consumed by the system is 18030 kWh. This includes solar energy consumed, auxiliary energy consumed, and energy required to power other components for operation e.g., pumps, DHW, and outdoor unit. The efficiency of the consumption is determined by the energy balance of the system. The energy balance is negative during the winter months due to energy lost to the environment. As a result, the system will consume more energy to make up for the lost energy.

5.2.2 The System Improvement Performance

The improvement performance result of the system for London, Toulouse and Rome are presented in this section. This is associated with their impact on the general performance of the system – the necessity is that the cooling demand must be covered. The supplementary components of the system can be added till satisfactory improvement is achieved. Thus, the system without augmentation has fewer segments, which essentially improves innovation. Through the cold demand, the cooling system generates cold that is hard to gauge. Thus, surpassing the cold production and henceforth, power utilisation can occur. The system cooling limit in this circumstance is deficient, and the building set temperature is not gotten. Therefore, the cooling system power is expanded on account of the subsystem.

Subsequently, the key focus of the performance of the cold storage for the three districts is to diminish the demand for electricity peak. In this way, if the system in view is updated basically with cold storage, the room temperature variances may be extensively diminished by way of affecting the pinnacle load. In the solar air-conditioning, the cold storage is obliged to overcome any issues between the cooling demand and solar power gain. The cooling system activity is nearer to the ideal driving temperature array with the inclusion of a cold storage tank, which marginally expands the auxiliary heat pump's regular productivity. Additionally, because of this expansion with the present cooling load of each district, the activity time for the generation of cooling could be decreased. Albeit to protect the cooling demand in times of low radiation of solar, the strategy of free cooling may be connected if the temperatures of the outdoor are in a suitable range. Moreover, Table 5.1 presents the annual improvement performance result for the three districts.

Table 5.1: Annual system improvement performance result.

System	Unit	London	Toulouse	Rome
COP	–	3.97	3.69	3.37
Self-consumption	kWh	813	1364	2196
Yield of Photovoltaic AC	kWh	4656.9	6306.8	6917.6
Yield of Photovoltaic DC	kWh	5158.2	6934.8	7590.4
To external grid	kWh	3843	4943	4723
From external grid	kWh	1352	1883	3159
Heat generator energy to the system	kWh	10874	15278	23369
Total energy consumption	kWh	8594	11991	18030
Energy deficit	kWh	1356	3500	7023
Total fuel and electricity consumption	kWh	–2491	–3060.5	–1563.3
Total electricity consumption	kWh	2166	3246	5354
Specific annual yield	kWh	862	1168	1281
Self-sufficiency	kWh	813	1364	2195
Primary energy factor	eP	0.28	0.28	0.32
CO_2 Savings	kg	2498	3383	3711

The impact of climate on the energy performance is examined to determine which climates provide the greatest additional energy saving benefit and system performance from the configuration as a representation of climatic conditions in London, Toulouse and Rome. The comparison of energy results in association with the examined weather conditions is shown in Table 5.1. In each of these three districts, the energy demands are expected to be covered to sustain the cooling demand. The total average annual savings of the system in Rome (reference location) is accounted for 38%. In London, the configuration yields an increased amount of energy savings of 16.2% as compared to the reference location and in Toulouse, the configuration yields an increased amount of energy savings of 14.6% as compared to the reference location. Therefore, it is evident that different weather condition does not only determine the savings of the system but also the system consumption. For instance, in Rome, there is more cooling demand than in London and Toulouse due to the hot weather condition during the summer months which necessitate for more cooling demand. The more the cooling demand, the more auxiliary system becomes more domineering which means there will be less savings. This present system performance permits a productive cooling demand covering. The electrical and thermal results are presented in Appendix A. Also, Figure 5.12 – Figure 5.23 presents the graphical evaluation of photovoltaic energy production, power from the grid, power to the grid and auxiliary heat pump cooling for the three locations considered in this study.

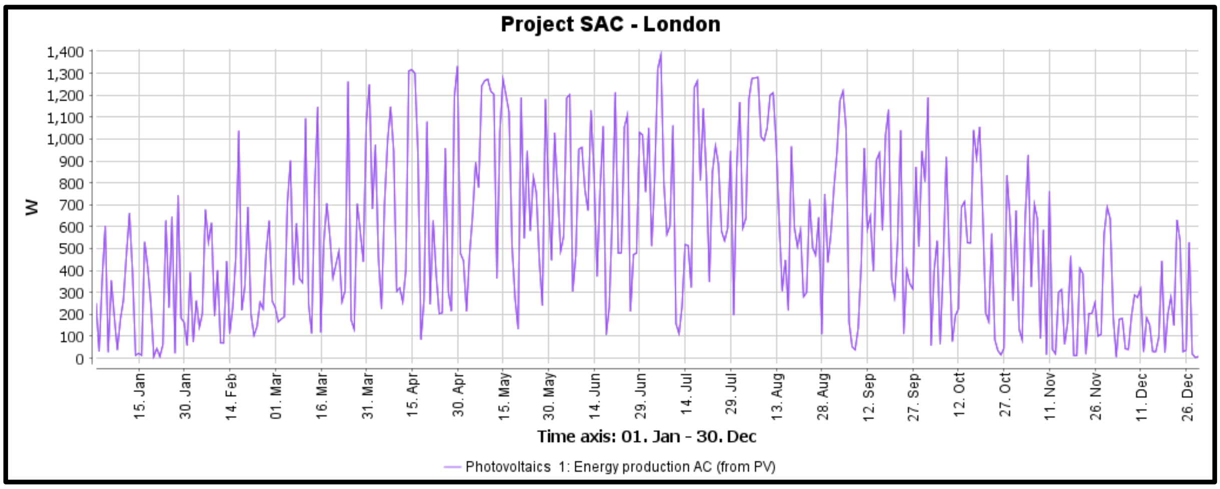

Figure 5.12: Photovoltaic energy production – London

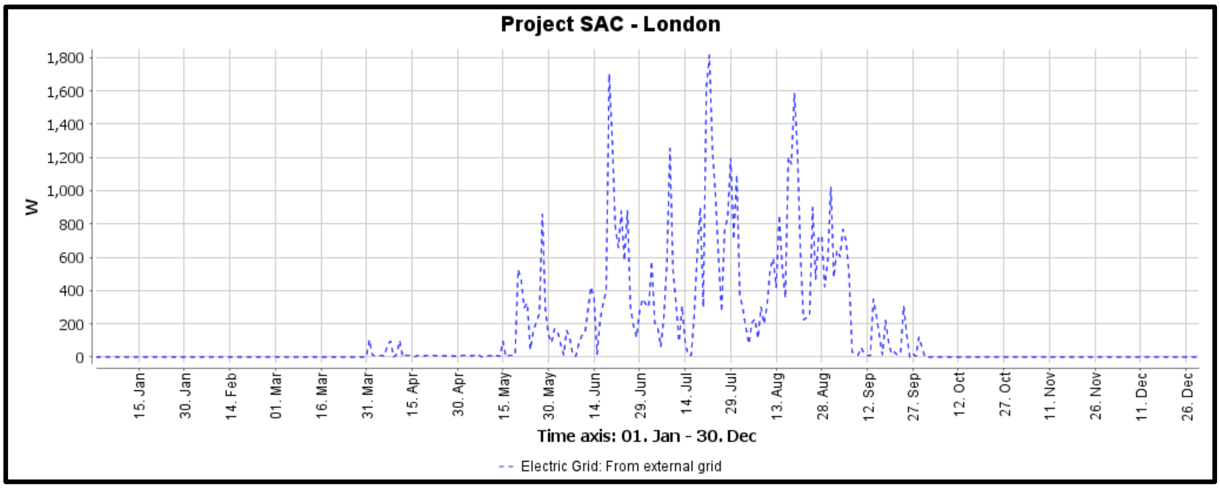

Figure 5.13: Power from the grid – London

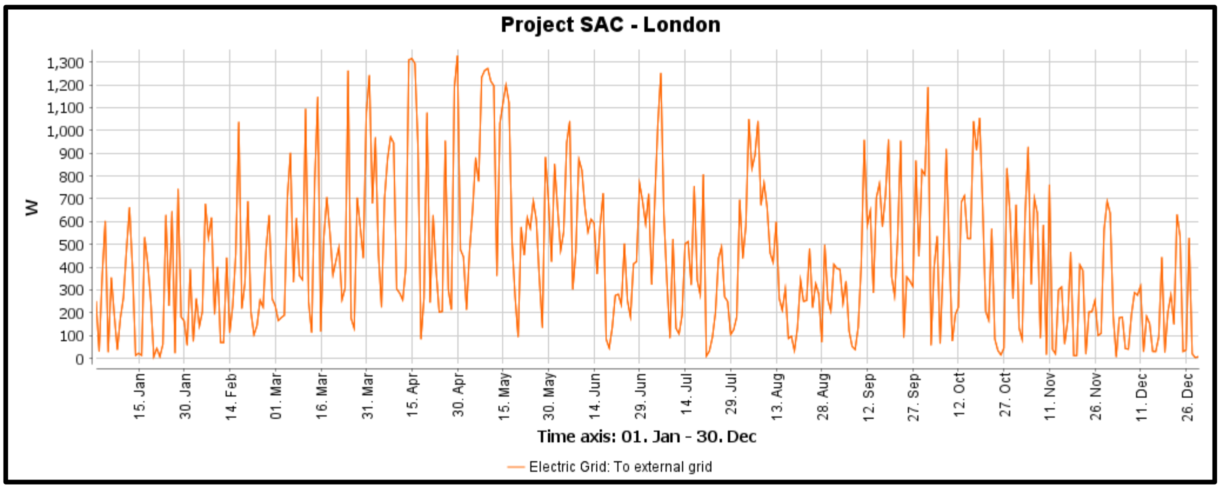

Figure 5.14: Power to the grid – London

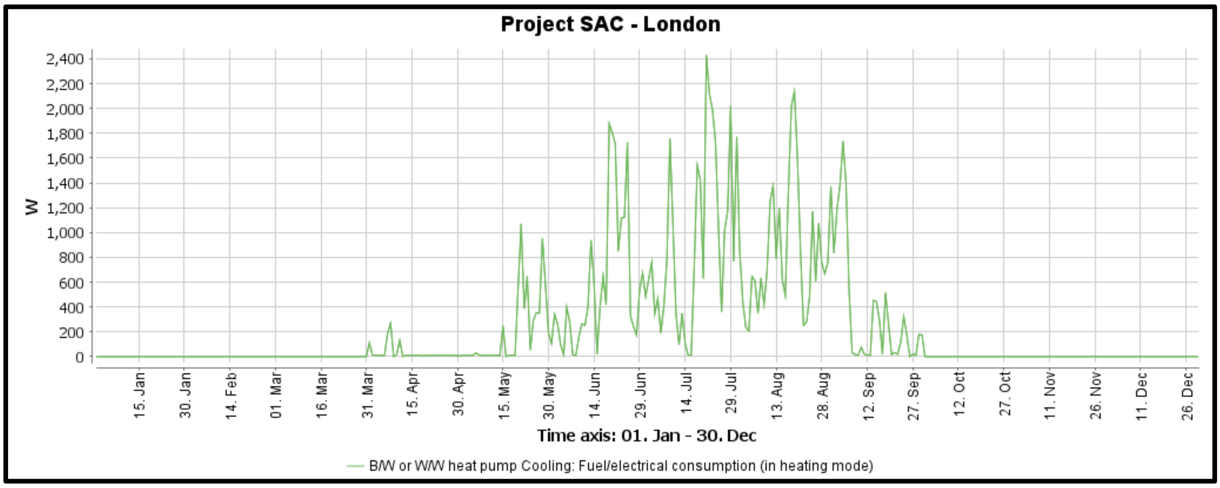

Figure 5.15: Auxiliary heat pump cooling – London

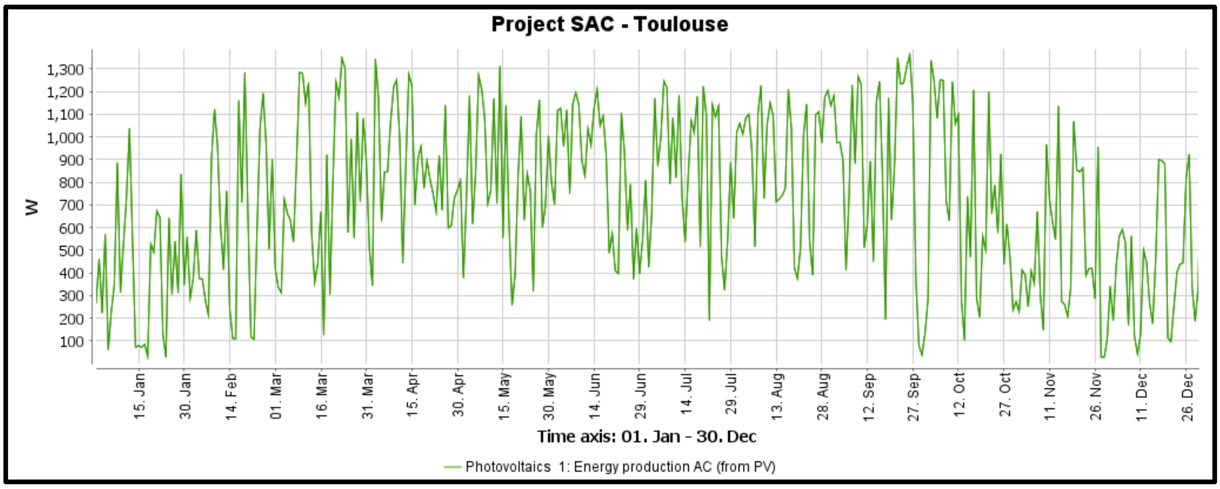

Figure 5.16: Photovoltaic energy production – Toulouse

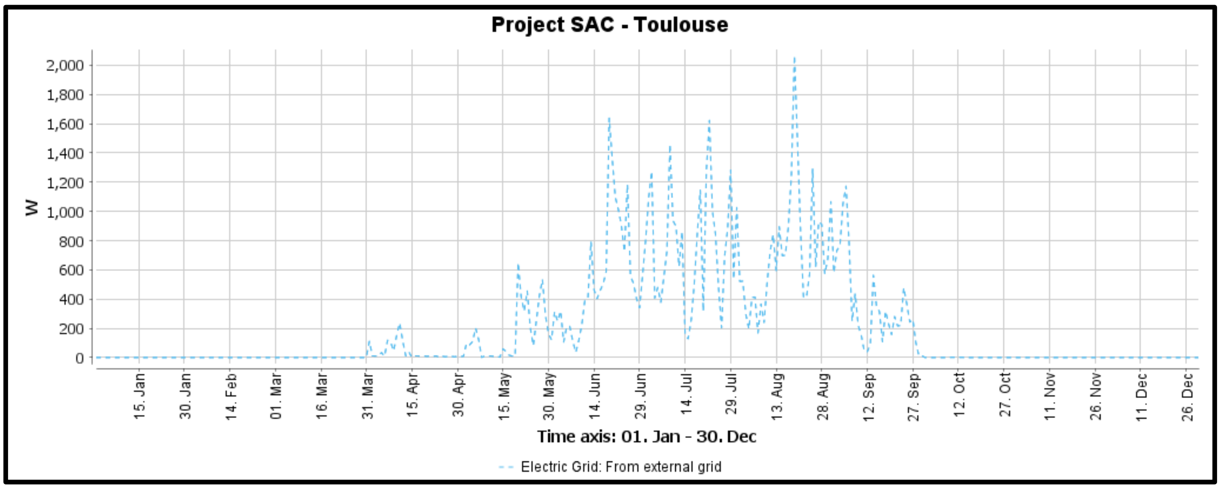

Figure 5.17: Power from the grid – Toulouse

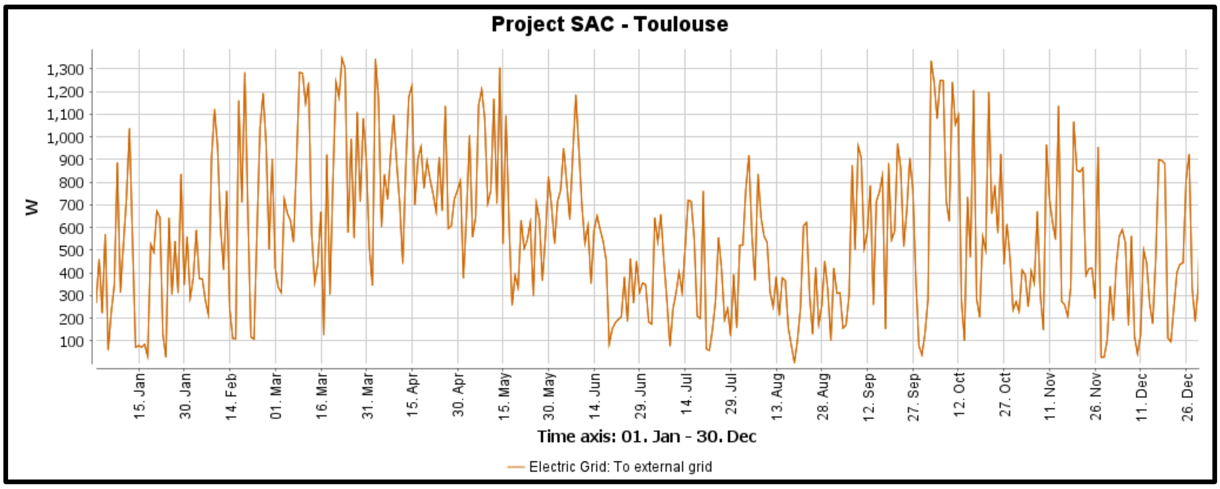

Figure 5.18: Power to the grid – Toulouse

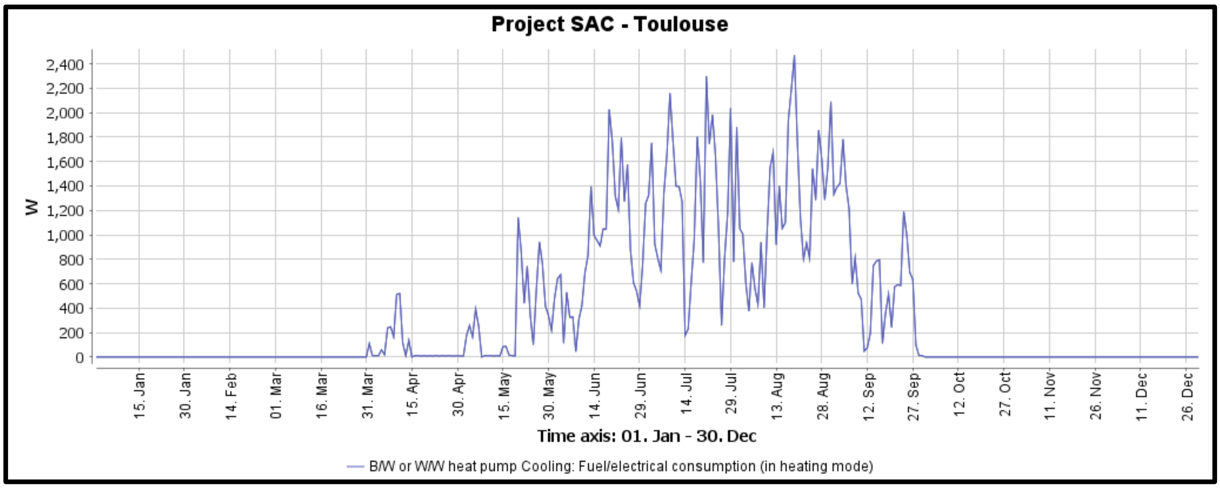

Figure 5.19: Auxiliary heat pump cooling – Toulouse

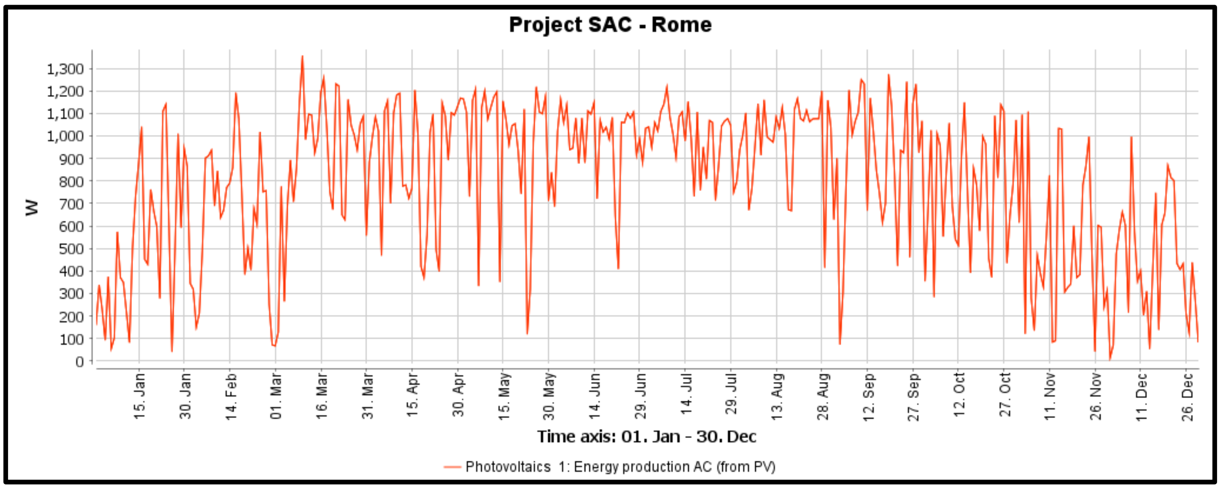

Figure 5.20: Photovoltaic energy production – Rome

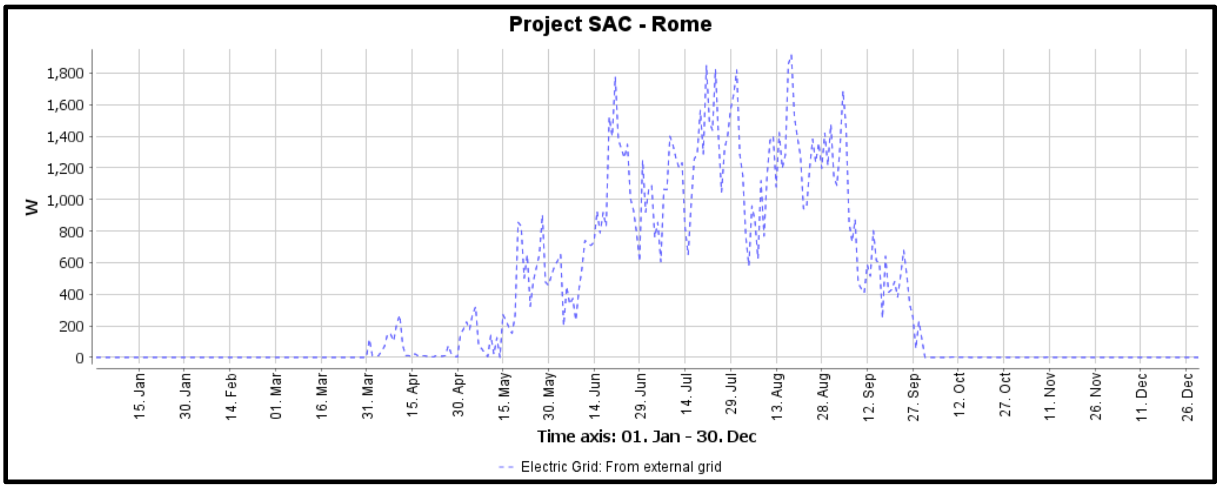

Figure 5.21: Power from the grid – Rome

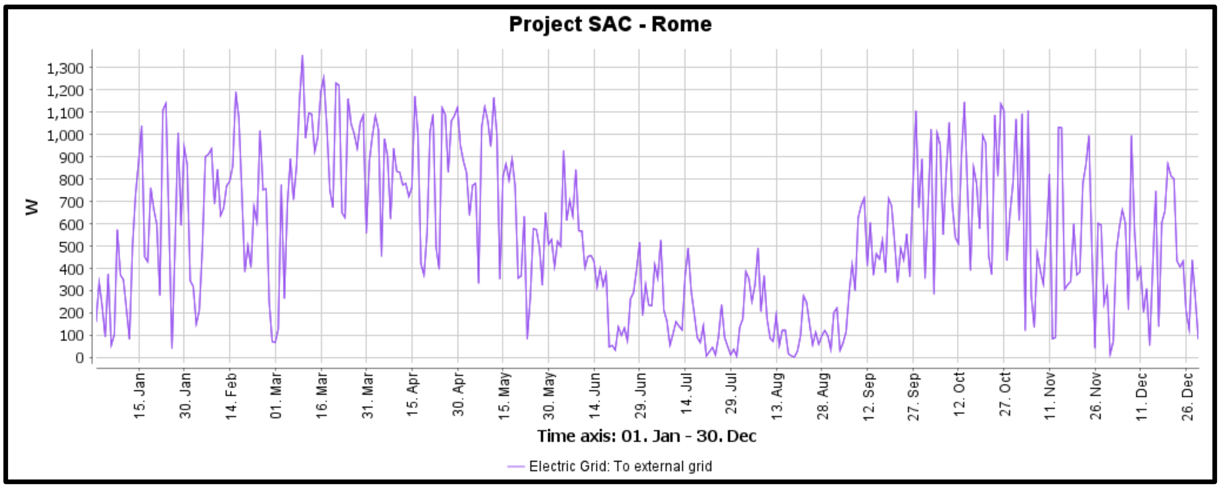

Figure 5.22: Power to the grid – Rome

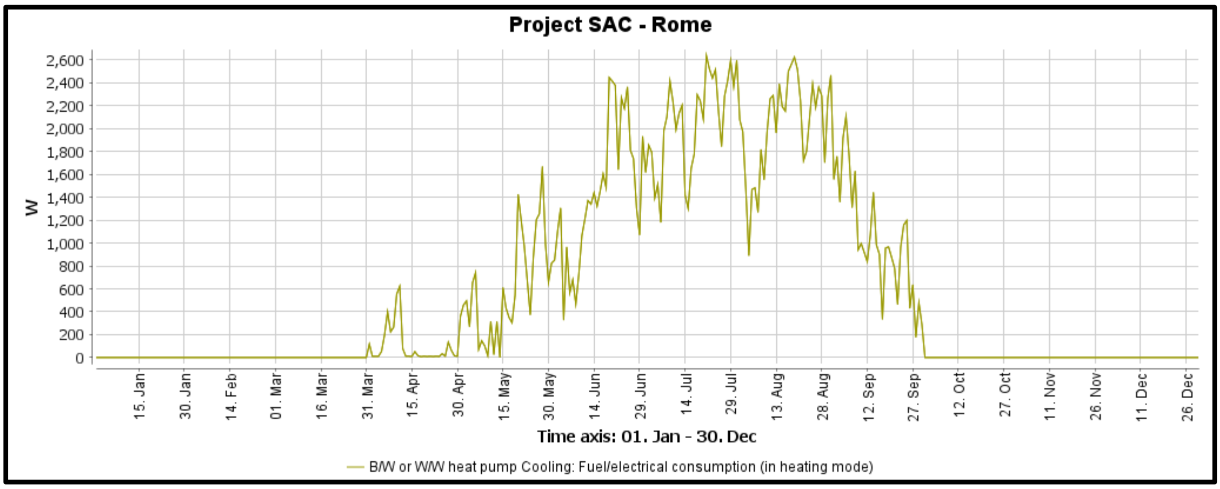

Figure 5.23: Auxiliary heat pump cooling – Rome

The building cooling demand is influenced through its envelope protection, via the proportion of window-to-divider zone through the measure of interior load, infiltration and ordinary ventilation. In the cooling season, the utilisation of resources with lesser thermal conductivity implies higher costs of investments and may prompt higher cooling energy requirements. Nonetheless, thermal improvement builds the demand for yearly cooling. Hence, there is a decrease in the level of energy consumption which leads to a significant amount of CO_2 savings in each district. However, the results show that photovoltaic solar air-conditioning can cover the cooling demand in the proposed locations while reducing the level of energy consumption and the rates of carbon emissions.

Reduction of CO_2 Emissions – After optimising the system, the solar air-conditioning system completely provided enough energy independently with overall annual solar CO_2 savings of 2498 kg, 3383 kg and 3711 kg for London, Toulouse and Rome, respectively. This indicates that the energy usage is efficient which enhances the performance of the overall system by making sure the system only uses the required energy needed for the system. This is the key benefit of the optimised system.

COP and Efficiency – The COP is a function of the solar fraction, energy supply and savings and the efficiency of the integrated interaction of the system component. The COP also points out how much energy is consumed per photovoltaic energy distributed into the system. It takes into consideration not only the internal energy consumption of the main components such as the heat exchanger and DHW but all the auxiliaries and distribution pumps as well. How efficient the system components interact together to generate effective outcomes is summed up into a single value. The higher the value the better the performance of the system. Higher COPs equate to higher efficiency, lower energy (power) consumption and thus lower operating costs. There is generally a better performance of the system during the summer months compared to the winter months. Even during the winter months, the performance is still good. The system COP in London, Toulouse and Rome are 3.97, 3.69 and 3.37, respectively.

This study provides a system having higher COP which equates to the higher efficiency of the system in the adapted locations as compared to low COP values of 0.6 and 0.71 provided in the research studies by Zhang et al. (2016) and, Jafari and Poshtiri (2017), respectively. Therefore, there are greater possibilities for the photovoltaic solar air-conditioning to achieve higher efficiency for the system sustainability.

5.2.3 Climatic Simulations of London, Toulouse and Rome

Accordingly, simulations of solar air-conditioning for three climatic districts are accomplished in this study. Moreover, Mauthner and Weiss (2014), suggested that the majority of the solar air-conditionings are situated in specific European districts due to their climatic conditions. Hence, the simulations were constrained to London, Toulouse and Rome and are performed via Meteonorm Version 8 – the state-of-the-art meteorological database. The temperate and northern latitude of the three locations is given in Table 5.2.

Table 5.2: Climatic districts for photovoltaic solar air-conditioning.

Temperate	**Location**	**Northern Latitude**
Oceanic, cold	London, UK	52.5°N
Mediterranean, mild	Toulouse, FR	43.6°N
Subtropical, hot	Rome, IT	41.9°N

Subsequently, Table 5.3 presents the annual meteorological data analysis for the districts of London, Toulouse and Rome. The monthly meteorological data analysis for the three districts is also presented in Appendix B. The uncertainty of the year for London is Gh=3%, Bn=6%, Ta=0.3℃ while the trend of $Gh/$decade is 5.1% and the variability of $Gh/$year is 6.5%. The uncertainty of the year for Toulouse is Gh=4%, Bn=9%, Ta=0.5℃ while the trend of $Gh/$decade is 1.5% and the variability of $Gh/$year is 3.3%. The uncertainty of the year for Rome is Gh=3%, Bn=7%, Ta=0.5℃, while the variability of $Gh/$year is 3.7%, respectively.

Table 5.3: Annual meteorological data analysis for London, Toulouse and Rome.

Parameter	**Unit**	**London**	**Toulouse**	**Rome**
Gh	kWh/m^2	974	1348	1433
Dh	kWh/m^2	572	648	650
Bn	kWh/m^2	820	1304	1387
Ta	℃	13.1	13.8	17.3
Td	℃	6.9	8.6	10
FF	m/s	2.0	3.8	1.2

Figure 5.24, Figure 5.25 and Figure 5.26 unfold the climatic conditions of the London borough for the proposed system. The London district possesses an oceanic temperate climate, with cool winters and mild summers. Unlike Rome and Toulouse, London has several extended periods of cloudy skies and recurrent precipitation that is light mist-type, which can account for the municipal rainy image. However, the climate of London like much of the UK districts is formed via the high latitude Atlantic Ocean of onshore flow which, in turn, conveys cool, moist air, and regular skies that are cloudy. In the existing restrictions of London, the maximum temperature ever logged was 38.1 °C and the coolest temperature ever logged was –16.1 °C, recorded during the European Heat Wave at Kew Gardens.

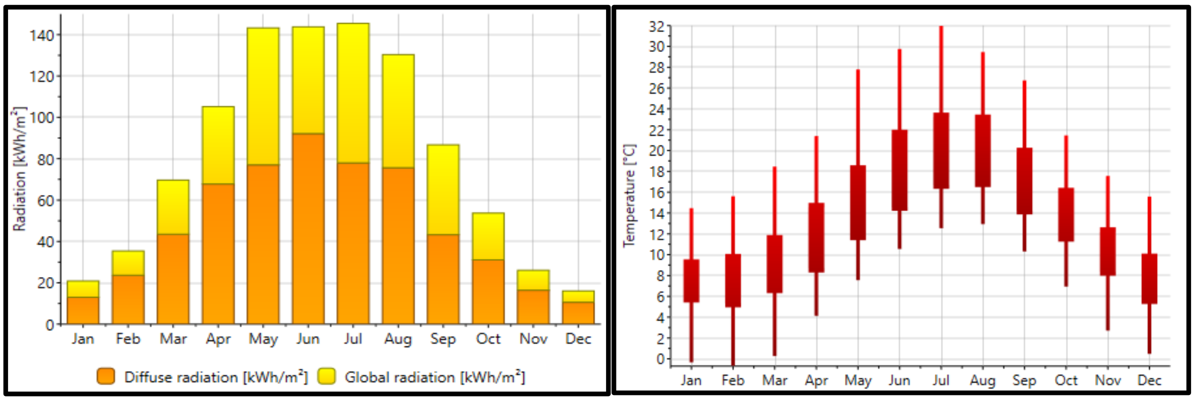

Figure 5.24: London’s yearly radiation and temperature.

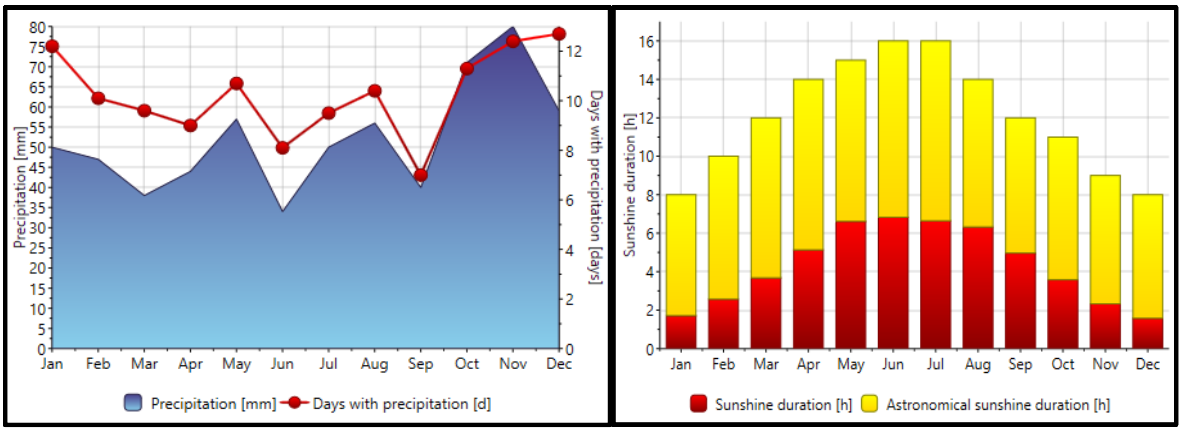

Figure 5.25: London’s yearly precipitation and sunshine duration.

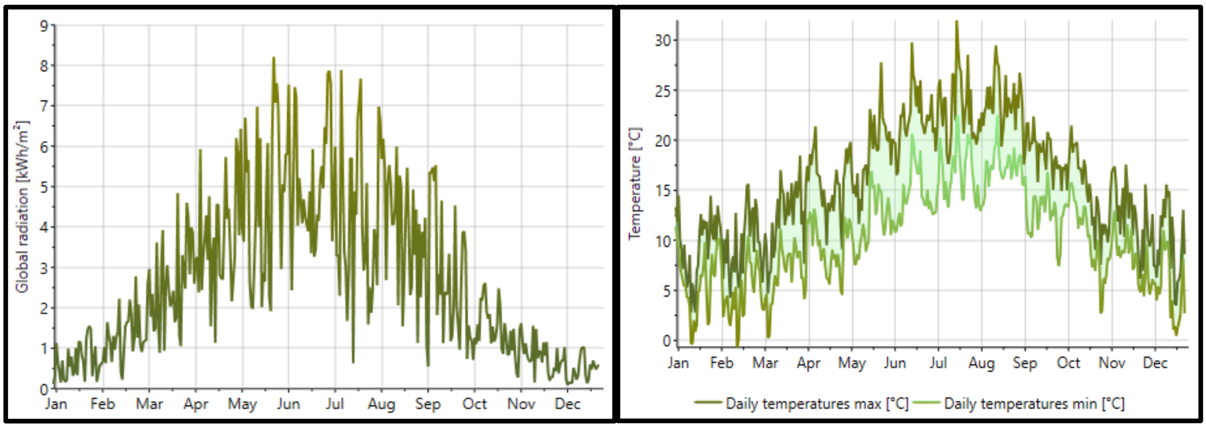

Figure 5.26: London’s global radiation and daily temperature.

Subsequently, Figure 5.27, Figure 5.28 and Figure 5.29 unfold the climatic conditions of the Toulouse district for the proposed system. Unlike Rome and London districts, the Toulouse region has a Mediterranean temperate climate which is mostly mild, and may be described as the transitional Mediterranean, having hot, sunny summers and moderately mild winters. Nevertheless, there may be cold days in winter with temperatures below freezing and very hot days in summer. In the Haute-Garonne department, the metropolitan is situated in the southwest of France. The average temperature of the warmest month is around 22.3 °C and the coldest month is around 6 °C.

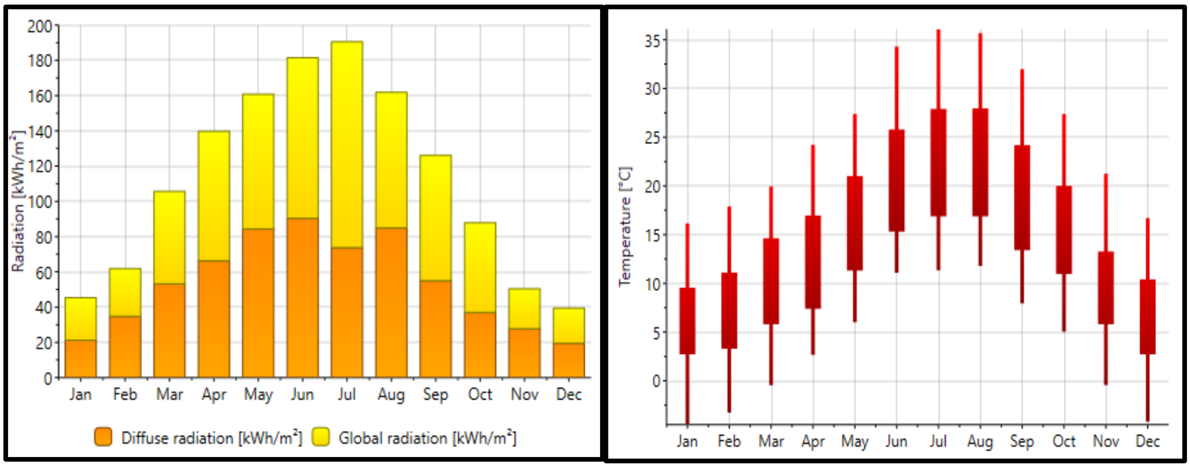

Figure 5.27: Toulouse’s yearly radiation and temperature.

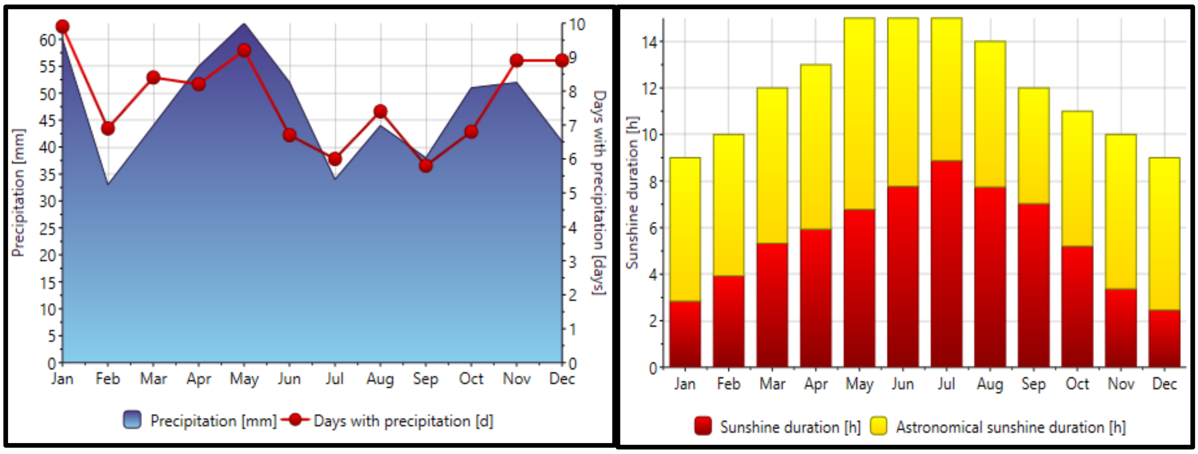

Figure 5.28: Toulouse’s yearly precipitation and sunshine duration.

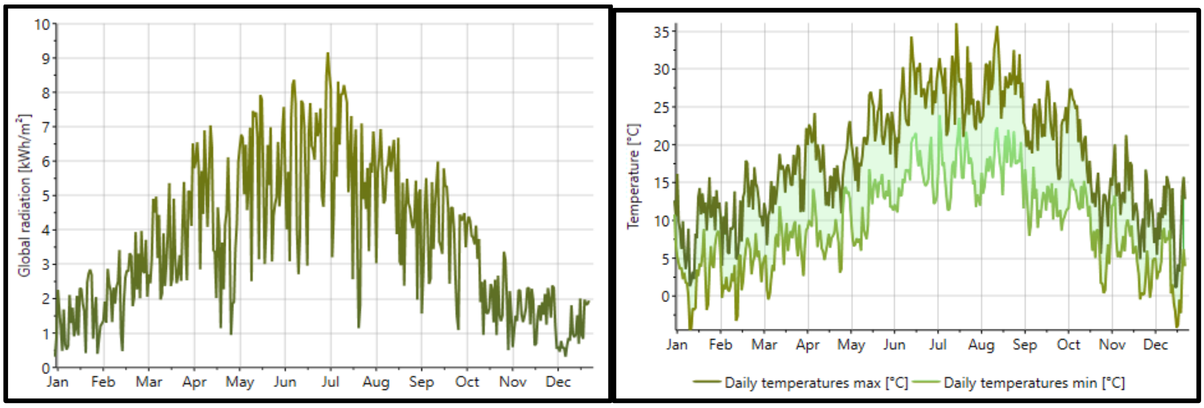

Figure 5.29: Toulouse’s global radiation and daily temperature.

Consequently, Figure 5.30, Figure 5.31 and Figure 5.32 unfold the climatic conditions of the Rome district for the proposed system. Unlike London and Toulouse, the district of Rome has a Subtropical/Mediterranean climate with some slight continentality elements. Winter is quite rainy and mild, nonetheless, it can get cold at night. Winter seasons are cold in Rome, and the average low temperature drops to 2.8°C during winter peaks while the summer periods are sunny and hot with a few afternoon thunderstorms, and the average high temperature can reach up to 27.8°C.

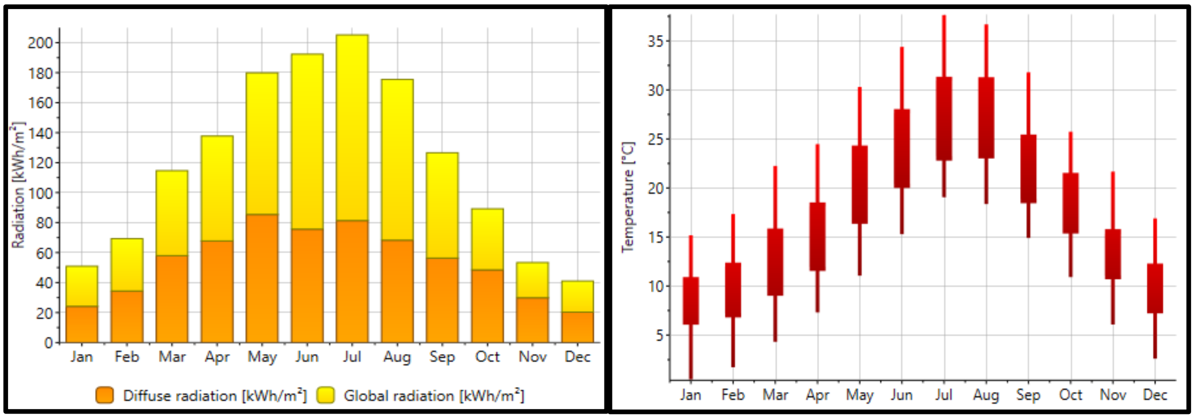

Figure 5.30: Rome’s yearly radiation and temperature.

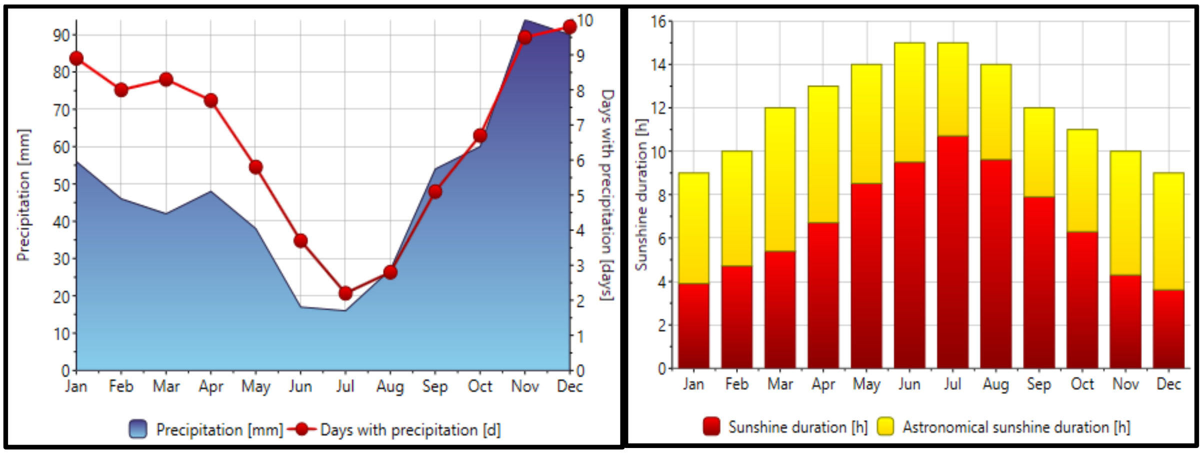

Figure 5.31: Rome’s yearly precipitation and sunshine duration.

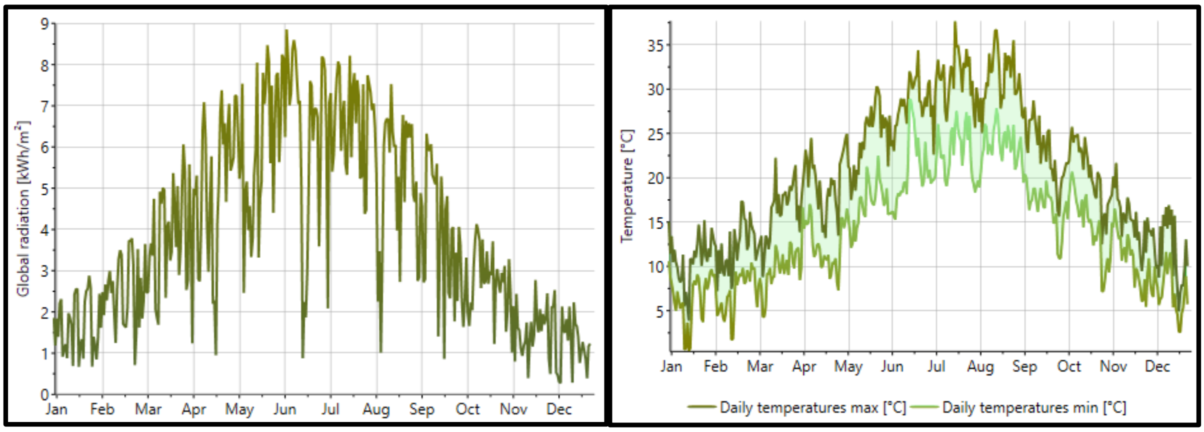

Figure 5.32: Rome’s global radiation and daily temperature.

The weather information for London, Toulouse and Rome has been complied using Meteonorm software Version 8 which, in turn, includes appropriate meteorological data required for the planning of solar applications (Meteonorm, 2019). Subsequently, the comparison of energy results in association with the examined weather conditions of London, Toulouse and Rome districts are uncovered in Figure 5.33, Figure 5.34, Figure 5.35 and Figure 5.36, respectively. In the entirely three areas, the chart demonstrates that the cooling systems are expected to sustain the comfort conditions of the building. Moreover, the cooling demand in the Mediterranean and subtropical climate is a lot higher than in the oceanic climate. In this way, the examination demonstrates that the cooling demand for the three locations is covered, and air-conditioning is required or else the living room temperature will never be comfortable.

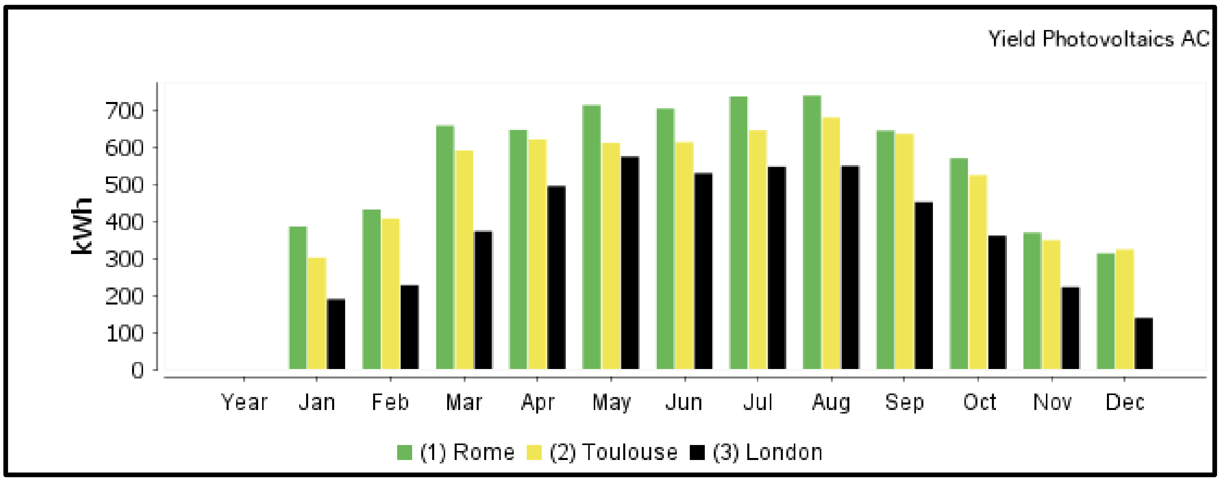

Figure 5.33: Photovoltaic yield of the system.

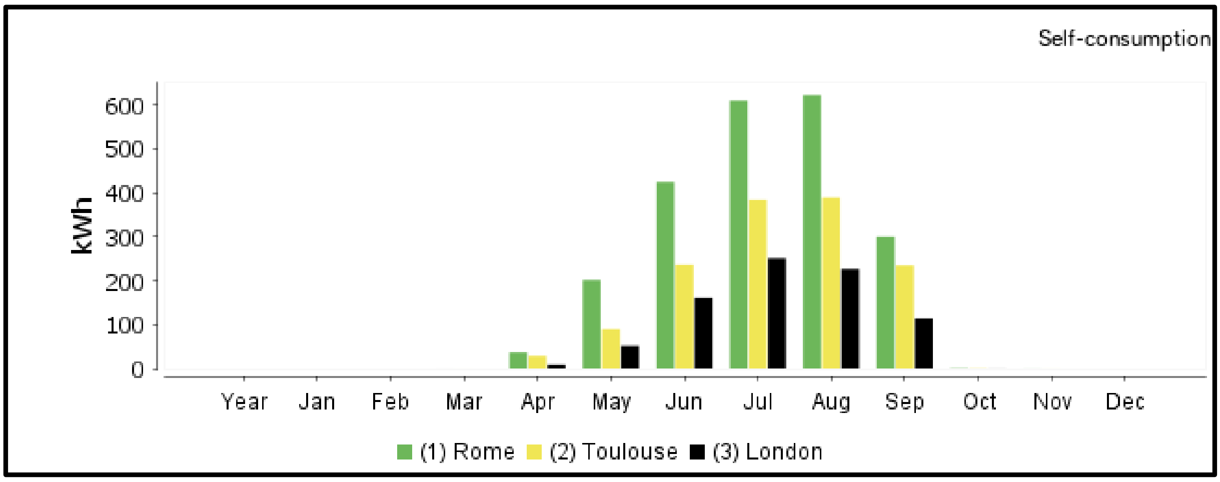

Figure 5.34: Self-consumption of the system.

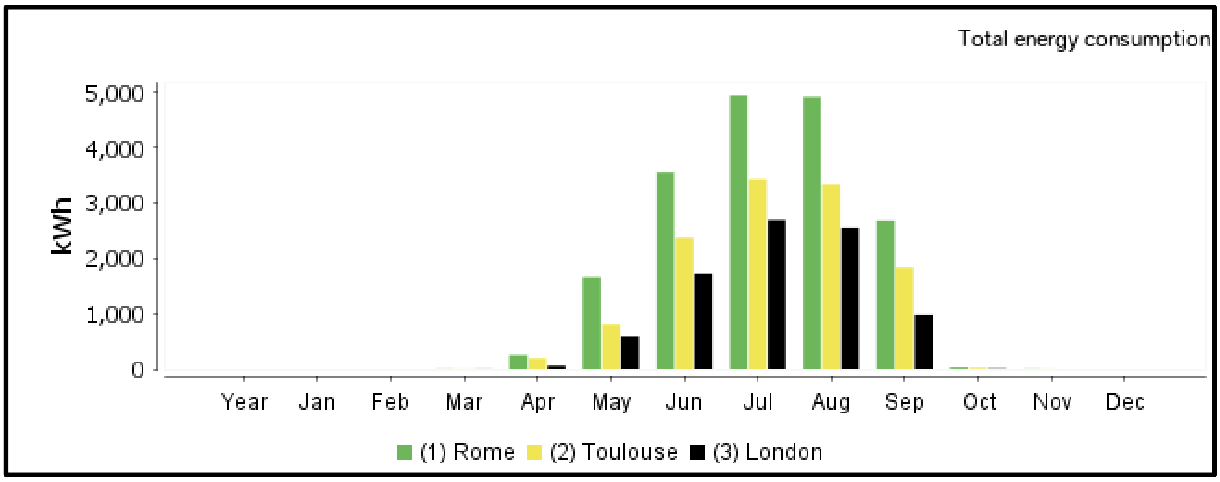

Figure 5.35: Total energy consumption of the system.

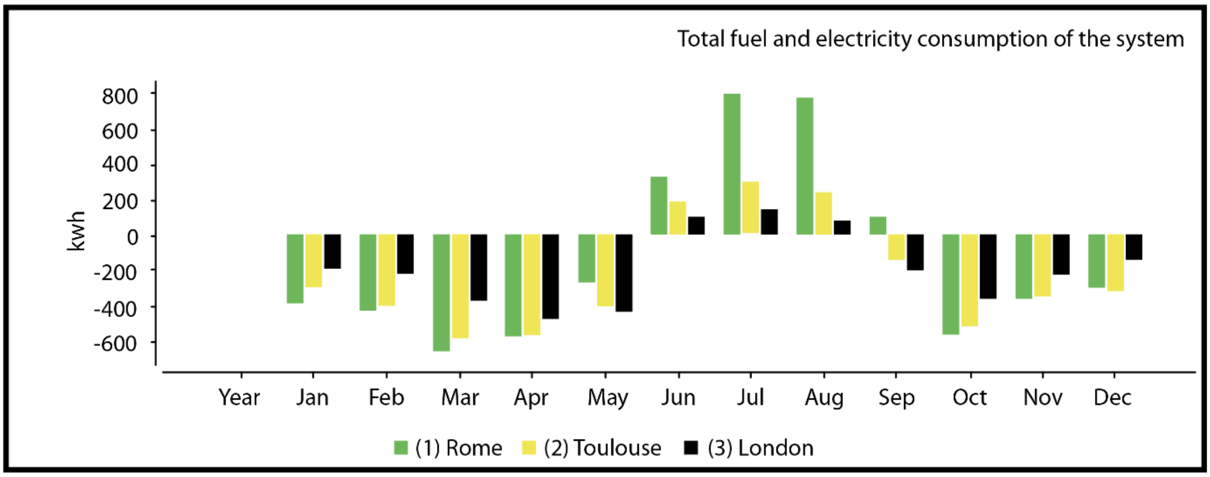

Figure 5.36: Total fuel and electricity consumption of the system.

The electric consumption of the system represents the total amount of heating and cooling energy production and the electricity needed for the system. Figure 5.36 shows that the total fuel and electricality consumption of the system in non-cooling season is negative. This implies that the net solar photovoltaic gain is negative because the total electricity consumption of the system outweighs the photovoltaic gains since the auxiliary heating system operates more. In the summer months, the total photovoltaic solar gain is positive because the electricity consumption of auxiliary heating and other system component is less domineering. Therefore, there is enough electricity required to power the system consumption via the solar photovoltaic system. This means the auxiliary heating system operates less during this period. On account of higher outdoor heat gains and interior loads – this system will give the room temperature a chance to rise out of the range of comfort which might aggravate the circumstance in a wet climate. The extent of the total energy demand covered through solar air-conditioning in Rome and Toulouse is higher than in London. This is because the photovoltaic electricity production well complements the yearly electricity demand and subsequently, there is a system lesser off-time considering constraints of freezing. In any case, a prolonged and incessant cold production prompts the overheating of an outdoor unit which, in turn, enables high outdoor temperature that increases the temperature of the outdoor unit which subsequently makes the cooling performance turnout to be more hostile.

In the temperate hot and cold regions of Rome and London, a little cooling power shortage will occur, and the temperature of the room will surpass the set point. The increase in the system power will reduce the peak of room temperature since the system operation time at nominal load occurs. In Toulouse and Rome, the distinction in a span of cooling seasons is similar. The outdoor temperature below extreme freezing temperature in winter may be enduring. In London, heat generation and DHW are in a smaller amount than in the climatic locale that is hot. These instances unfold that the system innovation components, such as the carriers of heat and cooling may be supplanted. Also, the components are to work at lesser temperatures, and this will be progressively coherent in a non-cooling season for accessibility of photovoltaic electricity utilisation at the operation of the system in London climate conditions. Therefore, a higher power of heating is required in temperate cold climatic areas. The low temperature of the outdoor is proposed to enhance the performance of the system.

In the light of this, the proposed optimised system offers to reduce the level of energy consumption and rates of carbon emissions which, in turn, combat global warming and climate change. Furthermore, the simulation of the system indoor temperature and IAQ utilising smart control technique is unfolded in the following sections of this chapter.

5.3 Simulation of Fuzzy Proportional Integral Derivative Controller

The simulation examination is performed in this section to study the performance of fuzzy PID for temperature control of the photovoltaic solar air-conditioning. Albeit the fuzzy logic is grounded upon the controller of PID which is designed basically for indoor temperature and the control of IAQ for the proposed system. Consequently, control of fuzzy PID is planned to resolve difficulties stated in explorations and to attain the purpose of sustaining the anticipated temperature of the indoor air. The design structure was deliberated upon in chapter four. This possesses two key portions: a PID control for indoor air temperature control and the controller of fuzzy logic for modifying PID controller parameters in line with the existing indoor situations. Hypothetically, the indoor environment analysis presented in the preceding chapter exhibited that, the projected fuzzy PID controller possesses the subsequent possibilities:

- selection of better parameters of PID can guarantee the required output of the system;
- ensuring that the controller of PID is appropriate for the control object;
- the control of fuzzy logic for optimal parameters of PID regulation to guarantee compliance with diverse conditions.

For the reason to evaluate and discuss the anticipated design of the indoor environment control in this section, the tests requiring simulation are carried out through the Matlab program. Likewise, the results of the simulation are utilised to specify the performance of the controller which is grounded upon some indexes such as adaptability, stability, time constant, response speed and time delay. Subsequently, if the projected controller can attain the selected requirement of the temperature control of the IAE, then it is deliberated upon the controller's execution on the indexes above. In the simulating test, the function constituting the object control stated via equation 4.16 is utilised.

$$\frac{T_i(s)}{Q_h(s)} = \frac{0.0527}{3373.42.s + 1} \qquad 5.1$$

5.3.1 Utilisation of Step Input Test

Accordingly, the temperature of the indoors is controlled through the heater in the air source network. Through the wall, it is correlated to heat loss and the heater's energy work. In this study, a smart/intelligent PID controller which is grounded upon the controller of fuzzy logic is projected for the control of the temperature of the indoor air. The designed controller is built upon the indoor environment model that is fundamentally deliberated in chapter four of this study. All through the process simulation, the change in indoor temperature transfer function as specified via equation 4.16 is utilised for precisely assessing the controller's execution. Through utilising the Matlab program, the simulating test is performed as offered in Appendix C – the program control code.

Nevertheless, the underlying indoor environment temperature of the structure is assumed to be unbearable, and it is required to be transformed. At that point, the ideal temperature is established, and the controller begins attempting to transmit the temperature of the indoor environment to the ideal level. To simulate this procedure, the step signal can be utilised. Consequently, a step signal is utilised as the input reference to test the projected controller's execution. Likewise, it is expected that the temperature contrast between the temperature of outdoor and indoor is 5°C. Therefore, the step signal (r (k)=5) is presented when the time equals zero. The system output control simulation is displayed in Figure 5.37. It demonstrates that, t_s is 34.8s (settling time), τ is 9.4s (time constant), and the control rapidly replies to the input signal with a quickly rising rate as appeared in Figure 5.37. There is no overshot in this control procedure other than the quick response speed. Moreover, the steady error state is 1.5 when the control procedure settles. This implies that the anticipated control is suitable for stability, control accuracy, avoiding overshoot and having a fast response speed.

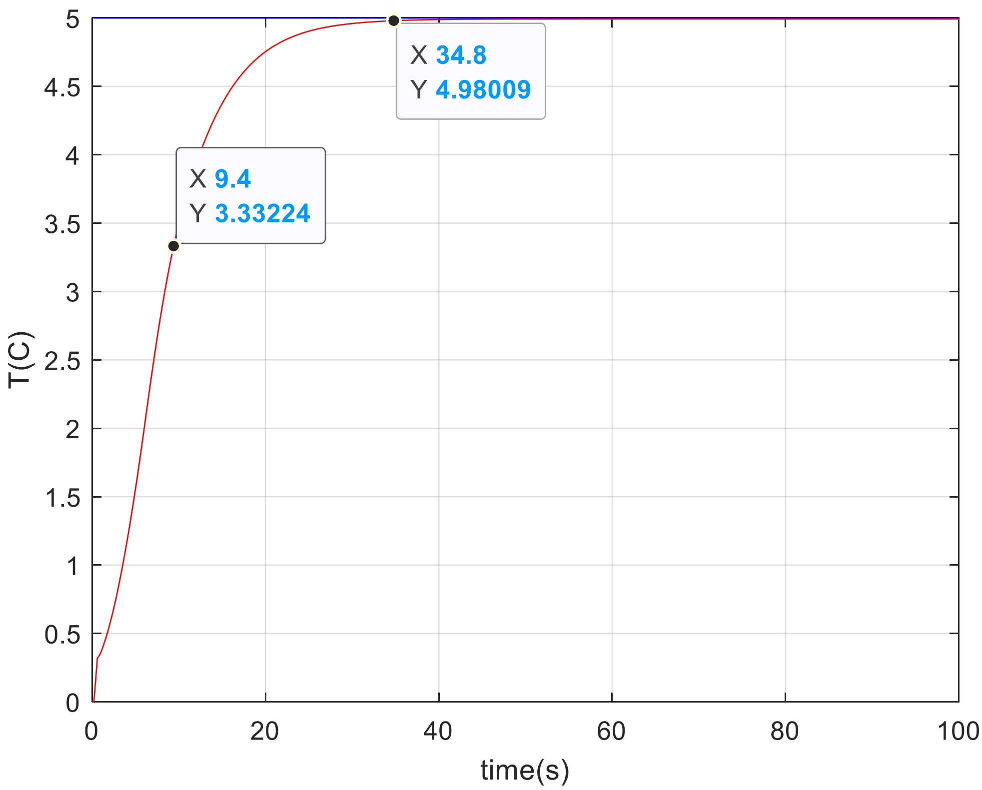

Figure 5.37: Response output to step input of the system.

Accordingly, the PID controller response output to the step signal input is offered in Figure 5.38. The regulator calculated the output, which is the command control for the plant (the command is directed to the apparatus and transform the quality of the indoor environment temperature). Subsequently, the system readily adjusts, grounded upon the regulator's output. In Figure 5.37, the system yield can be noticed. The PID control yield is utilised to guarantee the system output, progressing at the start of the process control, vis-à-vis close to the value of the set-point while evading overshot. The steady-state error is 1.5. The integral in PID is used to eliminate steady state error. As a result of the system being in the steady-state, the PID yield settles at 1.5. The settling time is the time in which the output of the controller settles at reference. The turn on and turn off time of the actuator are added to the controller settling time. Usually, complex devices have a small switching time in microseconds, but this can be adjusted based on preference.

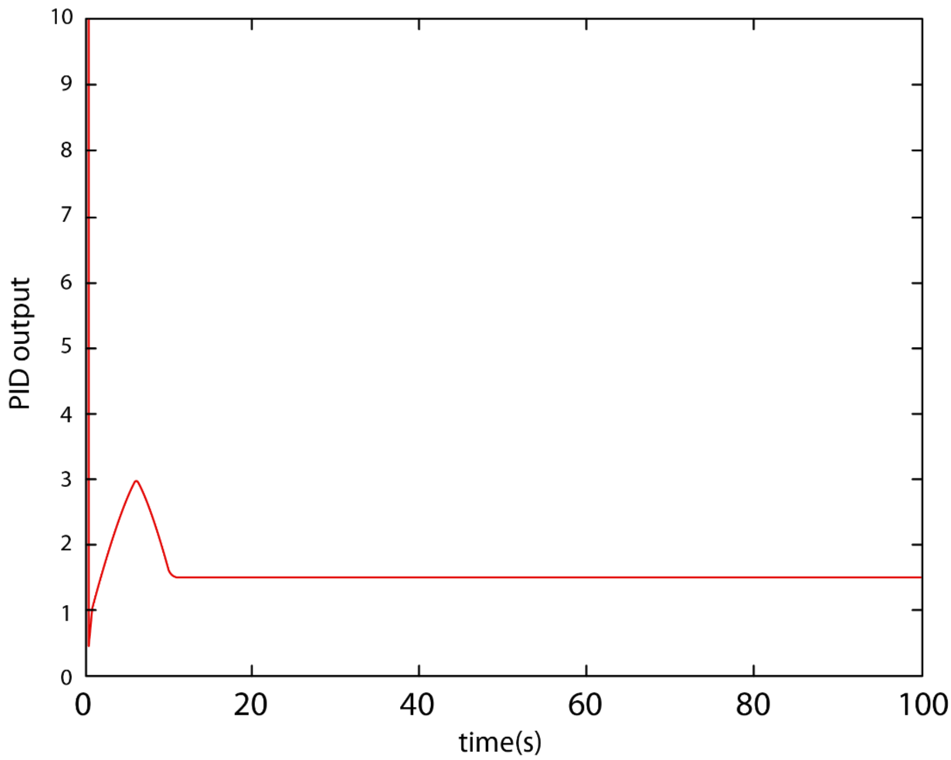

Figure 5.38: Response output to step input of PID.

In Figure 5.39, the process auto-regulating of k_p, k_i and k_d, which are the parameters of the PID controller can be systematically noticed over some time. As a result of the rules of FLC that are presented in Appendix C and designed in Matlab code, the parameters of the PID are tuned, and their values are kept changing to guarantee that the system yield transforms accurately and fast. At last, the values of the PID parameters are resolved, and the parameters demonstrate that k_i is 0.02, k_d is 2 and k_p is 0.2. As revealed in Figure 5.37, the system yield is resolved at the set-point having a state that is steady and stable. The outcome demonstrates that contrasting the standard PID controller, the fuzzy PID control can keep changing the parameters of PID control to improve the performance control.

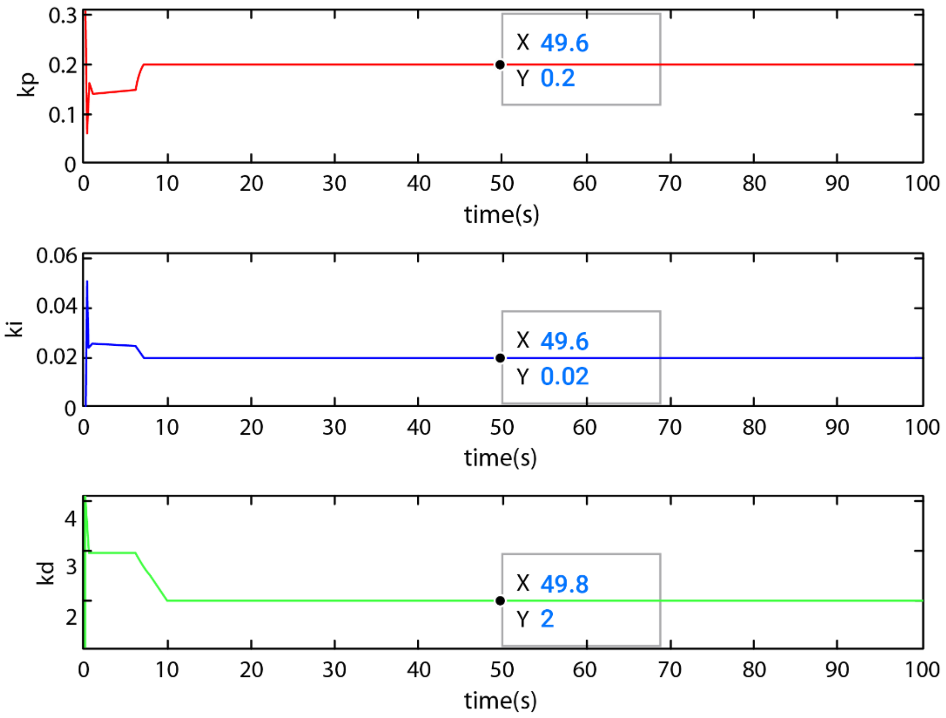

Figure 5.39: Parameters of PID auto tuning.

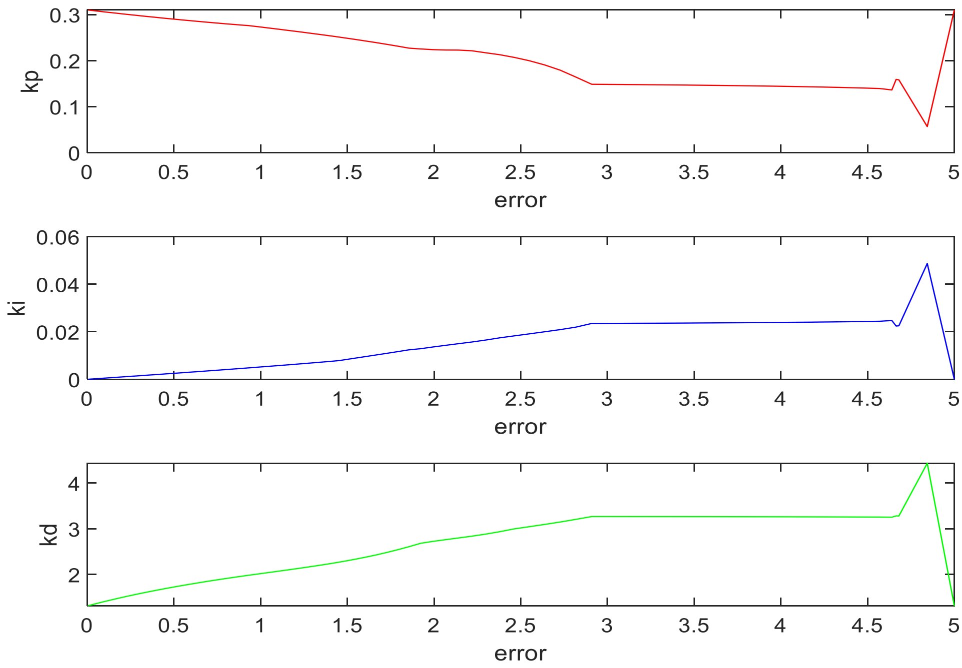

Figure 5.40: Parameters of PID changing based on e.

Consequently, Table 4.7 – Table 4.9 offered the base rule matrixes in chapter four through which the parameters of k_p, k_i and k_d will transform Δk_p, Δk_i and Δk_d when *e* and *ec* differs. In Figure 4.17 – Figure 4.21, the *e, ec,* k_p, k_i and k_d, which are the membership functions, are systematically offered. That is to say, the parameters of the PID are controlled as a result of these variables as presented in Figure 5.40 and Figure 5.41 – the change of output system error (*ec*) and output system error (*e*). Also, Figure 5.41 disclose that one *ec* value may sometimes constitute numerous parameters of PID. This unfolds that the inappropriate parameters of the PID can be formed should solitary input be employed for the fuzzy rule. By having variables of two inputs, the algorithm of FLC can calculate and subsequently offer the improved parameters of k_p, k_i and k_d for the highest degree of performance control.

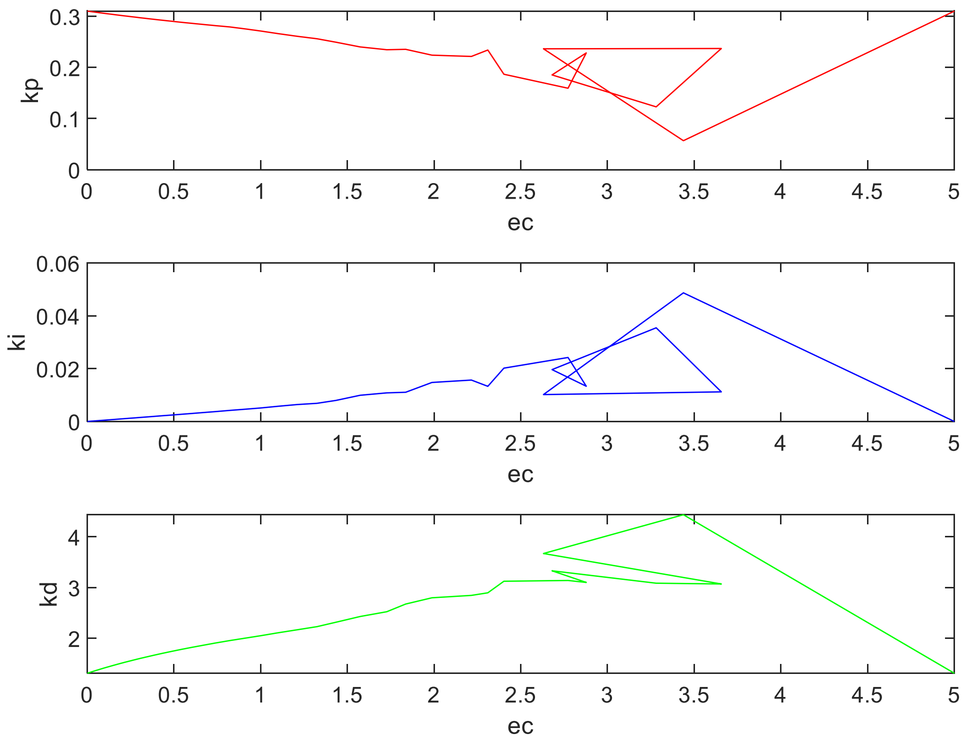

Figure 5.41: Parameters of PID changing based on ec.

5.3.2 Control Execution of Fuzzy-PID

Accordingly, the simulation of the mathematical model for the temperature control of the indoor environment transformation is accomplished to be the fuzzy PID control execution, and the attained test is grounded upon the signal of step input. As revealed from simulations, the FLC method can offer appropriate parameters for the controller of PID, and the selected system yield can be realised. As a result, the anticipated regulator possesses appropriate execution on stability with no error of steadiness and having no overshoot. It also possesses fast speed response and competent auto-tuning of the parameters of PID once required.

Consequently, the advantages brand the projected controller is appropriate for regulating the temperature of the IAE and proficient to resolve the control of indoor environment temperature problems. Therefore, the anticipated fuzzy PID control approach for the photovoltaic solar air-conditioning possesses the appropriate control execution for the temperature of IAE.

5.4 Simulation of Backpropagation Neural Network PID Controller

To attain and sustain the appropriate level of IAQ (CO_2), backpropagation NN which is based upon PID is designed in this study. The anticipated backpropagation NN which is based upon the PID controller integrates the PID controller and a NN which is, in turn, applied to the algorithm of backpropagation. The design structure was fundamentally discussed in chapter four. This controller structure comprises two key portions which are the PID control for IAQ and backpropagation NN for adjusting the PID controller parameters as stated by the existing conditions of the indoor environment. The IAQ can be well-controlled grounded upon the theoretical dialogue of the algorithm of the backpropagation NN which is based upon a PID controller that possesses the subsequent capacities:

- NNs for ideal parameters of PID regulation to guarantee rapid disturbance recovery;
- algorithm of backpropagation for weights adjustment in NN to guarantee the system rapidly responds to changes in the indoor environment;
- PID controller is appropriate for several object control as well as IAQ.

For the purpose to evaluate and discuss the proposed design of indoor environment control, the simulations are carried out in this section by means of utilising the Matlab code revealed in Appendix D. Likewise, the results of the simulation are employed to designate the performance of the controller grounded upon some indexes such as the adaptability, stability, time constant, overshot and speed response. Subsequently, if the projected regulator can attain the selected control of the IAQ environment obligation, then it is grounded upon the controller's performance on the indexes mentioned. Therefore, simulating tests are applied towards conduct and the outcomes are examined to discuss the presentation together with the anticipated control approach in the IAQ regulator. The precise modelling of the actual control object all through the simulation is the CO_2 concentration in an observed indoor environment. The transfer function for the control of IAQ is presented in chapter four, however, minor alteration is done to the theoretical transfer function to make it further precise to the actual indoor environment. The z-transform of the s-domain transfer function is taken in chapter four. $y(z)$ is the output which is the indoor CO_2 and is used as the transfer function:

$$y(z) = \frac{(1/V_i)z}{z - \exp(-1/T_{ico_2})}\ a(z) \tag{5.2}$$

For $a(z)$ is continuously changing time parameter and specified by $a(z)=1.4(1-0.9e^{-0.3z})$.

The principle alteration is to improve a time changing parameter characterised to the transformation of the CO_2 concentration of the indoor environment, vis-à-vis to the parameters that are unpredictable and uncertain. For instance, doors opening as a result of individuals leaving or entering the room can perhaps originate system disturbance.

5.4.1 Utilisation of Step Input Test

Accordingly, simulation is carried out through the step signal. Following numerous tests and setting the superlative preliminary factor of momentum and rate of learning. The α is 0.04 and η is 0.28. Also, the NN weights are set in the array [–0.5, 0.5] arbitrarily. The arbitrarily predetermined weights possibly will originate a slightly unbalanced control process; nonetheless, the algorithm of back-propagation is competent to rapidly answer indeterminate parameters and the NN weights are updated in a comparatively quick period to guarantee the selected yield.

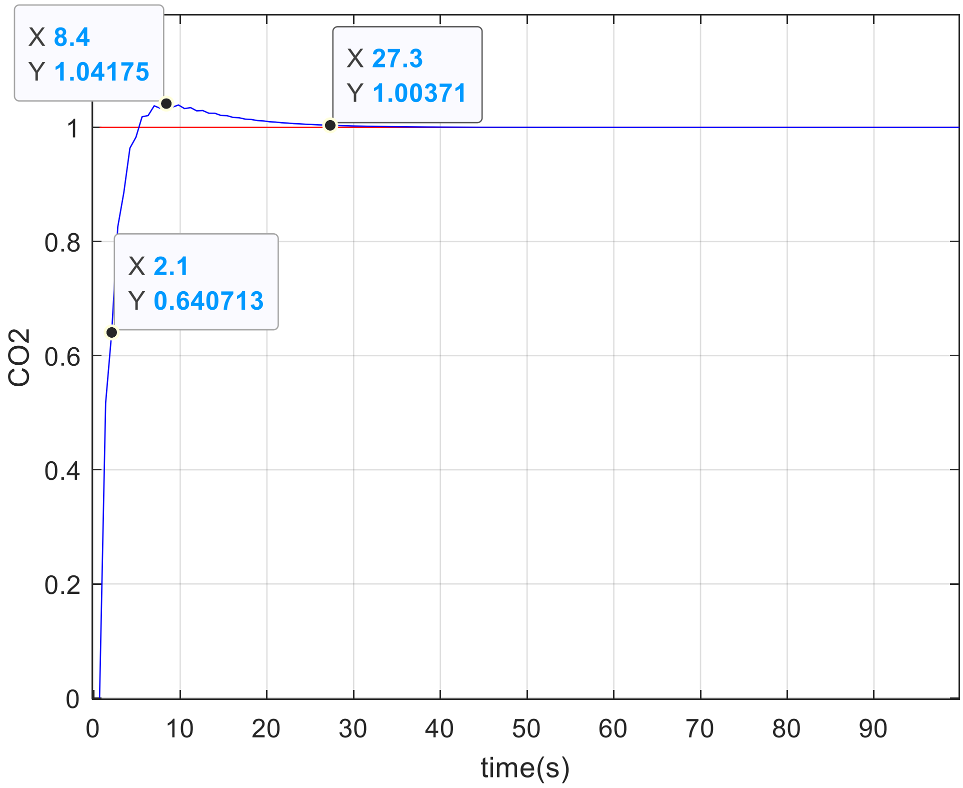

Figure 5.42: Response output to step input of the system.

At the time zero, the step signal represented as ($r(k)$=1) is presented. In Figure 5.42, the recommended control system output result of the simulation is offered. Also, the system appears to possess speedy increase together with an insignificant overshot as revealed in Figure 5.42. It demonstrates that t_s is 27.3s (settling time), τ is 2.1s (constant time) and σ is 4% (overshot maximum percentage). The unpredictability may be produced through arbitrarily predetermined NN weight values vis-à-vis, not possessing a substantial concerned control process basically at the response commencement, as the curve is speedily rising. Even though the overshot is still minute, it is fundamentally withdrawn to the set-point – 4% in the simulation test and the process of control is taken back to the definite steady-state as revealed in the profile with steady error. However, the error is steady because the function of the control object is calculated and grounded upon a perfect model of the indoor environment. Thus, the error of the system usually occurs in the control procedure.

The output response of the PID controller to the input step signal is offered in Figure 5.43. The regulator calculated the yield (control command) for the system (command is conveyed to the device and transformed into the IAQ). Therefore, in Figure 5.42, the results of the system output demonstrate that the controller is competent to attain the mandatory yield to guarantee a high-quality execution on control accuracy and speed.

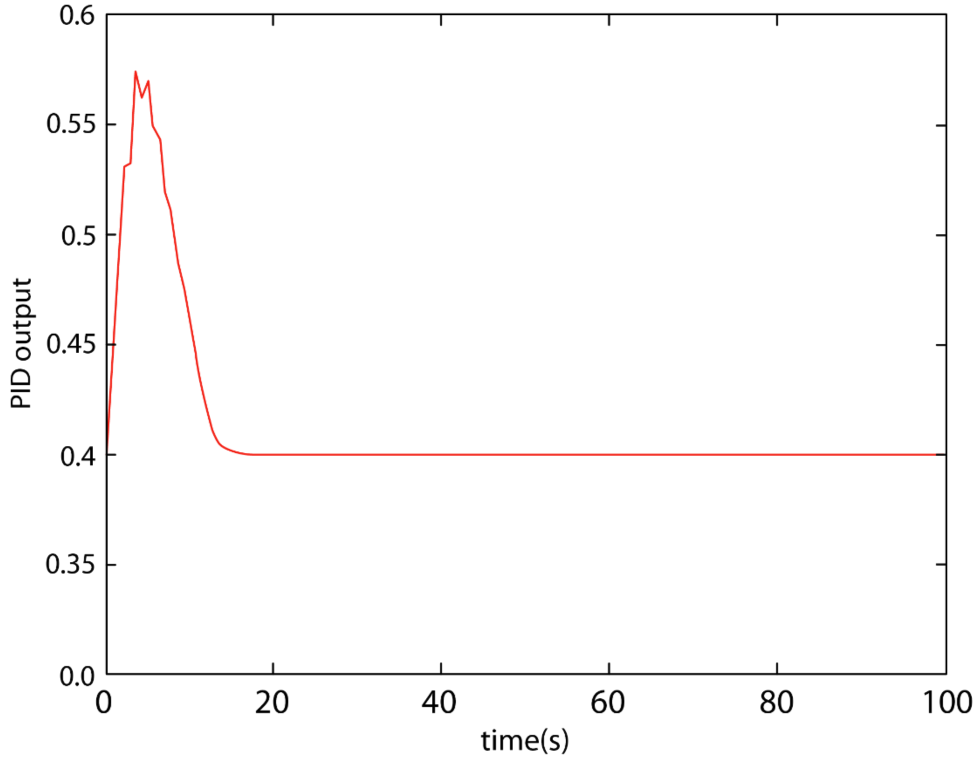

Figure 5.43: Response output to step input of PID.

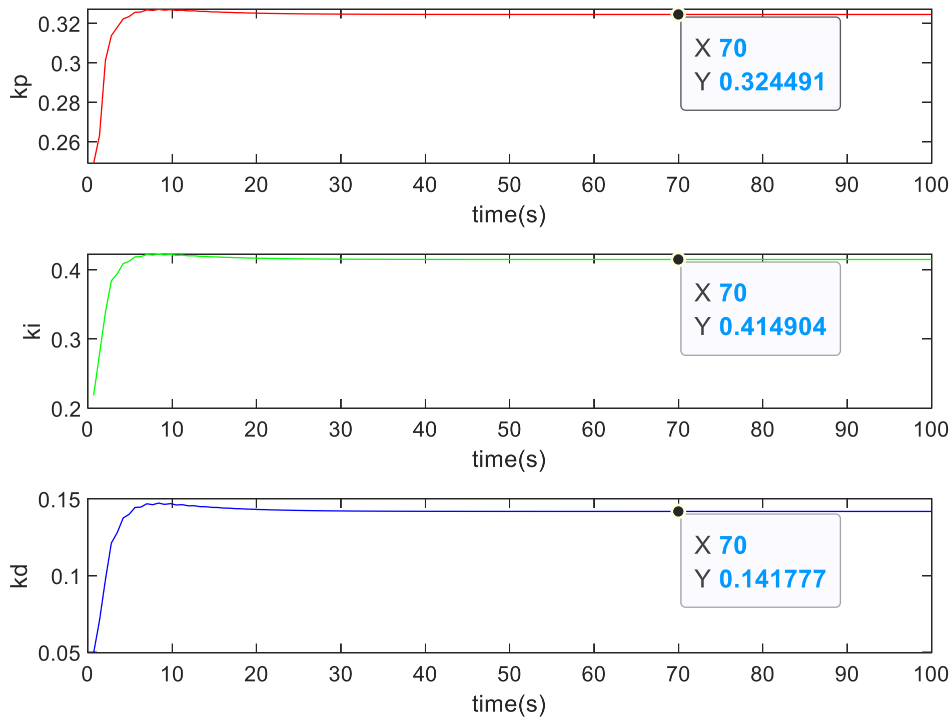

Figure 5.44: Parameters of PID auto-regulating.

In Figure 5.44, the k_p, k_i and k_d parameters of the PID auto-tuning process can be seen, and the parameters of PID are modified via the NN all through the process of control. Also, the results of the system yield show appropriate control execution. As a result, this illustrates that suitable parameter of PID can be attained using the algorithm online training which is grounded upon the control structure of NN. Likewise, the parameters of PID control value kept regulating to enhance the system control execution until it arrives at a state of steadiness. The parameters demonstrate that, k_p is 0.32, k_i is 0.41 and k_d is 0.14, and they remain steady when the system arrives at the state of steadiness The association between the parameters of the PID and the system error is given in Figure 5.45.

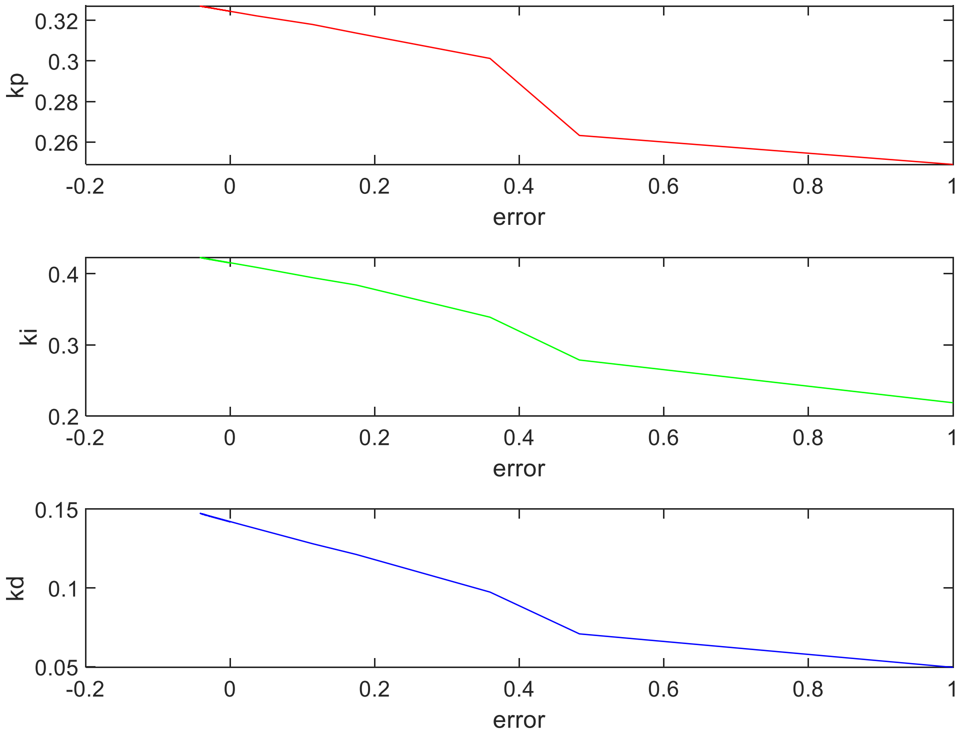

Figure 5.45: Association amongst parameters of PID and the system error.

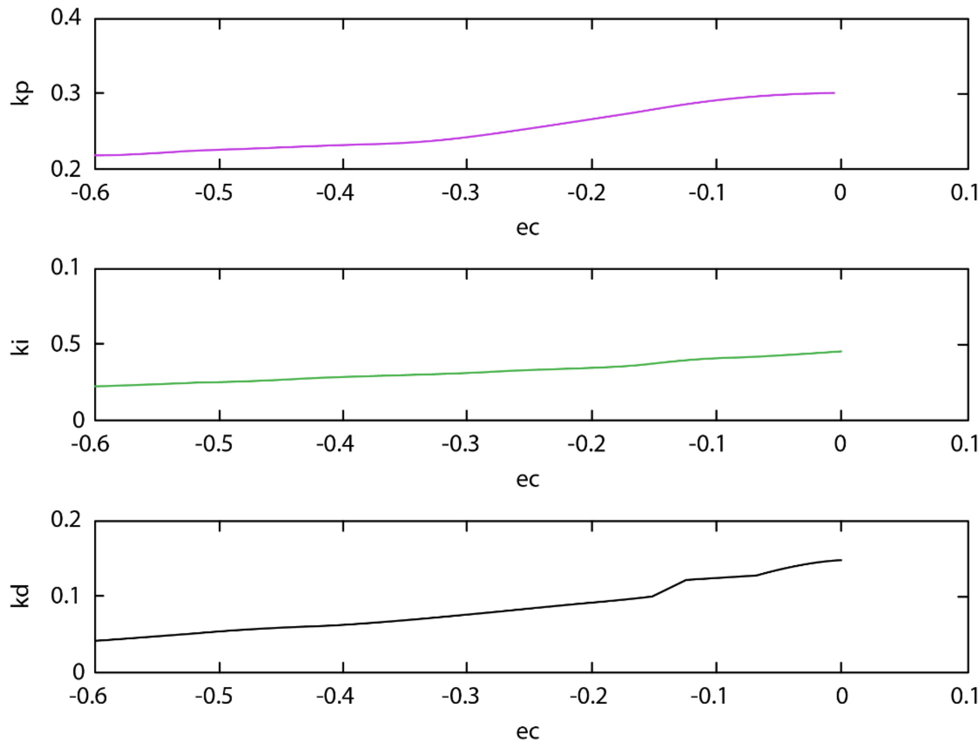

Figure 5.46: Parameters of PID response to ec.

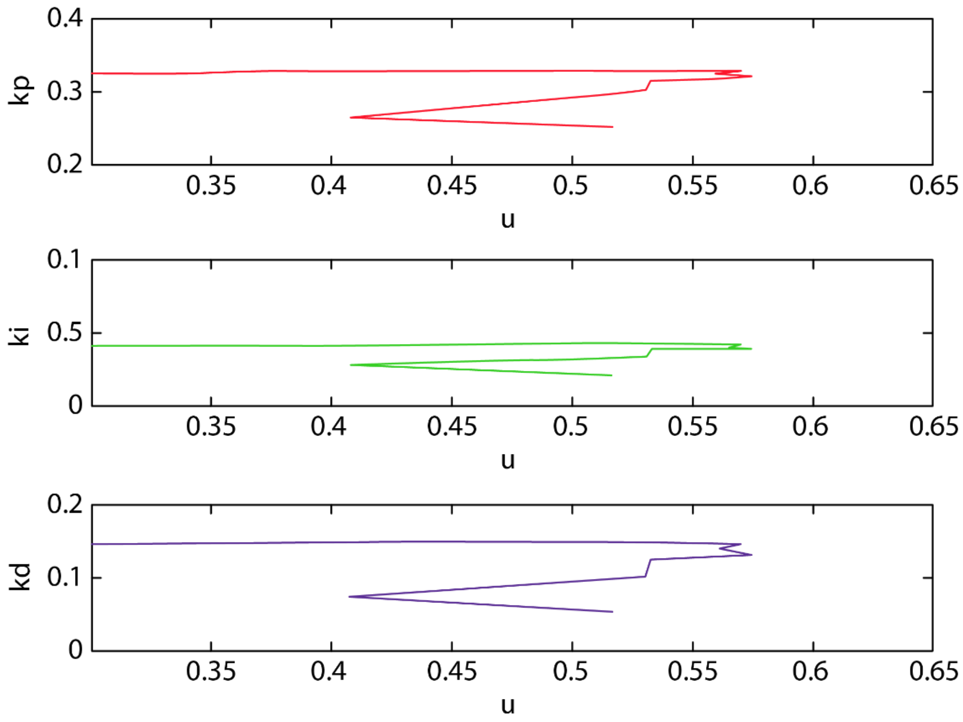

Figure 5.47: Parameters of PID response to PID output.

Subsequently, the parameters of the PID are controlled based upon the following variables namely, system output, PID controller error output, change of system error output and the system error output. Figure 5.46 and Figure 5.47 show that a single *ec* value or *u* value can sometimes signify more parameters of PID. This reveals that the incorrect parameters of the PID can be formed should one input is utilised to the NN. The NN weights are trained in the control process via the weights of backpropagation rule adjustment for the reason to acquire the optimum PID parameters for the controller of PID. It is shown using the simulating tests that the method of backpropagation can offer appropriate parameters for the controller of PID, and the chosen system yield can be accomplished. Therefore, the backpropagation NN algorithm design can calculate and then offer an optimised control performance of the k_p, k_i and k_d parameters.

5.4.2 Control Execution of Backpropagation Neural Network PID

Changing model of the indoor CO_2 concentration simulation is performed for the reason to appraise the control performance of backpropagation NN-PID. Therefore, dual input reference namely, sine and step signal are utilised in the process of control. For it is revealed using the simulating tests that the method of backpropagation can offer appropriate parameters for the controller of PID and then, the chosen system yield can be accomplished. As a result, the recommended controller possesses appropriate execution on tuning parameters of PID with adaptability and stability, managing with the time changing parameter, small steady error, small overshot, settling speed and speedy rising.

In addition, the advantages brand the projected controller appropriate for regulating IAQ and proficient to resolve the key indoor CO_2 control difficulties as well as disturbances, time delay, and mismeasurement existence. For instance, further individuals unexpectedly arrive at the indoor environment, meanwhile, CO_2 is extremely responsive to the level of habitation. Therefore, the projected backpropagation NN-PID control approach ascertained the suitable control execution for the IAQ environment.

5.5 Conclusion

In conclusion, simulations are executed to analyse the proposed photovoltaic solar air-conditioning and the smart indoor controllers (fuzzy PID controller for indoor temperature and backpropagation NN grounded upon PID controller for IAQ control). The results of the simulations are deliberated upon to evaluate the photovoltaic solar air-conditioning and the system controllers' executions on the indexes together with a time constant, overshot, stability and response speed. Additionally, the controller design potential for controlling indoor environment quality is deliberated which is grounded upon the results of the simulations.

In line with the basis of conceptual modelling in the previous chapter, the components of the system are simulated in the Polysun software, and the results revealed that the system could provide the required yearly energy yield without compromise. Consequently, the simulation results of photovoltaic solar air-conditioning uncover the importance of using renewable as a source of clean energy in air-conditioning systems and the particular contribution it makes to the level of energy consumption and carbon emissions. The system significantly demonstrates the importance of using solar energy as an alternative to fossil fuel to power air-conditioning systems, vis-à-vis combatting global warming and climate change, and hereby promoting sustainable development.

For the projected fuzzy PID controller, the input and step signal are fundamentally applied as the reference control. The outcomes demonstrated that the projected controller possesses appropriate execution on well-organised auto-tuning of the parameters of PID exclusively once required. This remains essentially because of the adaptability, stability, small steady error, small overshot and speedy response to indeterminate influences. In short, the anticipated smart temperature regulator can possess appropriate execution on controlling indoor temperature since the indoor environment temperature can be effectively regulated through the PID controller. Likewise, the parameters of the PID auto-tuning can guarantee improved PID control execution and then, the parameters of the PID rule are grounded upon the fuzzy logic rule which guarantees flexibility to various circumstances in temperature control procedure to guarantee steadiness. As a matter of fact, these advantages brand the projected controller appropriate for resolving the key problems in controlling the indoor environment temperature.

Accordingly, the indoor CO_2 concentration simulation changing model is accomplished in this study to designate the performance of backpropagation NN-PID control. Likewise, it is revealed using simulations that the backpropagation NN method can offer appropriate PID parameters and in turn, enables the selected system output to be attained. As a result, the projected controller possesses suitable control execution in terms of adaptability, stability, management with the time changing parameter, small steady error, small overshot, settling speed, speedy rising and online training of the regulator as requested. Consequently, these brands are the projected controller appropriate for IAQ control and proficient to solve the main difficulties of indoor environment CO_2 as deliberated upon in chapter four. Meanwhile, the deliberation of the execution indexes demonstrated that the PID controller is fundamentally appropriate for numerous control items as well as the IAQ. Likewise, the NNs are suitable for ideal parameters of PID controller tuning that guaranteed the controller’s steadiness, whereas the back-propagation algorithm is also appropriate for weights adjustments in NN which, in turn, guarantees that the system speedily respond to indoor environment transformation.

Therefore, the photovoltaic solar air-conditioning and the indoor smart environment (fuzzy PID controller and backpropagation NN-PID) presented the strong sustainability of the overall system – the social sustainability of the wellbeing and comfort of inhabitants which is, in turn, technically influenced by the environmental sustainability of the system. As a result, there is development, steadiness and productivity of the system for greener solutions to the world's energy requirements. The next chapter of this study assesses the economic impact of the photovoltaic solar air-conditioning system by way of revealing the financial profitability (NPV, IRR, ARR and the payback period) of the system.

Chapter Six

6.0 The System Economic Assessment

6.1 Introduction

This chapter unfolds the economic assessment of the photovoltaic solar air-conditioning. The analysis of the system in the previous chapter demonstrated appropriate functionality with maximum predictability and stability. Also, the analysis outcome in chapter five established that solar air-conditioning can cover the proposed cooling demand through the system's sufficiency of electricity consumption. The proposed system exhibits appropriate feasibility measures through producing sufficiency of electricity while reducing the rate of energy consumption and carbon emissions, which can tackle climate change. This study subsequently revealed the economic dynamics of the system, which is the financial profitability of the photovoltaic solar air-conditioning via analysing and calculating the ARR, NPV, payback period and the IRR of the proposed system. Also, the advantages and drawbacks of each financial assessment indicator are subsequently considered for proper assessment of the system.

6.2 Concept of Profitability

The meaning of profitability is the capability to create profit from the entire business pursuits of a firm, company, enterprise, organisation or system. It demonstrates by what means the productivity of the administration may produce profit through utilising the entire possessions accessible in the marketplace. A research study by Harward and Upton (1961), suggested that productivity or efficiency is the capability of a specified asset to make a return as a result of its utilisation.

Nevertheless, the expression represented as 'Efficiency' is not tantamount to the expression characterised as 'Profitability'. Profitability is an efficiency index; and is subsequently viewed as an efficiency measure and administration leads to better efficiency. Albeit profitability is a vital standard for determining efficiency, the profitability extent is unable to be confiscated as a concluding efficiency proof. Occasionally, acceptable profits can symbolise inefficiency and on the contrary, a suitable efficiency degree can go together with profit absence. Also, the figure of the net profit discloses an acceptable steadiness amongst the received values and given values. Although, operational productivity change is among the influences upon which an enterprise's profitability mainly relies. Hence, it can be presumed that profit is not fundamentally the key mutable upon which the foundation of an organisation's financial and operational productivity may be equated. For the reason to quantify the efficiency of assets utilised and to quantify the efficiency of operation, the analysis of profitability is contemplated as one of the best methods.

6.3 Profit and Profitability

From time to time, the expression represented as 'Profitability' and 'Profit' is interchangeably utilised. However, there is a dissimilarity between the two. Profitability is a comparative notion while profit is a complete word. Albeit both are meticulously connected and equally symbiotic, possessing different business roles. Profitability alludes to the venture efficiency of operation, whereas profit alludes to the entire revenue produced via the venture all through the stated time. For a venture can produce a profit on sales and to acquire adequate profit on the investment and personnel utilised in the operation of the business.

The research study by Weston and Brigham (1979) accurately stated, "To the financial management profit is the test of efficiency and a measure of control, to the owners a measure of the worth of their investment, to the creditors the margin of safety, to the government a measure of taxable capacity and a basis of legislative action and the country profit is an index of economic progress, national income generated and the rise in the standard of living", whereas profitability is the profit result and that is to say, no profit operates in the direction of profitability. Organisations possessing profit of equivalent quantity may differ in standings of profitability. For this reason, a research study by Kulshrestha (2015) has accurately specified that "Profit in two separate business concerns may be identical, yet, many a time, it usually happens that their profitability varies when measured in terms of size of the investment".

6.4 Analysis of Profitability

Discretely from the long-term and short-term creditors, management and owners likewise amuse in the reliability of the solar air-conditioning which can be sustained through profitability assessment. The profitability assessment is basically of two categories. The ones depicting profitability in connection to investment and the ones exhibiting profitability in connection to sales. In conjunction, both assessments designate the system's total operation effectiveness. For the reason to appraise the profitability of the proposed system, the analysis is carried out from the point of view of the management/owner of the system. The management/owner of the proposed system is certainly enthusiastic to measure the photovoltaic solar air-conditioning efficiency of operation. Correspondingly, the owners capitalise their resources in the anticipation of sensible yields. The capacity of the proposed solar system for the reference location is 6917.60 kWh as provided in Chapter 5. The photovoltaic solar air-conditioning operating efficiency and its capability to guarantee satisfactory yields rely eventually upon the profits produced through the system. In this study, the following assumptions have been considered for solar-air conditioning installation:

- The efficiency of the photovoltaic system reduces by 0.5% annually (Abu-Bakar et al. 2013).
- The maintenance cost increases by 3% annually (Cherrington et al. 2013).
- The system yearly inflation rate is 4% with a discount rate of 5% (Energy Saving Trust, 2021).

A research study by Kulshrestha (2015) suggested that the cost of the system installation is determined according to the following grounds:

- the equipment costs which are ascertained through its category;
- costs are contingent upon the specific place and the category of building involved;
- it also relies upon the level of salary in the engineering domains in the specific environment.

In this study, all values are calculated in pound sterling for accuracy and consistency in the assessment of financial profitability. Consequently, the costs of maintenance specified consist of the system adjustment and periodical check. 20 years is the lifespan of the system components as specified by the manufacturer. According to Eco Climate Solutions (2021), the maintenance cost for the proposed system having an auxiliary heat pump is £100 with 3% annual increase, while the system installation cost is £1612. The annual feed-in-tariff and the export tariff for the photovoltaic system are 14.90p/unit and 4.64p/unit, respectively, while having a guaranteed 20-year tariff lifetime (Abu-Bakar et al. 2014).

Table 6.1 reveals the capital cost for the system. This study presents the current market price of the proposed system. The bespoke cost of the photovoltaic modules is provided by Solar World (2021). A bespoke price is likewise provided by Hotspot Energy (2021) for the solar air-conditioning components and the auxiliary heat pump of the system. Therefore, the capital cost values presented in Table 6.1 are per the corresponding system capacities adapted for modelling and simulation in Chapter 4 and Chapter 5, respectively. The standard manufacturers' specifications are provided in Appendix E.

Table 6.1: Capital cost of the proposed photovoltaic solar air-conditioning

Description	Price in Pound Sterling £	References
Photovoltaic unit	2158.00	Solar World, (2021)
Inverter	891.02	Hotspot Energy, (2021)
Photovoltaic installation frame	231.30	Solar World, (2021)
Cold circulation	590.00	Hotspot Energy, (2021)
Auxiliary heat pump	1577.00	Hotspot Energy, (2021)
Hot water storage	848.18	Hotspot Energy, (2021)
Cold storage	419.81	Hotspot Energy, (2021)

Outdoor unit	616.84	Hotspot Energy, (2021)
Pipes	219.00	Hotspot Energy, (2021)
Pump, cold side	Added with auxiliary heat pump	Hotspot Energy, (2021)
Pump, hot side	Added with auxiliary heat pump	Hotspot Energy, (2021)
Brine	184.20	Hotspot Energy, (2021)
Total	**7735.35**	-

The profitability of the proposed system has been carried out by means of calculating the ARR, payback period, NPV and the IRR as discussed and analysed in the following subsections.

6.4.1 Accounting Rate of Return

Exploration of the ARR began with Harcourt (1965), Solomon (1966), and continued with work by Kay (1976, 1978), Peasnell (1982), Kay and Edwards (1986), Edwards et al. (1992), Brief (1996: 1999), Al-Ani (2015) and others. The key purpose was also to study the connection between the IRR and the ARR or to practice the valuation process of ARR. For the elementary framework was given in both cases through an economic model and the model of accounting was subsequently suitable in the context of economic procedures.

The ARR strategy for investment of capital evaluation seems to go under various appearances, with a large number of definitions utilised as the reason for its estimation (Brief. 1996: 1999). Studies by Magni and Peasnell (2012) and Al-Ani (2015) suggested that there is no solitary acknowledged calculation for the ARR, and there is impressive perplexity in the professional and academic literature with respect to which technique for calculation requires to be received. Thus, the board may choose either of the formulae that suits them most. Reference is formed to the ARR without offering an exact definition to its meaning or calculation. Correlations are formed on the fundamental suspicion that; one is contrasting similar with similar. This, as a rule, is a bogus presumption. Although differentiation is formed between the ARR dependent upon average investment and initial investment, there is no commonly acknowledged premise figures calculation to be utilised for whichever interest in or the return received from a project. The ARR is as well usually alluded to as the Return on Investment (ROI), Return on Capital Employed (ROCE) and Average Rate of Return (ARR). It is likewise recognised as the simple rate of return, unadjusted rate of return, book rate of return, return on book value and average book rate of return. Much of the time, the expressions are utilised synonymously, even though they infer unobtrusive contrasts in the calculation. Although the ARR, in whatsoever arrangement, experiences genuine deficiencies (it depends on an accumulation and not a cashflow idea; it considers not the way profits may change yearly and subsequently demonstrate an uneven example – it disregards the time estimation of funds flow and possibly not appropriate for contrasting ventures and diverse life expectancies), investigation demonstrates that it keeps on being utilised in the USA and UK for capital project appraisal. Purposes behind its utilisation have been specified as effortlessness and simplicity of calculation, prompt understandability, and its utilisation of gathering accounting measures through which administrators are much of the time assessed and compensated (Brief, 1996: 1999; Feenstra and Wang, 2000; Al-Ani, 2015). For it offers a possibility for control through creative accounting. Beneath the 'underlying' technique, the returns from an undertaking are communicated as a level of the underlying expense. The returns are expressed after deterioration and subsequently display reality – in an oversimplified way, the rate of return that is relied upon to be accomplished over that which is required to recoup the underlying investment expense. In any case, a way of thinking that develops the recommendation as the investment of capital will be discounted over the valuable existence of the task, at that point, the investment figure should be considered. For this would bring about an 'average' figure of investment in its utmost fundamental structure of one portion of the original cost. Under either approach, the income from the project would continue as before.

In this study, the formula for ARR is specified in equation 6.1 below (Magni and Peasnell, 2012):

$$ARR = \frac{Average\ Annual\ Profit}{Initial\ Investment}\ X\ 100 \tag{6.1}$$

According to Maroyi (2011), Magni and Peasnell (2012), the average annual profit is obtained by subtracting the cost of the system maintenance from the revenue.

$$Average\ Annual\ Profit = Revenue - Annual\ Maintenance\ Cost$$

$$Average\ Annual\ Profit = 9347.35\ - 100.00 = 9247.35$$

$$ARR_{20} = \frac{9247.35}{7735.35}\ X\ 100\ =\ 119.55\% \tag{6.2}$$

The photovoltaic solar air-conditioning investment is £7735.35 while its maintenance cost is £100 with 3% annual increase and in 20 years of the system operation, the maintenance cost is £2687.09. Also, the system investment which includes the maintenance cost in 20 years of operation is £10422.44. This is the addition of the initial investment and the cost of its maintenance for 20 years. The revenue of the system is £9347.35 while the average annual profit is £9247.35, and it is obtained by subtracting the yearly cost of the system maintenance from the revenue. The ARR is obtained by dividing the average annual profit and the system's initial investment. As a result, the ARR is 119.55%. However, there appear to be some advantages and drawbacks of the ARR as given in Table 6.2.

Table 6.2: Advantages and disadvantages of the ARR.

ARR	
Advantages	Disadvantages
● It is very easy to calculate and simple to understand like the payback period. It considers the total profits or savings over the entire period of the economic life of the project.	● This method ignores the time factor. The primary weakness of the average return method of selecting alternative uses of funds is that the time value of funds is ignored.

● This method recognises the concept of net earnings. This is a vital factor in the appraisal of an investment proposal. ● This method facilitates the comparison of new product projects with that of cost-reducing projects or other projects of competitive nature. ● This method gives a clear picture of the profitability of a project. ● This method alone considers the accounting concept of profit for calculating the rate of return. ● This method satisfies the interest of the owners since they are much interested in return on investment.	● A fair rate of return cannot be determined based on ARR. It is the discretion of the management. ● This method does not consider the external factors which are also affecting the profitability of the project. ● It does not take the cash inflows into consideration which are more important than the accounting profits. ● It ignores the period in which the profits are earned. ● This method cannot be applied in a situation when investing in a project is to be made in parts.

6.4.2 Net Present Value

The NPV is elucidated as the dissimilarity between cost inflows present value and the outflows of cash present value (Jory et al. 2016). That is to say, the NPV of a project – normally calculated as the initial investment time is the project's cash flow present value from activities and disinvestment less the initial investment amount. For instance, by calculating the NPV of the project, the flow of cash occurring at numerous emphases in a period is balanced for the estimation time of cash utilising the rate of discount, which is the return smallest rate required for the task to be satisfactory. The projects possessing positive NPV (or with values in any event equivalent to zero) are satisfactory and projects with negative NPV are unsatisfactory. On the off chance that the project is dismissed – it is dismissed because cash flows will likewise be negative. NPV is utilised in budging of capital to investigate the project or investment profitability and it is delicate to the dependability of imminent incomes that the investment, undertaking, project or venture will produce. For example, the NPV equates the value of the pound sterling today to the estimation of that equivalent future pound sterling considering returns and inflation.

In this study, the formula for the NPV is expressed in equation 6.3 below (Jory et al. 2016):

$$NPV = \Sigma \frac{C_i}{(1+r)^n} - Initial\ Investment \tag{6.3}$$

Where C_i is the cash flow generated per year; r is the rate of inflation and n is the number of years. Higher NPVs are advantageous and the rule for precise decisions is as follows:

- $NPV > 0$, accept the project
- $NPV \leq 0$, reject the project

Nevertheless, inflation can upsurge the future revenue of photovoltaic solar air-conditioning. Then, the feasibility of substitute investments reduces the future revenue value and interests of bank deposits may be of assistance in that circumstance. The proposed yearly inflation rate applied in this study is 4% with a discount rate 5% (Energy Saving Trust, 2021). Moreover, to obtain the income generated, the capacity of 6917.60 kWh solar system presented in Chapter 5 must be multiplied by the feed-in-tariff and the export tariff respectively, and subsequently added together. This technique systematically follows the guidelines specified by Jory et al. (2016). Hence, this can be calculated as follows:

$$Annual\ Income = (0.149 \text{ x } 6917.60) + (0.0464 \text{ x } 6917.60) = £1351.70 \tag{6.4}$$

As a result, Table 6.3 revealed the determination of NPV for 20 years and each annual calculation is systematically given in Appendix F and Appendix G, respectively, in this study.

Table 6.3: The determination of NPV for 20 years.

Annual	Initial Investment £	Photovoltaic system Performance %	Annual Solar Output kWh	Income Generated £	Annual Maintenance Cost £	Operating Profit £	Cash Flow £
Year 0	– £7735.35	–	–	–	–	–	–
Year 1	–	100.00	6917.60	1351.70	100.00	1251.70	1251.70
Year 2	–	99.50	6883.01	1398.74	103.00	1295.73	1351.69
Year 3	–	99.00	6848.42	1391.71	106.09	1285.62	1399.18
Year 4	–	98.50	6813.84	1384.68	109.27	1275.41	1448.31
Year 5	–	98.00	6779.23	1377.66	112.55	1265.11	1499.12
Year 6	–	97.50	6744.66	1370.61	115.93	1254.69	1551.63
Year 7	–	97.00	6710.07	1363.50	119.41	1244.19	1605.85
Year 8	–	96.50	6675.48	1356.57	122.99	1233.58	1662.16
Year 9	–	96.00	6640.80	1349.51	126.68	1222.83	1720.22
Year 10	–	95.50	6606.31	1342.50	130.48	1212.02	1780.32
Year 11	–	95.00	6571.72	1335.48	134.40	1201.08	1842.44

Year 12	–	94.50	6537.13	1328.44	138.43	1190.01	1906.64
Year 13	–	94.00	6502.54	1321.32	142.58	1178.74	1972.80
Year 14	–	93.50	6467.96	1314.39	146.86	1167.53	2041.60
Year 15	–	93.00	6433.37	1307.36	151.27	1156.09	2112.65
Year 16	–	92.50	6398.78	1300.33	155.81	1144.52	2186.01
Year 17	–	92.00	6364.19	1293.30	160.48	1132.82	2261.85
Year 18	–	91.50	6329.60	1286.27	165.29	1120.98	2340.24
Year 19	–	91.00	6295.02	1279.25	170.23	1109.02	2421.20
Year 20	–	90.50	6260.43	1272.23	175.34	1096.89	2505.06

Likewise, the NPV in equation 6.3 can further be expressed as (Jory et al. 2016):

$$\frac{C_i}{(1.05)^1} + \frac{1.04C_i}{(1.05)^2} + \frac{1.04C_2}{(1.05)^3} + \frac{1.04C_3}{(1.05)^4} + \frac{1.04C_4}{(1.05)^5} + \cdots \frac{1.04C_n}{(1.05)^n} \qquad (6.5)$$

To obtain the NPV of the proposed system, it is essential to substitute the yearly cash flow presented in Table 6.3 into equation 6.5. Therefore, the 20-year NPV at a discount of rate 5% (0.05) can be expressed as follows:

$$\begin{aligned} NPV = {} & \frac{1251.70}{1.05^1} + \frac{1351.69}{1.05^2} + \frac{1399.18}{1.05^3} + \frac{1448.31}{1.05^4} + \frac{1499.12}{1.05^5} + \frac{1551.63}{1.05^6} + \frac{1605.85}{1.05^7} \\ & + \frac{1662.16}{1.05^8} + \frac{1720.22}{1.05^9} + \frac{1780.32}{1.05^{10}} + \frac{1842.44}{1.05^{11}} + \frac{1906.64}{1.05^{12}} + \frac{1972.80}{1.05^{13}} \\ & + \frac{2041.60}{1.05^{14}} + \frac{2112.65}{1.05^{15}} + \frac{2186.01}{1.05^{16}} + \frac{2261.85}{1.05^{17}} + \frac{2340.24}{1.05^{18}} + \frac{2421.20}{1.05^{19}} \\ & + \frac{2505.06}{1.05^{20}} - Initial\ Investment \end{aligned}$$

$$\begin{aligned} NPV = {} & 1192.00 + 1226.02 + 1208.66 + 1191.52 + 1174.50 + 1157.85 + 1141.24 \\ & + 1125.02 + 1108.87 + 1092.96 + 1077.24 + 1061.69 + 1046.22 \\ & + 1031.15 + 1016.22 + 1001.44 + 986.84 + 972.42 + 958.15 + 944.13 \\ & - 7735.35 \end{aligned}$$

$$NPV = 21714.14 - 7735.35 = £13978.79$$

It can be observed that the proposed project yielded a positive value $NPV > 0$, which suggests the project is worth undertaking. However, the NPV appears to have some advantages and drawbacks as presented in Table 6.4 below.

Table 6.4: Advantages and disadvantages of NPV.

NPV	
Advantages	Disadvantages
• It is conceptually superior to other methods.	• The NPV calculations unlike the IRR method, expect the management to

• It does not ignore any period in the project life or any cash flows. • It is mindful of the time value of money. • It is easier to apply NPV than IRR. • It prefers early cash flows compared to other methods.	know the true cost of capital. • NPV gives distorted comparisons between projects of unequal size or unequal economic life. In other to overcome this limitation, NPV is used with the profitability index.

6.4.3 Payback Period

The payback period is characterised as the time required to recuperate the underlying interest in a venture from operations. The technique of the payback period for money related examination is applied to evaluate capital undertakings and to ascertain the yield each year from the beginning of the task until the aggregated revenues are equal to the expense of the venture. During that period, the speculation is pronounced to have been repaid and the time engaged to achieve this payback is referred to as the payback period (Ong and Thum, 2013; Al-Ani, 2015). The rule decision of payback expresses those worthy ventures must possess not exactly some extreme payback period assigned by the administrators. Payback is said to accentuate the administration's apprehension with liquidity and the need to limit chance through a fast recuperation of the underlying speculation. It is regularly utilised for little uses which has evident advantages that the utilisation of progressively refined capital planning techniques is not essential or advocated (Ong and Thum, 2013). The necessary payback period sets the limit boundary (obstacle rate) for the acceptance of the project. It regularly gives the idea that, as a rule, the assurance of the necessary payback period depends on personal evaluations, considering past encounters and the apparent degree of venture hazard. The payback period has been demonstrated to be a significant, well known, essential and conventional strategy in developed countries like the UK and the USA (Pike, 1985; Brigham and Ehrhardt, 2005).

Characteristically, the expected payback period by the owners of a system varies. For example, the account of the research studies by Fotsch (1983) and Ong and Thum (2013) revealed that the USA appraisal of average impediment payback period is 2.9 years whereas, a research study by Woods et al. (1985) stipulated from UK appraisal that, “regarding the firms using new technology and also using the payback investment appraisal methods for all their investments, we had 31 observations of the standard payback period: the minimum observed was 1 year and the maximum 5 years, with a mean of 2.9 years”. Likewise, studies by Drury et al. (1993), Ong and Thum, (2013) and Al-Ani, (2015) state that the average payback period for customary ventures was 2.83 years, whereas 3.11 years is for projects with new technology. Nevertheless, projects with shorter payback periods rank higher than those with longer paybacks. The philosophy behind the projects having a shorter payback period is that they are more liquid and thus less risky, for instance, they permit the establishments to recover their investment more readily, and subsequently, the money may be reinvested in a different project. By means of a quicker payback period, it is unlikely that the conditions of the market, economy, interest rates or supplementary factors that are influencing the proposed venture will change severely. Therefore, 3 years or less payback period is often encouraged, because it believes that the project is supposed to be indispensable if the payback period is less than a year. However, this study still applied the payback period as a result of the ease of usage and its broad application regardless of known limitations.

Since the proposed project possesses uneven cash flows, the formula employed for the payback period can be expressed in equation 6.6 as (Al-Ani, 2015):

$$Payback\ Period = \frac{Initial\ Investment}{Periodic\ Cash\ Flow} \tag{6.6}$$

As a result of an uneven cash flow and to determine how much time to recover the original investment, the payback period can further be expressed as (Al-Ani, 2015):

$$Payback = Years\ before\ full\ recovery + \frac{Unrecovered\ cost\ at\ start\ of\ the\ year}{Cash\ flow\ during\ the\ year} \tag{6.7}$$

Furthermore, year 5 is the year before the initial investment is fully recovered; however, to calculate the unrecovered cost at the start of the year, the initial investment must be subtracted from the addition of the cash flows by the end of the 5th year. Furthermore, the cash flow during the year is the flow of cash when the project has fully recovered from its initial investment.

$$\begin{aligned} &Unrecovered\ cost\ at\ start\ of\ the\ year \\ &= Initial\ Investment - Cash\ flows\ by\ the\ end\ of\ year\ 5 \end{aligned} \quad (6.8)$$

Subsequently, the payback period is expressed and calculated as follows:

$$Payback = 5 + \frac{785.35}{1551.63} \quad (6.9)$$

$$Payback\ period = 5.5\ years$$

In this study, the estimated payback period is 5.5 years, and this typically demonstrates that the system will begin to make a profit after 5.5 years of operation. This study provides a system having a lower payback period compared to a higher payback period of 13 years and 21 years provided in the research studies by Hadj et al. (2015), and Greenaway and Kohlenbach (2017), respectively. Therefore, there are greater possibilities of higher system efficiency with a lower payback period for more sustainable future use. In any case, there appear to be some advantages and drawbacks of the payback period as given in Table 6.5 below.

Table 6.5: Advantages and disadvantages of the payback period.

Payback Period	
Advantages	Disadvantages
• It is widely used and easily understood. • It favours capital projects that return large early cash flows. • It allows a financial manager to cope with risk by examining how long it will take to recoup the initial investment.	• It ignores any benefits that occur after the payback period i.e., it does not measure total income. • The time value of money is ignored. • It is difficult to distinguish between projects of different

• It addresses capital rationing issues easily. • The ease of use and interpretation permit decentralisation of the capital budgeting decision which enhances the chance of only worthwhile items reaching the final budget. • It remains a major supplementary tool in investment analysis.	sizes when initial investment amounts are vastly divergent. • It over-emphasises short-run profitability. • The overall payback periods are shortened by postponing the replacement of depreciated plants and equipment. This policy may do more harm than good to the production process.

6.4.4 Internal Rate of Return

The IRR appears to be the rate of discount frequently utilised in the budgeting of capital that forms all cash flows NPV from a particular venture equivalent to zero. This predominately implies that the IRR is subsequently the rate of return that forms the whole imminent cash flow's present value and the project's last market value equivalents to the value of the present market (Stefan, 1999; Rangel et al. 2016; Neil et al. 2018). The higher an investment IRR, the further alluring it is to accept the venture (Neil et al. 2018). Therefore, it is used to rank numerous potential ventures or systems an organisation or individual is contemplating. Thus, the IRR gives a straightforward impediment, from any venture should stay away from if the capital expense exceeds this rate. IRR is additionally alluded to as the economic rate of return. Straightforward criteria of decision making can be to acknowledge a task if its IRR surpasses the expense of capital and dismissed it if the IRR is not exactly the capital cost. Even though the utilisation of IRR could bring about various complexities, for example, a venture with numerous IRRs or possessing absolutely no IRR whereas, IRR dismisses the magnitude of the project and accept that incomes are reinvested at a steady rate. According to research studies by Rangel et al. (2016) and Neil et al. (2018), IRR is the other side of NPV, where NPV is a stream of cash flow discounted value, produced from speculation. IRR calculates the return of break-even rate indicating the rate of discount.

A research study by Pascual et al. (2018) revealed that IRR cannot be calculated analytically, it must as an alternative be calculated by utilising software programmes/ programs like Excel or trial-and-error techniques. Therefore, the IRR is calculated through IRRCalculator.net (IRR Calculator, 2020). As a result, the IRR for the economic assessment of the proposed system is 19.31%. That is to say, the assessment outcome demonstrates that at the discount rate of 19.31%, a photovoltaic solar air-conditioning investment is worth undertaking. Nevertheless, there also appear to be some advantages and drawbacks of the IRR as presented in Table 6.6 below.

Table 6.6: Advantages and disadvantages of IRR.

IRR	
Advantages	**Disadvantages**
• It is straight-forward and easy to understand. • It recognizes the time value of money. • It uses cash flows.	• It often gives unrealistic rates of return and unless the calculated IRR gives a reasonable rate of reinvestment of future cash flows, it should not be used as a yardstick to accept or reject a project. • It may give different rates of return; it entails more problems than a practitioner may think. • It could be quite misleading if there is no large initial cash outflow.

6.5 Conclusion

In conclusion, this chapter unfolded the economic assessment of the photovoltaic solar air-conditioning. The ARR, NPV, payback period and the IRR has been evaluated and the analysis portrayed that the project is worth undertaking. The economic assessment of the solar-based systems demonstrates how significant savings can be achieved through utilising a sustainable and renewable means of technology, the photovoltaic solar air-conditioning technology. Moreover, the financial profitability factors evaluated appear to possess several advantages and drawbacks; this has been taken into consideration in the assessment of the system. Therefore, the photovoltaic solar air-conditioning demonstrates to reduces the level of energy consumption, and carbon emissions and saves investment costs; however, it also analytically demonstrates to meets the sustainable agenda in this study, which is the economic sustainability of the renewable air-conditioning. Furthermore, the next chapter in turn presents the discussion and result validation of the study.

Chapter Seven

7.0 Discussion and Result Validation

7.1 Introduction

This chapter offers the discussion and result validation of the study. It systematically begins with the conceptual issues of sustainability that informed the studies, followed by the sustainable framework assessment and application of sustainability that fundamentally adds to the knowledge base of the system through the theoretically developed framework. This study takes forward some insightful suggestions proposed by researchers and addresses some deficiencies in previous studies. It also examines the implication of the environment, economic and social sustainability which forms the sustainable framework principles of the study. The penultimate section of this chapter presents the outcome of the semi-structured interviews with the system experts, used to externally validate the study.

7.2 Conceptual Issues of Sustainability

Currently, societies and humankind face sustainability challenges that primarily connect with the capacity to sustain ecosystems, humanity, and societies on the planet. In the future, these challenges are anticipated to turn out to be more substantial. Accomplishing sustainability in the aspect of air-conditioning is consequently one of the most vital objectives of a society and its people since air-conditioning has generally been applied as a result of the improvement in the way of life.

The concerns and issues personified through sustainability are comprehensive and many. They subsequently cover such various issues as pollution and climate change, government policies, stability and peace, anthropogenic and natural disasters, social and cultural sustainability, globalisation, urbanisation, population growth, energy consumption, carbon emissions, IAQ, energy efficiency, industrial development, production, technological systems such as smart control systems, ecosystem degradation, drought and water quality, loss of biodiversity and species extinction, desertification and land use, sanitation, resource supply (food, mineral, energy, water) and waste management (conventional, radioactive, hazardous toxic). However, the extensiveness of matters associated with sustainability proposed that a comprehensive and holistic tactic for sustainability is required. Sustainability actions are progressively becoming the businesses' and governments' agendas and operating strategies. The sustainability principles (environment, economic and social) are required to be associated if actions are to achieve the fundamental goals of sustainability. As a result of the three bottom line principles of sustainability adapted in this study, the results demonstrate accomplishment in the reduction of energy consumption and carbon emissions with appropriate control performance and inhabitants' comfort improvement.

7.3 Sustainable Framework Assessment

The sustainability assessment framework is significant for making sustainability functioning and monitoring and measuring progress in the direction of sustainability. Nevertheless, assessing sustainability is challenging, because no generally recognised sustainability technique exists for a system. There are several motives for this, as well as arduously in quantifying the key pillars of sustainability (Hacatoglu et al. 2016). For instance, albeit ozone-depleting substances and GHGs emissions are quantifiable, measuring their social and economic influences is challenging. Likewise, regardless of living standard frequently being quantified as 'gross domestic product per capita'; life quality can be a further important measure of satisfaction, comfort and human well-being. In this regard, the assessment of sustainability can also be argumentative (Morse and Fraser, 2005). However, several approaches for measuring or assessing sustainability have been established as discussed below:

- Several methods of assessment apply indicators or principles of sustainability, which are characteristically straightforward quantitative substitutions that systematically measure environmental, social and economic factors. The indicators of sustainability are typically integrated, unifying the bottom-line principles namely social, environmental and economic whereas, others are not integrated, quantifying only a single sustainability fragment. This method of unifying the bottom-line principles is analytically applied in this study as a result of their suitability and straightforward measuring proxies for the proposed system.

- Indexes of sustainability have been established grounded upon a composite or aggregate of certain indicators of sustainability. A single-value sustainability quantity grounded upon an aggregate index is valuable for communication and understanding, owing to its straightforwardness. Nevertheless, the resolve of such indicators requires aggregation, weighting and normalisation of data. These stages generally lead to a loss of beneficial information and can be problematic. The measure of single-value sustainability can cover facts that are essentially connected with the multidimensional nature of sustainability and therefore be deceptive. As a result of these known facts, this study refrained from using such quantifying methods for the framework sustainability assessment of the proposed system.
- A research study by Daly (1990: 1996) established sustainable development operational principles. Albeit beneficial, these are restricted to quasi-sustainable use of non-renewable resources and as result, this method is not applied in this study due to their limited usage.

Studies unfolded that a small number of sustainability assessment approaches simultaneously reflect the three bottom-line principles of sustainability namely economic, environmental and social. Conversely, several methodology assessments emphasize only one sustainability area or dimension such as the environment or economic sustainability. Numerous instances are contemplated to demonstrate this as highlighted below:

- Assessment of biophysical methods is suitable for assessing environmental sustainability, through measuring environmental impact and resource use. Nevertheless, they are usually inappropriate for addressing economic and social domains of sustainability.
- Financial assessment can be applied to environmental and social capital to evaluate sustainability. Nevertheless, financial assessments for non-market services and goods are not well established, inappropriate appraisals, and

problematic owing to our restricted ecosystems understanding and the resources they offer.

- The index of environmental sustainability positions countries grounded upon numerous environmental indicators aggregate. Nonetheless, these are generally incapable to associate economic growth and environmental sustainability.

The non-existence of a framework approach is the weakness of numerous existing approaches to assessing sustainability, which consider the system being measured as a whole and typically account for the connections amongst its subsystems. This is significant for the reason that attaining a sustainable society is a systems problem, where the economic, social and environment are completely interdependent. Integrated human-environmental systems have connections between diverse systems that lead to trade-offs; for example, costs reduction can originate a procedure to have lower efficiency or higher emissions. An approach of non-systems concentrating upon solitary factors can be regularly understood to be insufficient for holistically assessing sustainability. As earlier noted, for instance, biophysical methods lay emphasis primarily upon environmental sustainability and disregard social and economic dimensions, whereas approaches grounded upon weak sustainability typically emphasising factors of the economic and disregarding the biophysical sustainability domain. A system sustainability requires to be assessed with a systems framework method. Analysis of the life cycle is generally a fragment of such a method, as it recognises the system energy and material inputs and outputs or procedure and utilises this information to assess the effects of the economic, social and environmental domain of the system framework. In the light of this, the sustainability principles through a sustainable framework can demonstrate accomplishment in the reduction of the level of energy consumption and carbon emissions of renewable-based air-conditioning while having an appropriate smart control performance and inhabitants' comfort improvement.

Nevertheless, in recent years, the principles of the sustainability framework have subsequently been applied to some areas. Several illustrations are given in Table 7.1 below.

Table 7.1: Applications of the sustainable framework.

Authors and Year	**Applications of Sustainable Framework**
Sustainability of technology	
Dewulf et al. (2000)	Sustainability of technology via a range of illustrations
Sustainability of energy	
Evans et al. (2009)	Sustainability indicators for renewable energy
Gnanapragasam et al. (2011)	Sustainability of a national energy conversion system using hydrogen from solid fuels
Gomez-Echeverri et al. (2012)	Global energy assessment for sustainable routes identification
Sustainability of manufacturing operations	
Nazzal et al. (2013)	Sustainability as a tool for manufacturing decision making
Sustainability of infrastructure and buildings	
Khalid et al. (2015)	Sustainable building of heating, ventilation, and air-conditioning
Russell-Smith et al. (2015)	Sustainable target value design to improve buildings
Sustainability of energy, water and environment systems	
Krajacic et al. (2015: 2018)	Sustainability overview of the topic and description of sample studies
Sustainability of region	
Gomez-Echeverri et al. (2012)	Sustainability for the world
Gnanapragasam et al. (2011)	Sustainability for countries
Mansoori et al. (2016)	Sustainability for state
Oye (2018)	Sustainability for suburbs

Consequently, Figure 7.1 systematically consolidates and applied the three pillars of sustainability namely; environment, economic and social as a whole arising from the methodical framework which is individually presented as 'sustainable indicators' in chapter two of this study – it subsequently re-established the system to sustainability which necessitates a transformation in the system. In other words, it combines both renewable and smart systems as a unique system for the sustainability of the system which in turn improves the human adaptation to the well-being of occupants.

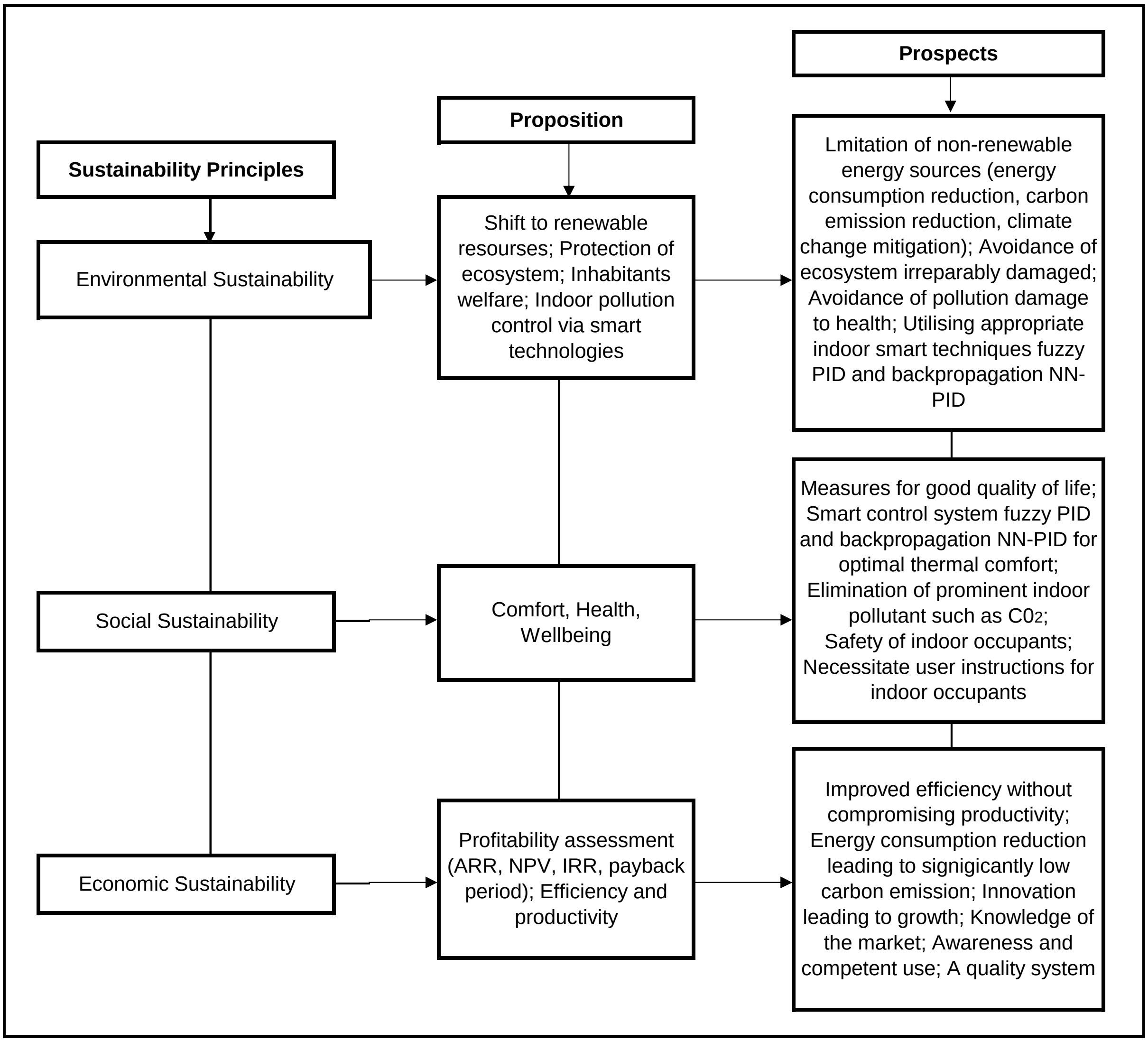

Figure 7.1: Proposed framework using sustainability principles and indicators.

Environmental sustainability requires economic sustainability, and social sustainability relies on environmental sustainability. On the other hand, the three areas of sustainability can be treated with equality as proposed by research studies in the literature. The promotion of sustainable practices is typically pursue a balance between environment, economic and social performance in project applications. That is to say, the connection between sustainability, renewable energy and smart control for air-conditioning becomes clear to reduce the level of energy consumption and rates of carbon emissions while tackling the health effects of inhabitants. Air-conditioning is of strong environmental significance and subsequently has high economic and social influences. Therefore, the principles of sustainability namely, environment, economic and social aimed for renewable smart air-conditioning are theoretically addressed in the following subsections.

7.3.1 The Environmental Sustainability

The subsystems of the environment are social and economic which are the basis and descent of the Earth's entire energy and material interactions. The sustainability of humankind suggests guaranteeing the Earth's ability to underpin the associated human activities. Inhabitants and human economies have developed such that activities of anthropogenic currently have long-term and global effects, with numerous consequences. These can reduce the planet's capacity to fundamentally sustain life. However, numerous environmental issues influence sustainability such as the energy consumption and carbon emissions emanating from the use of air-conditioning systems around the world thereby causing climate change and health effects on inhabitants. There is also loss of biodiversity all over the biosphere, owing to economic growth and other related factors as a result of the constant usage of the air-conditioning system during the hottest period of the year, and this subsequently puts threats to environmental sustainability.

The use or removal of deficient resources from the environment and the release of wastes and emissions emanating from the use of air-conditioning to the land, air and water likewise put sustainability in danger. The air pollutants emitted by fossil fuel-fired electrical power plants, internal combustion engines in vehicles and several industrial actions can badly influence IAQ and the health of human beings during the utilisation of air-conditioning since the outdoor air is not often mixed with the indoor air during the system operation. Hence, the solar air-conditioning coupled with the smart system controllers of the proposed system which is subsequently linked with the social sustainability can accomplish such comfortable and healthy indoor environment quality, while tackling the level of energy consumption, carbon emissions and the resulting climate change effects. The environmental sustainability outcome can demonstrate achievement in the reduction of energy consumption and carbon emissions with appropriate smart indoor control performance and inhabitants' comfort enhancement. However, the climate change which is the utmost key significant challenge to a sustainable environment emanating as a result of the rate of energy consumption and carbon emissions is likewise discussed below:

7.3.1.1 Climate Change

The steadiness of the GHGs concentrations in the atmosphere; the reason to avert the damaging consequences of climate change and global warming is established by most investigations as the significant challenge of the present-day. The GHGs consume infrared radiation released at the Earth's surface in the atmosphere. This subsequently leads to the effect of greenhouse and related terrestrial warming. The main GHG is CO_2, nevertheless, there are other GHGs such as nitrous oxide (N_2O) and methane (CH_4). The foremost anthropogenic origins of GHG emissions consist of the combustion of fossil fuel, ruminant animals' enteric fermentation and utilisation of agricultural nitrogen. Global warming and climate destabilisation risks are worsened through effects of positive response, for instance, the growth of absorption solar radiation occurring as a result of the loss of reflecting exteriors like ice. Since 1990, the IPCC published an inclusive report assessment revising the state-of-the-art climate science and forecasts trends for the future. In 2014, the finalised fifth reports assessment unfolded the warming trends because of anthropogenic actions as "very likely". A study by Berthiaume and Rosen (2017) proposed that the amount of projected warming has subsequently intensified as climate models turn out to be further sophisticated and as a consequence of the associated climate and supplementary influences. A considerable attempt at the UNs and universally is concentrated upon attaining worldwide treaties or agreements to stabilise concentrations of the GHG in the air at a level that evades unsafe anthropogenic climate change. As a result of this movement, this study likewise proposed renewable energy and smart control techniques which, in turn, contributed to such goals using diminishing the level of energy consumption and carbon emissions emanating from the use of air-conditioning systems. It revealed a combined solar and smart indoor control systems of air-conditioning to tackle climate change and the health effects on inhabitants.

7.3.2 The Social Sustainability

Social sustainability is a comprehensive notion such as cultural development, well-being, health, equity and several other factors. A specific meaning of social sustainability and its contribution is ongoing universally. The development of a sustainability rationale to comprise a strong social constituent took some time. Initial effort on sustainability is usually concentrated upon either economic sustainability or environmental sustainability while neglecting the social sustainability factors. The importance of the development of both society and humans has been recently realised. The health and well-being of the users of the air-conditioning systems are significant since a research study by Yu and Lin (2015) proposed that majority of people spent about 80% to 90% of their time at home. Therefore, the smart control systems for regulating IAQ of the renewable air-conditioning are vital in achieving a healthy living environment for the building inhabitants. With an appropriate smart control technique of the PID controller, the IAQ can be significantly improved. The social sustainability of the system can tackle poor IAQ and demonstrate accomplishment in appropriate smart control performance and occupants' comfort improvement. Furthermore, the main factor which is the health and wellbeing of the inhabitants in social sustainability is discussed below:

7.3.2.1 Human Health and Well-Being

Health and well-being are significant factors of social sustainability. The human health significant measures consist of infant mortality and life expectancy (Smil, 2007). Several factors contribute to human health and comfort, such as healthy living, safe waste disposal, and an environment without harmful substances that can lead to chronic or acute diseases as deliberated upon in the literature (e.g., carcinogens and toxins). Therefore, the social sustainability unfolded the smart indoor control system which is linked with the environmental sustainability of the sustainable framework to combat the aforementioned issues in a bit to improve the quality of the lives of the building inhabitants.

7.3.3 The Economic Sustainability

An economy that delivers standards of good living, the facilities that individuals need, and occupations are essential for society's sustainability. A sustainable society needs continuing economic development somewhat than unbiassed economic growth. What happens currently is the economic growth which is frequently measured as growth in a gross local product where consumerist economies rely upon economic growth to produce prosperity and occupations. For this reason, a study by Aghbashlo and Rosen (2018) unfolded that the economy functions within a globe possessing limited capacities and resources, over the long term, a constantly growing economy is not inevitably sustainable. Hence, the universal economy must function more in a stable-state manner, with zero or little development. This fundamentally suggests that the economic assessment of the renewable smart air-conditioning must be equated as a stable-state manner irrespective of the financial profitability analysis outcome to promote economic growth and the system benefits to the society since a growing economy is not certainly sustainable.

The economic sustainability assessment of the solar-based systems can demonstrate how significant savings can be achieved through utilising a sustainable and renewable means of technology. The economic sustainability opinions are divided into categories of strong and weak sustainability where the ‘strong’ focus more on the environment while the ‘weak’ focused more on the system's financial assessment. However, it can be concluded that it is beneficial to focus more on the strong sustainability of the renewable smart air-conditioning for the overall welfare of the society for constant economic growth.

7.4 Result Validation

The type of interview carried out is a qualitative research interview to externally validate the study, and its primary purpose is to gather interpretations of the worldview of the interviewee with respect to the basis of the newly developed sustainable system – this technique systematically follows the guidelines specified by King (1994). The interview is conducted after a quantitative study has been carried out, and the interviews aim to validate particular measures or elucidate and exemplify the meanings of the findings. In this context, the interviews were used to test the basis of the newly developed sustainable framework for renewable smart air-conditioning. Consequently, the consolidation of renewable energy, smart indoor environment control and profitability measures of air-conditioning to the developed sustainable theoretical framework aided in strengthening the internal validity of the exercise and enhancing the internal validity of this work. The reliability of this work is enhanced by the explicit procedure reporting and the sustainability principles of the theoretical framework and their indicators that have been discussed.

In this study, semi-structured interviews with the system experts were conducted to externally validate the sustainable theoretical framework for smart air-conditioning as shown in Appendix H. Semi-structured interviews were conducted with air-conditioning experts from different organisations to access the feasibility of the developed sustainable model using the sustainability principles and their indicators for the proposed system. Nine members from different organisations were approached but only seven people acceded to participate in the interviews. The seven participants consisted of the Operations Manager, Technical Specialist, Multi-Skilled HVAC Engineer, Senior Mechanical Design Engineer, HVAC Design and Sales Engineer, Air Conditioning and Ventilation Design/Estimating Engineer, Air-Conditioning Business Development Manager.

Consequently, an interview plan was developed with three main objectives:

- To access the basis of the sustainable framework developed for the smart air-conditioning;
- To find out if sustainability principles associated with renewable smart air-conditioning were contemplated and established;

- To find out the feasibility of the sustainable theoretical framework for smart air-conditioning.

It was unanimously agreed by the seven participants that the existing system affects the health of inhabitants and adds to the level of energy consumption and carbon emissions, and the proposed system is a commendable development toward improving air-conditioning systems for a sustainable future without compromising the health of inhabitants. One major disadvantage expressed by three of the participants was that the aspect of intelligent indoor environmental control had a rigorous equation form, and its procedure appears to be unconventional and difficult to understand. Generally, the interviewers agreed with the basis of the developed sustainable theoretical framework for smart air-conditioning systems and applauded its form in the easy-to-understand framework concept. The connection of the three pillars of sustainability namely environmental, economic and social with the air-conditioning system for an anticipated smart and sustainable future was likewise applauded by the interviewees. Nevertheless, it was suggested unanimously that future studies should perhaps test the result of the sustainable framework developed for smart air-conditioning in a bid for a clean and sustainable future.

One of the interviewees said:

> *Sustainability principles linked with air-conditioning had never been contemplated let alone established – this must be an exciting way towards a more sustainable future. The renewability of the system associated with the ability to use smart techniques to regulate the temperature and control indoor CO_2 to a desired level makes the proposed system much-admired. A future test is a must for this exhilarating model.*

Another interviewee expressed that:

> *The usage of air-conditioners was measured to be an item of luxury in the past – nowadays it has turned out to be the item of certainty in most buildings due to the extreme summer conditions. It is reckoned that the sustainable smart air-conditioning can be of great significance to fighting*

climate change and most importantly, eliminating poor IAQ that adversely affects human health.

All respondents mentioned that air-conditioning systems are generally known for their issues. There is a universal perception about the level of energy consumption, carbon emissions and health challenges associated with the use of air-conditioning. Surprisingly, nothing has changed. One of the respondents mentioned that:

> *Since the conventional air-conditioning system utilises a lot of electricity, it makes both financial difficulties for the public who must pay for the energy utilisation and more widespread environmental shortcomings triggered by energy consumption and carbon emissions. For a huge proportion of electricity is produced via coal-burning power plants; air-conditioning contributes circuitously to the rate of carbon emissions and release of GHGs and systematically causes climate change. Also, according to "The Independent", spending too much time in an air-conditioned environment mostly contributes to health difficulties such as tightness in the chest, asthma and further respiratory illnesses. However, the newly proposed model is a feasible way forward to conquer these challenges.*

Another respondent commented that:

> *The developed framework depicted the overall sustainability concept of the newly proposed system ranging from its simplicity to its technicality. The logical design of the theoretical framework unravels a reasonable output that can genuinely stand as a future model and criterion for achieving sustainable-based smart air-conditioning. There is hope for a more sustainable and clean future through the utilisation of the newly developed model.*

It can be surmised from the interviews that a sustainable framework assessment has not been carried out in sanctioning the sustainability of renewable energy and smart control for air-conditioning. Albeit the respondents were rationally familiar with some aspects of sustainability. It was suggested that the system challenges persist as a result of the non-application of the three bottom-line principles of sustainability namely, environment, economic and social. However, the development of a sustainable theoretical framework for renewable smart air-conditioning as provided in this work and the empirical validation of the study will not only be useful in the “built environment” to tackle poor IAQ, reduce the level of energy consumption and the rate of carbon emissions, but also to combat global warming and climate change.

Consequently, there appears to be no form of consensus from the interview conducted regarding the outcome of the payback period for the financial profitability assessment of the proposed system. One of the respondents said:

> *The payback period of the proposed system should not exceed 7 years as air-conditioning users are not willing to commit capital exceeding such period, as system owners are wary about any unforeseen associated future costs and investment returns.*

Another respondent mentioned that:

> *8.5 years is a realistic payback period for the proposed system. The system owners should get their return on investment afterwards. Moreover, allowance should be made for annual maintenance and to replace some short-lived equipment.*

It was also unanimously suggested that future studies should test the intelligent indoor controllers of the proposed system to provide its financial assessment, as well as the overall financial profitability assessment of the system.

Another respondent stated that:

> *The payback period can be within the range of 6.5 years to 14 years depending on the investment involved and the capacity of the solar air-conditioning.*

Nevertheless, it can be deduced that it depends on the amount of the initial investment that will provide the desired financial profitability assessment outcome. The study by Renewable Energy Hub (2021) revealed that solar system is becoming cheaper as a 3.5 kWh system cost about three times the current price of the system in the last 12 months. The need for further initial investment reduction of the photovoltaic solar air-conditioning is suggested. This will even be more beneficial for the owners of the system.

7.5 General Remarks

This study aims to challenge and extend existing knowledge on sustainability-related to smart air-conditioning systems considering social, environmental and economic dynamics. In line with these, this study has developed a sustainable theoretical framework for smart air-conditioning which is focused upon a conceptual modelling approach that is suitable and fundamentally connected to the scope of this study. The modelling approach is employed to model the photovoltaic solar air-conditioning and the smart IAE. The anticipated controller of the indoor environment is structured, and the PID control is utilised because of its feasibility. The indoor temperature and IAQ were designed for the solar-air conditioning to improve the quality of air in the indoor environment while achieving significant energy savings, reducing the level of CO_2 and the GHG emission, vis-à-vis tackling global warming and climate change.

Presently, the use of air-conditioning has generally been applied as a result of the life-threatening summer conditions. Thus, there is probably always air-conditioning in indoors from offices to every room in the household which subsequently adds to the level of energy consumption and carbon emissions, thereby causing climate change. Nevertheless, with so much contact with air-conditioning, there has been a continued debate as to whether the air-conditioning harms the human body and subsequently adds to the level of energy consumption and carbon emissions. Yes, is the answer to such a question. However, human health is considered the vocal point when considering sustainability. According to the literature, inhabitants in buildings with constant use of air-conditioning have higher illness rates with a high level of energy consumption than individuals in buildings with natural ventilation. The study demonstrates that individuals who work in an environment that is over-air-conditioned can experience constant fatigue and chronic headaches which also creates financial disadvantages for the individuals who have to pay for the energy due to the high rates of energy consumption. Individuals who work or live-in structures which are regularly being pumped full of cool air can similarly experience persistent breathing difficulties and mucous membrane irritation. This leaves individuals further helpless to contracting the flu, colds and other illnesses associated with the utilisation of air-conditioning. Air-conditioning may come in convenient on a certainly hot day; nonetheless, it is likewise the worst offender for circulating micro-organisms and germs that cause breathing difficulties and yet, increase the rates of energy consumption and carbon emissions. According to a recent study directed at Louisiana State Medical Centre, 8 categories of mould reside in 22 out of 25 indoors tested. Besides, residing in the air-conditioning zones for a lengthy period can potentially cause eyes, nose and throat respiratory problems. Air-conditionings are well-recognised for air-borne diseases circulation such as Legionnaire's Disease, a possibly deadly infectious disease that gives rise to pneumonia and high fever. It likewise assists with rhinitis circulation, a disorder that causes the nasal mucous membrane inflammation.

Indoor occupants are further expected to become dehydrated due to poor IAQ in an area with unregulated air-conditioning as equated to other areas with regulated air-conditioning. The regulated air-conditioning can further be smart controlled through an appropriate smart control technique of FLC, PID and backpropagation NN controller to optimise IAQ within the indoor environment as proposed in this study. The unregulated air-conditioning sucks humidity from the apartment while leaving inhabitants dehydrated and with the necessity to drink water. Dehydration emanating from air-conditioning utilisation can cause migraines and headaches. Unexpected contact with the sun or heat after a lengthy contact with air-conditioning might cause headaches. Likewise, in cases of air-conditioning housings which are not appropriately sustained, inhabitants are further susceptible to migraines and headaches. Unregulated contact with air-conditioning can cause dry and itchy skin and eyes. Individuals having symptoms of dry eyes are recommended not to reside for too long in air-conditioning zones since it deteriorates effects whereas, extreme contact with air-conditioning alongside sun contact can make the skin itchy and dry. The utilisations of central air-conditioning systems are also well-recognised to boost the effects of the disease that inhabitants may hitherto be suffering from. Air-conditioning is infamous for increasing the rates of energy consumption and carbon emissions and thereby causing climate change, and subsequently, it intensifies the indications of low blood pressure while making management of pain further problematic for individuals obstinate in utilising their central air-conditioning. Nevertheless, this study has revealed a realistic and feasible technique via a theoretical assessment framework from the principles of sustainability to challenge these problems.

7.6 Conclusion

This chapter presents the discussion and external validation of the study. It analytically begins with the conceptual issues of sustainability that informed the studies followed by the sustainable framework assessment and application of sustainability that fundamentally adds to the knowledge base of the system through the theoretically developed framework. It goes on to discuss the results and the implications of those results for the sustainable practice of the environment, and economic and social sustainability for the proposed system. The subsequent section of the chapter discusses the influence of air-conditioning on human health and the resultant climate change effect. The penultimate section endeavours to externally validate the proposed model through semi-structured interviews with air-conditioning experts.

Chapter Eight

8.0 Conclusions and Recommendations for Future Studies

8.1 Introduction

This chapter unfolds the overall conclusion of the study. It systematically synopsises the entire study and reviews the stated research objectives. The subsequent section details the main findings from the study and discusses their implications for a sustainable theoretical framework. The penultimate section of the chapter subsequently presents the contribution to the knowledge of the study and suggests recommendations for future research studies.

8.2 Synopsis of the Study

The synopsis offers an overview of the problem statement and how it systematically connects with the objectives of the study. This study addressed each of the objectives which contributed to the knowledge base in diverse ways. The problem statement and research objectives are synopsised in the following section.

8.2.1 Problem Statement

In the quest for optimum energy performance Building Regulations enforce improved airtightness. Without natural ventilation, Mechanical Ventilation with Heat Recovery (MVHR) is the recommended solution (NHBC, 2011). However, NHBC (2009) and Beama (2016) recognised that studies have not taken into account the adverse impact of these approaches on IAQ and the health effect on inhabitants. Poor air quality is linked to asthma, pneumonia, dementia, COPD, lung cancer, stroke, etc. Existing systems were not capable of monitoring outdoor air quality and its impact on the IAQ; polluted air is simply drawn in regardless. The principles of sustainability namely environment, economic and social which, in turn, reinforce renewable and smart options for more sustainable and energy-efficient control systems are the main points in developing a sustainable theoretical framework for future smart air-conditioning systems. The past issues and current challenges highlight the requirement for a detailed analysis of social, environmental and economic aspects of smart air-conditioning systems focused on supporting sustainable future developments.

8.2.2 Objectives of the Study

This study aims to challenge and extend existing knowledge on sustainability-related to smart air-conditioning systems considering social, environmental and economic dynamics. In line with these, this study has developed a sustainable theoretical framework for smart air-conditioning which is focused on the system modelling approach that is suitable and fundamentally connected to the scope of the study. The conceptual modelling approach is employed to model the photovoltaic solar air-conditioning and the smart IAE. This study also justified and evaluated the basis of the existing study. Nevertheless, the research objectives of the study were reviewed, and the main findings are systematically discussed below:

Objective One: Conducting a comprehensive literature review of sustainable-based smart air-conditioning systems with a holistic view.

One of the most extreme troubles confronting humankind in the 21st century is energy. Non-renewable energy sources, such as petroleum, natural gas and coal, have been the fundamental energy assets for human culture. The consumption of non-renewable energy sources has caused and is still causing harm to the environment. By 2050, the demand for energy could be twofold, or possibly threefold, as the worldwide populace develops, and emerging districts grow their economies. This has recently raised concerns in sustainable development over climate change, global warming, accelerating environmental influences like ozone layer reduction, energy resources reduction, insufficient thermal comfort, health issues, high cost and possible supply problems. However, the most generally utilised meaning of sustainability is the Brundtland report's meaning of sustainable development according to Mebratu (1998), *meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (WCED, 1987).* For Giddings et al. (2002), it is contended that this definition is human-centric as it proposed that human rely upon the environment to address our issues, it is just our human needs that is of major importance (Hopwood et al. 2005). In any case, it assumes that in any event as far as human lifetimes, a long-haul view should be established with the goal of sustainability to be accomplished. Principally, the economy is a subset of society which therefore is a subset of the environment. As indicated by Van der Vorst et al. (1999) and Thomas (2015), environmental sustainability requires economic, and social sustainability relies on environmental sustainability. On the other hand, the three areas of sustainability can be treated with equality as suggested by Newton (2003), Thomas (2015) and Hak et al. (2016). In the light of this, an inquiry about whether a system is sustainable should be considered in light of the three bottom line principles of sustainability.

Subsequently, the increasing utilisation of air-conditioning innovation empowers innovative development which can proficiently use renewable energy, for example, solar-controlled systems for its task. Discrepancies in fossil fuel costs have offered an increase to a dynamic quest for other energy sources (Rafique et al. 2015; Watt et al. 2015). Comprehending the concealed effects of fossil fuels and their outcomes on the well-being of humans is crucial for evaluating the sustainability of air-conditioning and for reinforcing more noteworthy decisions for future energy generation. However, Gao et al. (2012) and Beama (2016) uncovered that poor air quality within the conditioned environment is linked to asthma, pneumonia, dementia, COPD, lung cancer, stroke, etc. Therefore, a smart-based indoor control system for improvement of the IAQ and performance on energy management is vital in achieving the system's overall sustainability goal.

Research studies by Akadiri (2012) and Hak et al. (2016) suggested that the system approach accentuates that discrete technologies are not only upheld by the more extensive technological system yet in addition by the framework of economic, environmental and social standards that fortifies that innovative system. These incorporate formal limitations, for example, economic viewpoints, policies and casual requirements, for example, behavioural and social hindrances. Consequently, this study recommends that one must deliberate upon all the drivers in sustainability when designing transformations to air-conditioning; one also must take into account that individual technology is not only buttressed by the extensive technological system but the sustainability framework that underpins the technological system. So, it is important to understand the sustainability indicators of the three bottom line principles of sustainability namely, environment, economic and social, and how the renewable and smart approach can contribute to the overall sustainability of the system. This can even offer substantiated insight into sustainable approaches for promoting the novelty of smart air-conditioning for greater sustainability. What is key to the sustainable-based smart air-conditioning as a sustainable system (environment, economic and social) is not so much the levels of energy consumption and carbon emission, but the renewables and smart control it is based on and the theoretical sustainable framework this founds. This is because, without these key components, it would not be possible to suggest whether or not the IAQ management; levels of energy consumption and carbon emissions are elevating this proposed system into sustainable trouble.

Objective Two: Development of scenario modelling of sustainable-based smart air-conditioning.

This study substantiated the development of the system modelling in accordance with the proposed sustainable theoretical framework. The conceptual modelling approach is employed to model the photovoltaic solar air-conditioning and the smart IAE. Subsequently, the modelling of solar air-conditioning, the indoor temperature and IAQ are designed to improve the quality of air in the indoor environment while achieving significant energy savings and carbon reductions, vis-à-vis tackling global warming, climate change and health effects on residents.

The modelling of photovoltaic solar air-conditioning is studied, and examinations suggested that it can give the anticipated power to an electrically controlled cooling. The conceptual modelling of photovoltaic solar air-conditioning is methodically examined, and each component of the system and its specifications are described. The system components of the adsorption and absorption of solar air-conditioning are studied and used as a basis for the system's description. The modelling offers to provide the energy efficiency and the CO_2 savings which is, in turn, an absolute necessity in each building to accomplish a decent level of appropriate indoor comfort within the building, vis-à-vis improving human adaptation in the indoor environment. Consequently, indoor environment quality has fundamentally influenced inhabitants' well-being, individuals' efficiency and comfort feelings. Thus, significant factors, for example, the indoor temperature and IAQ are examined and must be properly controlled for the growing demand expectation for everyday comforts. In any case, significant troubles exist that cut off the control innovations development for the control of indoor environment quality.

For the purpose to resolve the difficulties of indoor environment control, this study designed smart controllers (fuzzy PID controller and backpropagation NN-PID) for controlling indoor temperature and IAQ (CO_2), respectively. The controller designs which incorporate the algorithms and structures control are thoroughly examined. In the literature, the indoor temperature control problems are described, and a fuzzy PID controller is designed in this study to resolve the difficulties, vis-à-vis to attain the purpose of sustaining and optimising the anticipated indoor environment quality. This controller structure comprises two key portions which are the PID control for indoor air temperature control and FLC for adjusting the PID controller parameters as stated by the existing conditions of the indoor environment. The indoor environment quality can be well-controlled grounded upon the theoretical dialogue of the algorithm of the projected fuzzy PID controller as-long-as:

- selection of better parameters of PID can guarantee the required output of the system;
- ensuring the controller of the PID is appropriate for the control object;
- the control of fuzzy logic for optimal parameters of PID regulation to guarantee compliance to diverse conditions.

Subsequently, the indoor environment control has several problems as described in the literature and backpropagation NN which is based upon PID is designed in this study to resolve the problems. The IAQ control difficulties can be finalised as follows:

- occurrence of mismeasurement;
- delay of time;
- lag-behind system response: the change of indoor environment.

To optimise and sustain the appropriate level of IAQ (CO_2), backpropagation NN which is based upon PID is designed in this study. The anticipated backpropagation NN based upon the PID controller integrate the PID controller and a NN which is applied to the algorithm of backpropagation. This controller structure comprises two key portions which are the PID control for IAQ and backpropagation NN for adjusting the PID controller parameters as stated by the existing conditions of the indoor environment. The IAQ can be well-controlled grounded upon the theoretical dialogue of the algorithm of the backpropagation NN which is based upon a PID controller that possesses the subsequent capacities:

- NNs for ideal parameters of PID regulation to guarantee rapid disturbance recovery;
- algorithm of backpropagation for weights adjustment in NN to guarantee the system rapid answer to changes in the indoor environment;
- PID controller is appropriate for several object control as well as IAQ.

In the drive towards the development of a sustainable-theoretical framework for renewable smart air-conditioning, this examination unfolds that using photovoltaic power and smart indoor controllers provides a realistic sustainable approach.

Objective Three: Using a computer model to analyse the efficiency and effectiveness of the developed sustainable theoretical framework.

The developed sustainable theoretical framework reveals that the proper performance of the proposed system is essential to depict the fundamental ideology of sustainability. Therefore, the proposed photovoltaic solar air-conditioning and the two system controllers namely, fuzzy PID controller and backpropagation NN which is grounded upon PID controller are sustainable based. It can accomplish a comfortable and healthy indoor environment quality while reducing the rate of energy consumption and carbon emissions.

The simulations are systematically carried out on the Polysun and Matlab program, respectively, which is theoretically grounded upon the modelling of photovoltaic solar air-conditioning and indoor environment control. The results of the simulations are deliberated upon to evaluate the performance of photovoltaic solar air-conditioning, and the indoor environment controllers' executions on indexes such as stability, adaptability, speed response, overshot and time constant. As well, the controller design potential for controlling indoor environment quality is deliberated grounded upon the results of the simulations. In this study, the components of the photovoltaic solar air-conditioning are simulated in the Polysun software, and the results revealed that the system could provide the required yearly energy yield without compromise. Also, the simulation results of photovoltaic solar air-conditioning uncover the importance of using renewable as a source of clean energy in air-conditioning systems and the particular contribution it makes to the level of energy consumption and carbon emission. The system significantly demonstrates the importance of using solar energy as alternative to fossil fuel to power air-conditioning systems, vis-à-vis combatting global warming and climate change and hereby promoting sustainable development.

The input and step signals are fundamentally applied as the reference control for the projected fuzzy PID controller. The outcomes demonstrated that the projected controller possesses appropriate execution on well-organised auto-tuning of the parameters of PID exclusively once required. This remains essentially in view of the adaptability, stability, small steady error, small overshot and speedy response to indeterminate influences. In short, the anticipated smart temperature regulator can possess appropriate execution on controlling indoor temperature since the indoor environment temperature can be effectively regulated through the PID controller. Likewise, the parameters of the PID auto-tuning can guarantee improved PID control execution and then, the parameters of the PID rule are grounded upon the fuzzy logic rule which guarantees flexibility to various circumstances in temperature control procedure. Therefore, these advantages brand the projected controller appropriate for resolving the key problems in controlling the indoor environment temperature. Accordingly, the indoor CO_2 concentration simulation changing model is accomplished in this study to designate the performance of backpropagation NN which is based on PID control. Likewise, it is revealed using simulations that the backpropagation NN method can offer appropriate PID parameters and, in turn, enable the selected system output to be attained. As a result, the projected controller possesses suitable control execution in terms of adaptability, stability, management with the time changing parameter, small steady error, small overshot, settling speed, speedy rising and online training of the regulator as requested. Consequently, these brands the projected controller appropriate for IAQ control and proficient to unravel the main difficulties of indoor environment CO_2. Meanwhile, the execution indexes demonstrated that the PID controller is fundamentally appropriate for numerous control items as well as IAQ. Likewise, the NNs are suitable for ideal parameters of PID controller tuning that guaranteed the controller's steadiness, whereas the backpropagation algorithm is also appropriate for weights adjustments in NN which, in turn, guarantees that the system speedily responds to indoor environment transformation. As a result, there is development, steadiness and productivity of the system for greener solutions to the world's energy and wellbeing requirements.

Objective Four: Assessment of the economic impact of the renewable-based system.

In line with the principles of sustainability, the economic assessment of the renewable-based system is unfolded in this study. The economic assessment using the financial profitability of the solar air-conditioning namely, the ARR, NPV, payback period and the IRR. The financial profitability is systematically performed while highlighting the advantages and drawbacks of each financial assessment indicator for proper assessment of the system.

The economic assessment of the solar-based system demonstrated that ARR = 119.55%, payback period = 5.5 years, $NPV > 0$ and IRR = 19.31%. This implies that significant savings can be achieved through utilising a sustainable and renewable means of technology – the photovoltaic solar air-conditioning technology. Each financial assessment indicator portrayed that the project is worth undertaking. Therefore, the photovoltaic solar air-conditioning demonstrates to reduces the level of energy consumption, and carbon emissions and saves investment costs. However, it also analytically demonstrates to meets the sustainable agenda in this study, which is the economic sustainability of the renewable air-conditioning.

Albeit over a long period, all project ought to earn profits that is sufficient to grow and survive. For improved living standard and national income is the index to the system's economic progress. Indubitably, profit is the legitimate object of the proposed photovoltaic solar air-conditioning; even so, it must not remain fundamentally over-emphasised. Possessors of the proposed system may attempt to make the best use of the project profit considering the society's welfare. Therefore, profit is not just the return to possessors; however, it is likewise associated with the interest of the society and other sectors. Profit is the measure for arbitrating not only for the economic sustainability, but likewise the social purposes, management and efficiency of the system. In essence, the economic assessment analysed in this study yielded a profitable outcome and therefore, the proposed solar-based air-conditioning is envisaged to yield an achievable return while reducing the rate of energy consumption and carbon emissions.

Objective Five: Refine and validate the theoretical framework resulting into the sustainability of the system.

This study uncovered an analytical grid that is subsequently augmented by the three pillars of sustainability namely, environment, social and economic which, in turn, unfolds the basis of sustainable smart air-conditioning. The sustainable theoretical framework of the proposed system is methodically designed by way of the adaptation strategy of the three bottom line principles of sustainability.

- *Environmental Sustainability:* Numerous environmental issues influence sustainability such as the energy consumption and carbon emissions emanating from the use of air-conditioning systems around the world causing climate change and health effects on inhabitants. There is also a loss of biodiversity all over the biosphere, owing to economic growth and other related factors as a result of the constant usage of the air-conditioning system during the hottest period of the year, and this subsequently put threats to sustainability. The use or removal of deficient resources from the environment and the release of wastes and emissions emanating from the use of air-conditioning to the land, air and water likewise put sustainability in danger. The air pollutants emitted by fossil fuel-fired electrical power plants, internal combustion engines in vehicles and several industrial actions can badly influence IAQ and the health of the human beings. This can occur during the utilisation of air-conditioning since the outdoor air is not often mixed with the indoor air during the system operation. Hence, the environmental sustainability result of the proposed photovoltaic solar air-conditioning coupled with the smart controllers of the indoor environment – linked with the social sustainability can accomplish such comfortable and healthy indoor environment quality. It can also combat global warming and climate change effects. The environmental sustainability outcome demonstrated achievement in the reduction of energy consumption and carbon emissions with appropriate control performance and inhabitants' comfort improvement.

- *Social Sustainability:* The development of a sustainability rationale to comprise a strong social constituent took some time. Initial effort on sustainability is usually concentrated upon either economic sustainability or environmental sustainability while neglecting the social sustainability factors. The importance of the development of both society and humans has been recently realised. The health and wellbeing of the users of the air-conditioning systems are significant as studies in the literature proposed that majority of people spent about 80% – 90% of their time at home. Therefore, the social sustainability which is, in turn, linked with the environmental sustainability of indoor environment control for the indoor temperature and IAQ (CO_2), which are fundamentally connected to the renewable energy of the proposed system is vital in achieving a healthy living environment for the building inhabitants. The social sustainability outcome of the system can tackle poor IAQ and demonstrate accomplishment in the reduction of the level of energy consumption and carbon emissions with appropriate control performance and occupants' comfort improvement.

- *Economic Sustainability:* A sustainable society needs continuing economic development somewhat than unbiassed economic growth. What happens currently is the economic growth as described in the literature which is frequently measured as growth in a gross local product where consumerist economies rely upon economic growth to produce prosperity and occupations. For this reason, studies unfolded that the economy functions within a globe possessing limited capacities and resources, over the long term, a constantly growing economy is not inevitably sustainable. Hence, the universal economy must function more in a stable-state manner, with zero or little development. This fundamentally suggests that the economic assessment of the proposed system in this study must be equated as a stable-state manner irrespective of the financial profitability analysis outcome to promote economic growth and the system benefits the society since a growing economy is not certainly sustainable. In this study, the economic sustainability assessment result of the solar-based system demonstrated how significant savings can be achieved through utilising a sustainable and renewable means of technology which uncovers that the proposed system is worth undertaking. As highlighted in the literature, economic sustainability opinions are divided into categories of strong and weak sustainability where the 'strong' focus more on the environment while the 'weak' focused more on the system's financial assessment. Albeit this study focused more on the strong sustainability of the system for the benefit and overall welfare of the society for constant economic growth. This is because, without this key component of strong sustainability, it would not be possible to suggest whether or not the levels of energy consumption, carbon emissions and the indoor environment smart control are developing this proposed system into a sustainable misfortune.

Consequently, semi-structured interviews with the system experts were conducted to externally validate the sustainable theoretical framework for smart air-conditioning. The outcome revealed that the existing system affects the health of inhabitants and adds to the rate of energy consumption and carbon emissions, and the proposed system is a commendable development towards improving air-conditioning systems for a sustainable future without compromising the health of inhabitants. One major disadvantage expressed by three of the participants was that the aspect of intelligent indoor environmental control had a rigorous equation form, and its procedure appears to be unconventional and difficult to understand. Generally, the interviewers agreed with the basis of the developed sustainable theoretical framework for smart air-conditioning systems and applauded its form in the easy-to-understand framework concept. The connection of the three pillars of sustainability namely environmental, economic and social with the air-conditioning system for an anticipated smart and sustainable future was likewise applauded by the interviewees. However, the lack of consideration of the three pillars of sustainability in the existing air-conditioning system suggested the continuance of the increase in the level of energy consumption, carbon emissions, health problems and climate change effects.

8.3 Academic Significance and Relevance to Practice

In the feasibility study for the development of a sustainable theoretical framework for smart solar air-conditioning for this research work, it was necessary to construct a conceptual framework to enable this research to map out the state-of-the-art in terms of how to achieve sustainability balance from three standpoints, namely: the environmental, economic and social sustainability. Although from the literature review, several frameworks have been mapped out in the area of sustainability for districts, sustainability as a tool for manufacturing decision making and sustainable developments projects according to studies from Nazzal et al. (2013), Russell-Smith et al. (2015), Krajacic et al. (2015: 2018). This collective body of evidence failed to establish a sustainability approach that simultaneously reflects the three bottom-line principles of sustainability namely economic, environmental and social for smart sustainable systems. Conversely, several methodology assessments emphasise only one sustainability area or dimension such as the environment or economic sustainability.

Environmental sustainability requires economic sustainability, and social sustainability relies on environmental sustainability. Like wisely, the three areas of sustainability can be treated with equality as proposed by this study. The promotion of sustainable practices is typically pursue a balance between environment, economic and social performance in project applications. That is to say, the connection between sustainability, renewable energy and smart control for air-conditioning becomes clear to reduce the level of energy consumption and rates of carbon emissions while the associated link to social sustainability tackles the thermal comfort of inhabitants; the air-conditioning system is of strong environmental significance and subsequently has high economic and social influences. Therefore, Table 8.1 presented the research contributions and relation to previous publications associated with principles of sustainability.

Table 8.1: Research contributions and relation to previous publications

	Previous publications	Contributions to the state-of-the-art
Environmental Sustainability	Zhang et al. (2016), Jafari and Poshtiri (2017) and Buonomano et al. (2018) presented the current state-of-the-art of solar air-conditioning system performance and design without considering optimisation opportunities through the combination of sub-system components. Their studies presented a low COP of 0.6 and 0.71, respectively, having low efficiency. The low COP is a result of the poor performance of the system due to the system components employed. Moreover, they failed in their studies by focusing on one aspect of sustainability to achieve a sustainable development goal. Therefore, their studies were unable to improve the overall sustainability of the solar air-conditioning system.	• This study contributed to the current state-of-the-art by optimising the solar air-conditioning to achieve an efficient performance of the system through using appropriate design. Holistic and integrated interaction of the improved system components saved significant energy usage with high carbon emission savings. • This study contributed by presenting an improved sustainable system having a higher COP of 3.97, 3.69 and 3.37 in the three locations explored. This equates to the higher efficiency of the system due to the appropriate sub-system components employed. • This study contributed to knowledge by providing an improvement of the system by combining the three sustainability principles to achieve the overall system sustainability. The concept of the new sustainable system using the sustainability principles enhanced the sustainability of air-

		conditioning to reduce the level of energy consumption and carbon emissions.
Social Sustainability	De-Maity and Mudi (2015), and Doroshenko (2017) presented the current state-of-the-art knowledge of smart air-conditioning system using conventional control methods of PID. The PID was designed according to the model of the building, and model mismatch produced poor control performance. The fuzzy controllers have inaccurate membership functions and lack of adequate methodical technique for expert knowledge transformation into the rule base. However, Behrooz et al. (2018) presented a system requiring an expert knowledge with certain skills to operate and this restricts the usefulness of such controllers. The current state-of-the-art of control algorithms offered by Behrooz et al. (2018) does not have appropriate control performance and do not offer precise control for air-conditioning. Therefore, recent studies failed to offer adequate technique and suitable control performance for the sustainability of the air-conditioning system.	• For better performance and more efficiency, this study contributed to the current state-of-the-art by providing new control approaches for air-conditioning. This study offered an improved model matching and parameters tuning having model-independent control approaches that enabled an appropriate time constant and settling time for indoor temperature and CO_2, respectively. • The newly innovative control methods combined with advanced and conventional control (FLC-PID and Backpropagation NN-PID) techniques are presented in this study. • Improved and accurate membership functions and adequate methodical technique for expert knowledge transformation into the rule base are presented. This offers improved algorithm control which can observe the level of habitation and adjust the change of the air-conditioned area to improve energy efficiency and IAQ.

		• The indoor level of air pollutants is incorporated in the newly developed control process, which will allow regulating of air changing rate precisely to enhance the system energy efficiency which does not require an expert knowledge with certain skills to operate. • This study contributed to knowledge by providing a new improved smart approach for observing human behaviour, to enable it adapt to the control process for precise control response. The performance of the indoor environment quality assessment system is incorporated for improvement to make the control process have a modifying and self-learning capability.
Economic Sustainability	Gilding (2011) and Thomson (2013) provided that the use of cost saving technology having reduced running cost with minimum maintenance are paramount to achieve economic sustainability of a system. Therefore, Al-Ani, (2015) and Neil et al. (2018) recently revealed that ARR, NPV, payback period and IRR recognises the concept of net	• This study contributed to the current state-of-the-art by presenting a bespoke price of the system components and reduced running costs with minimum maintenance to achieve the economic sustainability of the system. • This study examined all profitability assessment indicators to provide a clear picture of the

	earnings and is a vital factor in the appraisal of a system investment proposal. It facilitates the comparison of new product project with that of cost reducing project or other projects of competitive nature. Their studies further proposed that system designers/engineers often fail to employ all the profitability indicators in their analysis and only focussed on the payback period. Subsequently, Hadj et al. (2015), and Greenaway and Kohlenbach (2017) presented the current state-of-the-art of solar air-conditioning system having high payback period of 13 years and 21 years, respectively. Their project is not sustainable and can be expensive, especially for low-income earners. They likewise failed in their studies by focusing on economic sustainability to achieve a sustainable development goal for the system.	profitability of the proposed system. The ARR = 119.55%, payback period = 5.5 years, $NPV > 0$ and IRR = 19.31%. This implies that significant savings can be achieved through utilising a sustainable and renewable means of technology. • This study offered a sustainable and efficient system having a low payback period of 5.5 years. Each financial assessment indicator portrayed that the project is worth undertaking. This study significantly improved on previous studies by consolidating the three sustainability principles through a framework approach to achieve the overall sustainability of the presented system.

The proposed system for smart solar air-conditioning takes into consideration the three dimensions of sustainable development. It is widely recognised and accepted that sustainability assessment should take into account the three dimensions of sustainable development (Thomas, 2015; Hak et al. 2016). Various key issues and indicators have been taken into consideration in order to ensure effective application of the sustainable framework. The developed sustainable assessment framework guide encourages clients, designers, contractors and facilities managers to embrace the sustainability agenda from the inception of a project, and to treat sustainability equally as an integral concern throughout rather than as a technological fix that can be bolted on at the end. This framework covers every phase of an air-conditioning system from the development of a vision for sustainability shared between the client and design team, to good practice in the day-to-day operation of the completed system.

The framework proposed in this study also strives for evaluating how the framework can be utilised in practice to inform investment decisions, providing the researcher with the opportunity to further their research, and more importantly, the significant contribution it may make in practice. Integrating sustainability in practice implies that the definition and perception of project success take into account the ‘triple bottom line’ of economic, social and environmental benefits as provided in this study, both in the short term and in the long term. This suggests that the success of the project is assessed based on its sustainable outcome and not only based on a financial assessment.

The developed framework highlighted sustainability issues, acted as a starting point for clients and designers, and provide a range of ideas for consideration. While some principles, like energy conservation, are fundamental, many emerging technologies are undergoing rapid development. Furthermore, this study has great potential in improving the method in developers, engineers and designers use in addressing the issue of sustainability in air-conditioning. This will offer designers a systematic approach to achieving sustainability and presents a model assisting in making this decision. Each phase of this study can be used in practice.

8.4 Contributions to Knowledge

This study uncovered the contribution of renewable energy source and smart control technologies in the air-conditioning and the significant contribution it makes to the IAQ, levels of energy consumption and carbon emissions. It is attributed to the sustainability of the system and the contribution this, in turn, makes to tackling the associated health challenges and climate change as part of a sustainability-based strategy. It demonstrates that for this research, renewables and smart control options are the key components for the sustainability of air-conditioning study as they promote to reduce levels of energy consumption and carbon emissions. This establishes a comfortable and healthy indoor environment as an exercise in the development of sustainable smart air-conditioning. It reveals the key green values they make to the levels of energy consumption, rate of carbon emissions and the health effects on inhabitants. It sets a standard of “sustainable-based framework” that not only tackles poor IAQ but also combats global warming and climate change. This study also contributes to knowledge in the following ways:

- Delivered outstanding innovative standards to the current state-of-the-art that uncovers a standard of the sustainable-based framework through the three bottom-line principles of sustainability for the development of sustainable smart air-conditioning.
- Identified the degree to which the sustainability of smart air-conditioning is green. In particular, based on renewable energies, vis-à-vis solar power as alternatives to fossil fuels and the contribution this alternative source of energy makes to the social, environmental and economic aspects of embracing sustainable future developments. It enables to reduce of energy consumption, and carbon emissions and enhances smart control systems for IAQ as part of ensuring low cost for residents and maintaining optimum thermal comfort.
- Unfolded a procedure that makes a significant contribution to the sustainability of air-conditioning study. This, in turn, serves as a future criterion in structuring, selecting and sustaining a green (environmentally friendly) sustainable-based smart air-conditioning system that is focused on supporting sustainable development.

- Revealed significant sustainability indicators for developing future energy-efficient smart air-conditioning systems designed for the use of buildings. This, in turn, supports and promotes the clean, secure, and economically viable practice, vis-à-vis tackling poor IAQ and mitigating the worst effects of climate change.
- Demonstrated the use of renewable-powered air-conditioning systems associated with reduction of economic peak loads and related low costs while embracing sustainability, especially in the long term to make future urban suburbs more climate-resilient.
- Substantiated a significant and sustainable-based smart control technology that can combat future related issues of IAQ which is associated with the use of inhabitants in buildings. This, in turn, brings environmental, economic and social significance to the air-conditioning system that significantly sets the standards of a “sustainable-based framework”.

Consequently, this study proved that the best way to implement a sustainable framework technique is by using a key renewable-smart-based model of the principles of sustainability that is designed and examined for an air-conditioning system. It theoretically opens more possibilities to examine different attributes of renewable-smart-based models associated with the inhabitant of buildings while eliminating poor IAQ, reducing the rate of energy consumption and carbon emissions as part of climate change adaptation approaches. This shall assist future studies not only with the newly developed sustainable-based framework but also with a more applicable way to analyse diverse attributes of a renewable-smart-based model of sustainability associated with the use of the air-conditioning system.

To reveal the degree to which the contribution of solar energy and smart control technology greens the sustainability of air-conditioning: connections between the three pillars of sustainability and the derived values of photovoltaic solar air-conditioning and indoor environment quality are presented. By consolidating the contribution of solar energy, smart control innovation and profitability measures to the principles of sustainability – it demonstrated how the unique framework model of sustainable smart air-conditioning allows considering environmental, economic and social factors. This is associated with the major impacts they make in the development of the theoretical framework as a sustainable strategy for the sustainable-based smart air-conditioning, that not only tackles poor IAQ but also combats global warming and climate change.

8.5 Recommendations for Future Studies

The main work of this study is to challenge and extend existing knowledge on sustainability-related to smart air-conditioning systems considering social, environmental and economic dynamics. The outcome established that renewables and smart control options revealed from the sustainability indicators are the key components for the sustainability of air-conditioning study. The system promotes to reduce levels of energy consumption and carbon emissions, vis-à-vis establishing a comfortable and healthy indoor environment as an exercise in the development of sustainable-based smart air-conditioning. It reveals the key green values it makes to the levels of energy consumption, rate of carbon emissions and the health effects on inhabitants. It sets a standard of “sustainable-based framework” that not only tackles poor IAQ but also combats global warming and climate change.

The external validity of sustainable-based smart air-conditioning provided a basis to test the model through semi-structured interviews. However, it will be helpful to access the validity of the sustainable theoretical framework through a more quantitative technique. Testing the actual data through experimental investigation of the photovoltaic solar air-conditioning and the indoor smart control with predictions from the proposed theoretical sustainable framework will enhance the external validity and overview of the theoretical framework. It will likewise be highly beneficial for future studies to reduce or eliminate the assumptions made and limitations of the study. Therefore, the external validity is considered as moderate as it aims to accomplish an analytic overview, rather than a statistical overview of the study.

Nevertheless, the following directions of future studies can be considered as the continuation of this research:

- Further studies need to be done to reduce or eliminate the assumptions made and limitations of the study.

- Future studies can extend the developed theoretical sustainable framework to include sustainability principles for HVAC systems. This suggests that mechanisms of HVAC can be incorporated into the sustainable-based smart air-conditioning framework. It can consider the environment, economic and social dynamics of the system to systematically provide a comprehensive framework and analysis of the entire HVAC system.
- Further research can subsequently perform the experimental test of the system since the modelling and the theoretical working analysis of the photovoltaic solar air-conditioning are unfolded in this study.
- Future studies can perform an experimental test of the developed fuzzy PID and backpropagation NN-PID in a specified indoor environment.
- Future studies can consider other renewable energy technologies such as wind energy, hydropower, geothermal energy, etc., and subsequently integrate such renewable energy into the developed sustainable framework as an alternative source of energy. Thereby, comparing the outcome of solar energy to other renewable energy sources and further extending the developed sustainable framework. This would provide an even better understanding of carbon emissions and the energy performance of sustainable-based air-conditioning associated with the influence of the developed sustainable-based theoretical framework.
- Future studies can further extend the social sustainability of the theoretical framework to include public opinion. This suggests undertaking further research to consider the perceptions and interests of the public on the sustainability of the system.
- The sustainable-theoretical framework can be developed further into a morphological model for a regional sustainable smart system. This suggests that the developed theoretical sustainable framework can be reviewed into a morphological model to achieve a mass sustainable smart air-conditioning of either a suburb, state, country, or the world in general.
- Further studies can be done to consider air-conditioning and the transmission of COVID-19 in an indoor environment. This suggests that epidemic transmission can be included in the theoretical framework and a sustainability approach to combat such epidemic spread can be proposed.

- Further research can consider retrofit options and extend the framework further by way of introducing a retrofit-based approach in the environment and social domain of the developed theoretical framework and then, assess the overall economic feasibility of the system. This suggests that retrofitting of buildings can be considered with the developed theoretical framework. It can be applied to a specific structure to achieve building-based retrofit of sustainable smart air-conditioning in a bid to further reduce the level of energy consumption and carbon emissions, and subsequently combat climate change.

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Appendixes

Appendix A

Electrical Result (Annual Values) – London District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Degree of self-sufficiency	Raut	%	37.6	100	100	100	39.8	35.9	37.6	36.4	35.8	45.9	95.9	100	100
Self-consumption fraction	Rocs	%	17.5	0	0	0.002	1.8	9	30.3	45.9	41.2	25.2	0.04	0	0
Feed-in ratio	Rocsp	%	82.5	100	100	100	98.2	91	69.7	54.1	58.8	74.8	100	100	100
Radiation onto module area	Esol PV	kWh	47,546.1	1,873.4	2,267.3	3,728.9	4,974.1	5,836.3	5,490.3	5,725.4	5,709.9	4,661	3,650.7	2,221.2	1,407.6
Soiling losses	Qsoil	kWh	111.2	4.5	5.4	8.9	11.8	13.7	12.6	13.1	13.1	10.8	8.6	5.3	3.4
Mismatching losses	Qmism	kWh	216.8	8.8	10.6	17.4	23	26.7	24.6	25.5	25.5	21	16.8	10.4	6.6
Degradation losses	Qdegr	kWh	27.2	1.1	1.3	2.2	2.9	3.4	3.1	3.2	3.2	2.6	2.1	1.3	0.8
Cable losses	Qcbl	kWh	46	1.6	1.9	3.6	5.4	5.9	4.9	5.4	5.7	4.7	3.6	2.1	1.1
Yield Photovoltaics DC	Qpvf	kWh	5,158.2	210.6	253	413.5	547.1	634.9	586.5	605.4	606	499.3	398.6	246.7	156.7
Yield Photovoltaics AC	Qinv	kWh	4,656.9	188.7	226.7	372.8	494.9	574.8	529.6	547.1	549.1	452.2	360.4	221.6	138.9
Self-consumption	Eocs	kWh	813	0	0	0.01	9	51.9	161	251	226	114	0.1	0	0
Direct consumption	Edcs	kWh	813	0	0	0.01	9	51.9	161	251	226	114	0.1	0	0
To external grid	Eteg	kWh	3,843	189	227	373	486	523	369	296	323	338	360	222	139
From external grid	Efeg	kWh	1,352	0	0	0	13.7	92.9	267	438	406	135	0.01	0	0
CO2 savings	PvImp...	kg	2,498	101	122	200	265	308	284	293	295	243	193	119	74.5
Total fuel and/or electricity con...	Etot	kWh	-2,491	-188.7	-226.7	-372.8	-472.2	-430	-102.3	142	83.6	-203.5	-360.3	-221.6	-138.9
Performance ratio	PvPR	%	76.2	78.3	77.8	77.8	77.4	76.6	75	74.3	74.8	75.5	76.8	77.6	76.8
Specific annual yield	PvSpe...	kWh/k...	862	34.9	42	69	91.6	106	98.1	101	102	83.7	66.7	41	25.7
Own AC production	Eacp	kWh	4,657	189	227	373	495	575	530	547	549	452	360	222	139
Total electricity consumption	Ecs	kWh	2,166	0	0	0.01	22.7	145	427	689	633	249	0.2	0	0

Thermal Result (Annual Values) – London District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat removed from tank	Sout	kWh	8,572	0	0	-2.1	58.4	589	1,715	2,690	2,543	973	3.7	0	0
Heat generator energy to the s...	Qaux	kWh	10,874	0	0	0	124	758	2,151	3,394	3,190	1,256	0	0	0
Total energy consumption	Quse	kWh	8,594	0	0	2.1	58.3	589	1,719	2,697	2,548	974	7	0	0
Total energy demand	Qdem	kWh	8,393	0	0	0.2	26.6	418	1,626	2,908	2,549	829	36	0	0
Pump heat to system	Qpar	kWh	4.4	0	0	0.002	0.1	0.4	0.9	1.3	1.3	0.5	0.05	0.000001	0.000001
Heat loss to indoor room (inclu...	Qint	kWh	-131.9	0	0	-0.04	-27.3	-24.9	-18.1	-14.6	-14.5	-22.1	-9.2	-1	-0.2
Heat generator fuel and electri...	Eaux	kWh	2,151	0	0	0	22.5	144	424	685	628	247	0	0	0
Electricity consumption of pumps	Epar	kWh	14.8	0	0	0.01	0.2	1.2	2.9	4.3	4.4	1.6	0.2	0	0
Total fuel and/or electricity con...	Etot	kWh	-2,491	-188.7	-226.7	-372.8	-472.2	-430	-102.3	142	83.6	-203.5	-360.3	-221.6	-138.9
Seasonal performance factor (...	SPF-S...		4	0	0	0	2.6	4.1	4	3.9	4	3.9	0	0	0
Primary energy factor	eP		0.28	0	0	0.01	0.42	0.29	0.28	0.29	0.29	0.25	0.04	0	0

Electrical Result (Annual Values) – Toulouse District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Degree of self-sufficiency	Raut	%	42	100	100	100	51.5	44.2	37.8	40.3	42.3	48.1	83.4	99.8	100
Self-consumption fraction	Rocs	%	21.6	0	0	0.01	4.6	14.7	38.5	59.4	57.2	36.9	0.1	0.03	0
Feed-in ratio	Rocsp	%	78.4	100	100	100	95.4	85.3	61.5	40.6	42.8	63.1	99.9	100	100
Radiation onto module area	Esol PV	kWh	64,406	2,962.1	3,988.8	5,879.5	6,230	6,266.7	6,400.2	6,840	7,169.3	6,619.8	5,382.1	3,490.7	3,176.9
Soiling losses	Qsoil	kWh	149.6	7.2	9.7	14	14.7	14.5	14.6	15.3	16.1	15.1	12.5	8.3	7.7
Mismatching losses	Qmism	kWh	291.8	14	18.9	27.4	28.7	28.3	28.4	29.9	31.4	29.4	24.3	16.2	15
Degradation losses	Qdegr	kWh	36.7	1.8	2.4	3.4	3.6	3.6	3.6	3.8	3.9	3.7	3.1	2	1.9
Cable losses	Qcbl	kWh	69	2.9	4.5	7.2	6.8	6.4	6.2	6.8	7.6	7.7	6.2	3.6	3.1
Yield Photovoltaics DC	Qpvf	kWh	6,934.8	333.7	448	649.4	682.4	673.7	675.3	710.5	746.7	697.4	576.6	384.2	356.8
Yield Photovoltaics AC	Qinv	kWh	6,306.8	301.7	407.2	591.4	621.9	612	613.7	646.1	680.5	635.9	524.7	348.4	323.5
Self-consumption	Eocs	kWh	1,364	0	0	0.03	28.8	89.7	236	384	389	235	0.7	0.1	0
Direct consumption	Edcs	kWh	1,364	0	0	0.03	28.8	89.7	236	384	389	235	0.7	0.1	0
To external grid	Eteg	kWh	4,943	302	407	591	593	522	377	262	291	401	524	348	323
From external grid	Efeg	kWh	1,883	0	0	0	27.1	113	389	569	531	253	0.1	0.0001	0
CO2 savings	PvImp...	kg	3,383	162	218	317	334	328	329	347	365	341	281	187	174
Total fuel and/or electricity con...	Etot	kWh	-3,060.5	-301.7	-407.2	-591.4	-566.1	-409	12.1	306	240	-147.7	-523.9	-348.3	-323.5
Performance ratio	PvPR	%	76.2	79.2	79.4	78.2	77.6	76	74.6	73.5	73.8	74.7	75.8	77.6	79.2
Specific annual yield	PvSpe...	kWh/k...	1,168	55.9	75.4	110	115	113	114	120	126	118	97.2	64.5	59.9
Own AC production	Eacp	kWh	6,307	302	407	591	622	612	614	646	680	636	525	348	323
Total electricity consumption	Ecs	kWh	3,246	0	0	0.03	55.8	203	626	952	920	488	0.8	0.1	0

Thermal Result (Annual Values) – Toulouse District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat removed from tank	Sout	kWh	11,924	0	0	-2.5	194	796	2,365	3,413	3,321	1,833	7.5	-2.8	0
Heat generator energy to the sy...	Qaux	kWh	15,278	0	0	0	290	1,017	2,997	4,373	4,250	2,350	0	0	0
Total energy consumption	Quse	kWh	11,991	0	0	2.5	193	796	2,370	3,430	3,337	1,836	22.5	3	0
Total energy demand	Qdem	kWh	13,984	0	0	5.2	118	599	2,555	4,332	4,090	1,756	507	21	0
Pump heat to system	Qpar	kWh	6.1	0	0	0.01	0.2	0.5	1.2	1.6	1.6	0.9	0.3	0.03	0.000001
Heat loss to indoor room (inclu...	Qint	kWh	-107.2	0	0	-0.03	-26.1	-23	-13.2	-9.7	-9.5	-16.3	-5.4	-2.9	-1
Heat generator fuel and electric...	Eaux	kWh	3,225	0	0	0	55.4	202	622	947	915	485	0	0	0
Electricity consumption of pumps	Epar	kWh	21.2	0	0	0.03	0.4	1.5	4.1	5.6	5.5	3.1	0.8	0.1	0
Total fuel and/or electricity con...	Etot	kWh	-3,060.5	-301.7	-407.2	-591.4	-566.1	-409	12.1	306	240	-147.7	-523.9	-348.3	-323.5
Seasonal performance factor (S...	SPF-SHP		3.7	0	0	0	3.5	3.9	3.8	3.6	3.6	3.8	0	0	0
Primary energy factor	eP		0.28	0	0	0.02	0.25	0.26	0.3	0.3	0.29	0.25	0.06	0.06	0

Electrical Result (Annual Values) – Rome District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Degree of self-sufficiency	Raut	%	41	100	100	100	51.8	45.4	41.1	39.7	41	39.8	78.8	79	100
Self-consumption fraction	Rocs	%	31.7	0	0	0.01	5.8	28.2	60.2	82.6	84	46.5	0.2	0.04	0
Feed-in ratio	Rocsp	%	68.3	100	100	100	94.2	71.8	39.8	17.4	16	53.5	99.8	100	100
Radiation onto module area	Esol PV	kWh	71,619.9	3,809.4	4,247.9	6,595.6	6,567.5	7,426.8	7,486	7,952.2	8,000.3	6,786.7	5,873.1	3,750.8	3,123.5
Soiling losses	Qsoil	kWh	163.8	9.2	10.2	15.6	15.3	16.9	16.7	17.4	17.5	15.3	13.5	8.8	7.4
Mismatching losses	Qmism	kWh	319.5	17.9	19.9	30.4	29.9	33	32.6	34	34.1	29.8	26.3	17.1	14.5
Degradation losses	Qdegr	kWh	40.1	2.2	2.5	3.8	3.8	4.1	4.1	4.3	4.3	3.7	3.3	2.2	1.8
Cable losses	Qcbl	kWh	77	4.1	4.6	7.9	7.2	8.2	7.8	8.1	8.5	7.5	6.3	4	2.9
Yield Photovoltaics DC	Qpvf	kWh	7,590.4	424.8	473.3	721.7	709.5	783.9	773.5	808.3	810.6	706.9	625	407.4	345.5
Yield Photovoltaics AC	Qinv	kWh	6,917.6	385.9	431.1	659	647.1	714.1	705	737.1	740	645.1	570.7	369.4	312.9
Self-consumption	Eocs	kWh	2,195	0	0	0.04	37.3	201	425	609	622	300	0.9	0.1	0
Direct consumption	Edcs	kWh	2,195	0	0	0.04	37.3	201	425	609	622	300	0.9	0.1	0
To external grid	Eteg	kWh	4,723	386	431	659	610	513	280	128	118	345	570	369	313
From external grid	Efeg	kWh	3,159	0	0	0	34.7	242	609	924	896	453	0.3	0.04	0
CO2 savings	PvImp...	kg	3,711	207	231	353	347	383	378	395	397	346	306	198	168
Total fuel and/or electricity con...	Etot	kWh	-1,563.3	-385.9	-431.1	-659	-575.1	-270.9	328	796	778	108	-569.5	-369.2	-312.9
Performance ratio	PvPR	%	75.1	78.8	78.9	77.7	76.6	74.8	73.2	72.1	71.9	73.9	75.6	76.6	77.9
Specific annual yield	PvSpe...	kWh/k...	1,281	71.5	79.8	122	120	132	131	137	137	119	106	68.4	58
Own AC production	Eacp	kWh	6,918	386	431	659	647	714	705	737	740	645	571	369	313
Total electricity consumption	Ecs	kWh	5,354	0	0	0.04	71.9	443	1,033	1,533	1,518	753	1.2	0.2	0

Thermal Result (Annual Values) – Rome District

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat removed from tank	Sout	kWh	17,929	0	0	-3.4	250	1,655	3,533	4,928	4,881	2,682	4.7	-2.8	0
Heat generator energy to the sy...	Qaux	kWh	23,369	0	0	0	362	2,110	4,569	6,464	6,404	3,459	0	0	0
Total energy consumption	Quse	kWh	18,030	0	0	3.4	250	1,655	3,547	4,946	4,911	2,686	28.4	4	0
Total energy demand	Qdem	kWh	23,713	0	0	10.1	148	1,383	4,268	7,230	7,087	2,703	812	71.4	0
Pump heat to system	Qpar	kWh	8.6	0	0	0.01	0.2	0.8	1.6	2.1	2.1	1.2	0.4	0.1	0.000001
Heat loss to indoor room (includ...	Qint	kWh	-85.8	0	0	-1.6	-25.7	-18.5	-8.8	-4.2	-4.5	-12.1	-5.6	-3.5	-1.3
Heat generator fuel and electrici...	Eaux	kWh	5,324	0	0	0	71.4	440	1,028	1,525	1,510	749	0	0	0
Electricity consumption of pumps	Epar	kWh	30.3	0	0	0.04	0.6	3	5.6	7.7	7.7	4.4	1.2	0.2	0
Total fuel and/or electricity cons...	Etot	kWh	-1,563.3	-385.9	-431.1	-659	-575.1	-270.9	328	796	778	108	-569.5	-369.2	-312.9
Seasonal performance factor (S...	SPF-SHP		3.4	0	0	0	3.5	3.8	3.4	3.2	3.2	3.6	0	0	0
Primary energy factor	eP		0.32	0	0	0.02	0.25	0.26	0.31	0.34	0.33	0.3	0.08	0.08	0

Appendix B

Meteorological data for the district of London.

	Gh kWh/m^2	Dh kWh/m^2	Bn kWh/m^2	Ta °C	Td °C	FF m/s
January	21	13	33	7.4	3.2	3
February	35	24	34	7.4	2.2	2.6
March	70	43	60	9	2.8	2.7
April	105	68	73	11.8	4.5	2.2
May	143	77	110	15.1	7.7	2.4
June	144	92	91	18.4	10.1	2.1
July	145	78	112	19.7	11.9	2.3
August	130	76	95	19.8	12.4	1.9
September	87	43	88	17.2	10.5	2
October	54	31	59	13.6	8.4	2.2
November	26	16	39	10.3	5.5	2.2
December	16	11	26	7.5	3.3	2.4
Year	974	572	820	13.1	6.9	2.3

Meteorological data for the district of Toulouse.

	Gh kWh/m^2	Dh kWh/m^2	Bn kWh/m^2	Ta °C	Td °C	FF m/s
January	45	21	73	5.9	3.3	3.6
February	62	35	66	6.9	3	4
March	106	53	104	9.9	4.6	4.3
April	140	66	124	12.4	7	4.3
May	161	84	122	16.3	10.5	3.8
June	182	90	139	20.9	13.5	3.7
July	191	74	181	22.3	14.2	3.7
August	162	85	125	22.2	14.3	3.5
September	126	55	133	18.8	12.1	3.4
October	88	37	107	15.2	11	3.7
November	50	28	65	9.3	6.1	3.6

December	39	19	65	6.1	3.4	3.4
Year	1348	648	1304	13.8	8.6	3.8

Meteorological data for the district of Rome.

	Gh kWh/m^2	Dh kWh/m^2	Bn kWh/m^2	Ta °C	Td °C	FF m/s
January	51	24	78	8.2	2.6	0.9
February	69	34	80	9.3	2.4	1.2
March	115	58	106	12.3	5.5	1.4
April	138	68	110	15.3	8.6	1.3
May	180	85	145	20.4	12.3	1.2
June	192	76	174	24.4	15	1.4
July	205	81	189	27	16.6	1.6
August	175	68	167	27	17.5	1.4
September	127	56	126	22.3	14.6	1.2
October	89	48	88	18.4	12.7	0.8
November	53	30	62	13.4	8.1	1
December	41	20	63	9.5	4.2	0.9
Year	1433	650	1387	17.3	10	1.2

Appendix C

```
%Fuzzy Tunning PID Control
clear all;
close all;
warning off
a=newfis('fuzzpid');
a=addvar(a,'input','e',[-3,3]); %Parameter e
a=addmf(a,'input',1,'NB','zmf',[-3,-1]);
a=addmf(a,'input',1,'NM','trimf',[-3,-2,0]);
a=addmf(a,'input',1,'NS','trimf',[-3,-1,1]);
a=addmf(a,'input',1,'Z','trimf',[-2,0,2]);
a=addmf(a,'input',1,'PS','trimf',[-1,1,3]);
a=addmf(a,'input',1,'PM','trimf',[0,2,3]);
a=addmf(a,'input',1,'PB','smf',[1,3]);
a=addvar(a,'input','ec',[-3,3]); %Parameter ec
a=addmf(a,'input',2,'NB','zmf',[-3,-1]);
a=addmf(a,'input',2,'NM','trimf',[-3,-2,0]);
a=addmf(a,'input',2,'NS','trimf',[-3,-1,1]);
a=addmf(a,'input',2,'Z','trimf',[-2,0,2]);
a=addmf(a,'input',2,'PS','trimf',[-1,1,3]);
a=addmf(a,'input',2,'PM','trimf',[0,2,3]);
a=addmf(a,'input',2,'PB','smf',[1,3]);
a=addvar(a,'output','kp',[-0.3,0.3]); %Parameter kp
a=addmf(a,'output',1,'NB','zmf',[-0.3,-0.1]);
a=addmf(a,'output',1,'NM','trimf',[-0.3,-0.2,0]);
a=addmf(a,'output',1,'NS','trimf',[-0.3,-0.1,0.1]);
a=addmf(a,'output',1,'Z','trimf',[-0.2,0,0.2]);
a=addmf(a,'output',1,'PS','trimf',[-0.1,0.1,0.3]);
a=addmf(a,'output',1,'PM','trimf',[0,0.2,0.3]);
a=addmf(a,'output',1,'PB','smf',[0.1,0.3]);
a=addvar(a,'output','ki',[-0.06,0.06]); %Parameter ki
a=addmf(a,'output',2,'NB','zmf',[-0.06,-0.02]);
```

```
a=addmf(a,'output',2,'NM','trimf',[-0.06,-0.04,0]);
a=addmf(a,'output',2,'NS','trimf',[-0.06,-0.02,0.02]);
a=addmf(a,'output',2,'Z','trimf',[-0.04,0,0.04]);
a=addmf(a,'output',2,'PS','trimf',[-0.02,0.02,0.06]);
a=addmf(a,'output',2,'PM','trimf',[0,0.04,0.06]);
a=addmf(a,'output',2,'PB','smf',[0.02,0.06]);
a=addvar(a,'output','kd',[-3,3]); %Parameter kp
a=addmf(a,'output',3,'NB','zmf',[-3,-1]);
a=addmf(a,'output',3,'NM','trimf',[-3,-2,0]);
a=addmf(a,'output',3,'NS','trimf',[-3,-1,1]);
a=addmf(a,'output',3,'Z','trimf',[-2,0,2]);
a=addmf(a,'output',3,'PS','trimf',[-1,1,3]);
a=addmf(a,'output',3,'PM','trimf',[0,2,3]);
a=addmf(a,'output',3,'PB','smf',[1,3]);
rulelist= [1 1 7 1 5 1 1;
   1 2 7 1 3 1 1;
   1 3 6 2 1 1 1;
   1 4 6 2 1 1 1;
   1 5 5 3 1 1 1;
   1 6 4 4 2 1 1;
   1 7 4 4 5 1 1;
   2 1 7 1 5 1 1;
   2 2 7 1 3 1 1;
   2 3 6 2 1 1 1;
   2 4 5 3 2 1 1;
   2 5 5 3 2 1 1;
   2 6 4 4 3 1 1;
   2 7 3 4 4 1 1;
   3 1 6 1 4 1 1;
   3 2 6 2 3 1 1;
   3 3 6 3 2 1 1;
```

3 4 5 3 2 1 1;
3 5 4 4 3 1 1;
3 6 3 5 3 1 1;
3 7 3 5 4 1 1;
4 1 6 2 4 1 1;
4 2 6 2 3 1 1;
4 3 5 3 3 1 1;
4 4 4 4 3 1 1;
4 5 3 5 3 1 1;
4 6 2 6 3 1 1;
4 7 2 6 4 1 1;
5 1 5 2 4 1 1;
5 2 5 3 4 1 1;
5 3 4 4 4 1 1;
5 4 3 5 4 1 1;
5 5 3 5 4 1 1;
5 6 2 6 4 1 1;
5 7 2 7 4 1 1;
6 1 5 4 7 1 1;
6 2 4 4 5 1 1;
6 3 3 5 5 1 1;
6 4 2 5 5 1 1;
6 5 2 6 5 1 1;
6 6 2 7 5 1 1;
6 7 1 7 7 1 1;
7 1 4 4 7 1 1;
7 2 4 4 6 1 1;
7 3 2 5 6 1 1;
7 4 2 6 6 1 1;
7 5 2 6 5 1 1;
7 6 1 7 5 1 1;

```
    7 7 1 7 7 1 1];
a=addrule(a,rulelist);
a=setfis(a,'DefuzzMethod','centroid');
writefis(a,'fuzzpid');
a=readfis('fuzzpid');
%PID Controller
ts=0.2;
sys=tf(0.0527,[3373.42,1]);
sys1 = 10^6;
sys = sys*sys1;
dsys=c2d(sys,ts,'tustin');
[num,den]=tfdata(dsys,'v');
u_1=0.0;u_2=0.0;u_3=0.0;
y_1=0;y_2=0;y_3=0;
x=[0,0,0]';
error_1=0;
e_1=0.0;
ec_1=0.0;
ec = gradient(error_1);
kp0=0.3;
kd0=2.0;
ki0=0.0;
for k=1:1:500
    time(k)=k*ts;
    rin(k)=5;
    %Using fuzzy inference to tunning PID
    k_pid=evalfis([e_1,ec_1],a);
    kp(k)=kp0+k_pid(1);
    ki(k)=ki0+k_pid(2);
    kd(k)=kd0+k_pid(3);
```

```
    u(k)=kp(k)*x(1)+kd(k)*x(2)+ki(k)*x(3);
    if u(k)>=10
       u(k)=10;
    end
    if u(k)<=-10
       u(k)=-10;
    end
    yout(k)=-den(2)*y_1+num(1)*u(k)+num(2)*u_1;
    error(k)=rin(k)-yout(k);
    %%%%%%%%%%Return of PID parameters%%%%%%%%%%
    u_3=u_2;
    u_2=u_1;
    u_1=u(k);
    y_3=y_2;
    y_2=y_1;
    y_1=yout(k);
    x(1)=error(k); % Calculating P
    x(2)=error(k)-error_1; % Calculating D
    x(3)=x(3)+error(k); % Calculating I
    e_1=x(1);
    ec_1=x(2);
    error_2=error_1;
    error_1=error(k);
end
showrule(a)
figure(1);plot(time,rin,'b',time,yout,'r');
xlabel('time(s)');ylabel('T(C)');
grid on
figure(2);plot(time,error,'r');
xlabel('time(s)');ylabel('error(C)');
```

```
figure(3);plot(time,u,'r');
xlabel('time(s)');ylabel('PID output');
figure(4)
subplot(3,1,1);
plot(time,kp,'r');
xlabel('time(s)');ylabel('kp');
subplot(3,1,2);
plot(time,ki,'b');
xlabel('time(s)');ylabel('ki');
subplot(3,1,3);
plot(time,kd,'g');
xlabel('time(s)');ylabel('kd');
figure(5)
subplot(3,1,1);
plot(error,kp,'r');
xlabel('error');ylabel('kp');
subplot(3,1,2);
plot(error,ki,'b');
xlabel('error');ylabel('ki');
subplot(3,1,3);
plot(error,kd,'g');
xlabel('error');ylabel('kd');
figure(7);plotmf(a,'input',1);
figure(8);plotmf(a,'input',2);
figure(9);plotmf(a,'output',1);
figure(10);plotmf(a,'output',2);
figure(11);plotmf(a,'output',3);
plotfis(a);
fuzzy fuzzpid
```

Appendix D

```
%PID Control based on Backpropagation NN
clear all;
close all;

xite=0.28;
alfa=0.04;

IN=4;H=5;Out=3; %NN Structure

%wi= random [-0.5,0.5];

wi=[-0.4394 -0.2696 -0.3756 -0.4023;
-0.4603 -0.2013 -0.3024 -0.2596;
-0.4749 0.4543  -0.3820 -0.2437;
-0.3625 -0.4724 -0.3463 -0.2859;
0.1425  0.4279  -0.2406 -0.4660];

wi_1=wi;wi_2=wi;wi_3=wi;
wo=[0.3576 0.2616 0.2820 -0.1416 -0.1325;
    -0.1146 0.2949 0.1352    0.2205    0.4508;
0.3201 0.4566 0.3672    0.4962  0.3632];
%wo= ramdom[-0.5,0.5];
wo_1=wo;wo_2=wo;wo_3=wo;


x=[0,0,0];
du_1=0;
u_1=0;u_2=0;u_3=0;u_4=0;u_5=0;
y_1=0;y_2=0;y_3=0;


Oh=zeros(H,1);  %Output from NN hidden layer
error_2=0;
error_1=0;

ts=0.7;
for k=1:1:1000
time(k)=k*ts;
 rin(k)=1.0;
```

```
%nonlinear model
a(k)=1.4*(1-0.8*exp(-0.1*k));
yout(k)=a(k)*y_1/(1+y_1^2)+u_1;

error(k)=rin(k)-yout(k);

xi=[rin(k),yout(k),error(k),1]

x(1)=error(k)-error_1;
x(2)=error(k);
x(3)=error(k)-2*error_1+error_2;

epid=[x(1);x(2);x(3)]
I=xi*wi';
for j=1:1:H
Oh(j)=(exp(I(j))-exp(-I(j)))/(exp(I(j))+exp(-I(j))); %hidden Layer
end
K=wo*Oh;    %Output Layer
for l=1:1:Out
        K(l)=exp(K(l))/(exp(K(l))+exp(-K(l))); %Getting kp,ki,kd
end
kp(k)=K(1);ki(k)=K(2);kd(k)=K(3);
Kpid=[kp(k),ki(k),kd(k)];

du(k)=Kpid*epid;
u(k)=u_1+du(k);

dyu(k)=sign((yout(k)-y_1)/(du(k)-du_1+0.0001));

%Output layer
for j=1:1:Out
dK(j)=2/(exp(K(j))+exp(-K(j)))^2;
end
for l=1:1:Out
delta3(l)=error(k)*dyu(k)*epid(l)*dK(l);
end

for l=1:1:Out
     for i=1:1:H
 d_wo=xite*delta3(l)*Oh(i)+alfa*(wo_1-wo_2);
```

```
    end
end

wo=wo_1+d_wo+alfa*(wo_1-wo_2);
%Hidden layer
for i=1:1:H
dO(i)=4/(exp(I(i))+exp(-I(i)))^2;
end
segma=delta3*wo;
for i=1:1:H
     delta2(i)=dO(i)*segma(i);
end

d_wi=xite*delta2'*xi;
wi=wi_1+d_wi+alfa*(wi_1-wi_2);

%Parameters Update
du_1=du(k);
u_5=u_4;u_4=u_3;u_3=u_2;u_2=u_1;u_1=u(k);
y_2=y_1;y_1=yout(k);

wo_3=wo_2;
wo_2=wo_1;
wo_1=wo;

wi_3=wi_2;
wi_2=wi_1;
wi_1=wi;

error_2=error_1;
error_1=error(k);
end

ec = gradient(error);

figure(1);
plot(time,rin,'r',time,yout,'b');
xlim([0 100])
xlabel('time(s)');ylabel('CO2');
grid on
```

```
figure(2);
plot(time,error,'r');
xlim([0 100])
figure(3);
plot(time,u,'r');
xlim([0 100])
xlabel('time(s)');ylabel('PID output');
figure(4);
subplot(311);
plot(time,kp,'r');
xlim([0 100])
xlabel('time(s)');ylabel('kp');
subplot(312);
plot(time,ki,'g');
xlim([0 100])
xlabel('time(s)');ylabel('ki');
subplot(313);
plot(time,kd,'b');
xlim([0 100])
xlabel('time(s)');ylabel('kd');
figure(5);
subplot(311);
plot(error,kp,'r');
xlabel('error');ylabel('kp');
subplot(312);
plot(error,ki,'g');
xlabel('error');ylabel('ki');
subplot(313);
plot(error,kd,'b');
xlabel('error');ylabel('kd');
figure(6);
subplot(311);
plot(ec,kp,'r');
xlabel('ec');ylabel('kp');
subplot(312);
plot(ec,ki,'g');
xlabel('ec');ylabel('ki');
subplot(313);
plot(ec,kd,'b');
xlabel('ec');ylabel('kd');
```

```
figure(7);
subplot(311);
plot(u,kp,'r');
xlabel('u');ylabel('kp');
subplot(312);
plot(u,ki,'g');
xlabel('u');ylabel('ki');
subplot(313);
plot(u,kd,'b');
xlabel('u');ylabel('kd');
figure(8)
subplot(311)
plot(yout,kp,'r');
xlabel('yout');ylabel('kp');
subplot(312);
plot(yout,ki,'g');
xlabel('yout');ylabel('ki');
subplot(313);
plot(yout,kd,'b');
xlabel('y');ylabel('kd');
```

Appendix E

Specifications of solar panel

Sseries | SOLAR PANEL

SC 20

SC 20 Sseries charge controller that adopts the most advanced digital technique and operates fully automatically. The Pulse Wigth Modulation (PWM) battery charging can greatly increase the lifetime of battery.

Specifications

Code Type	53-031	
Model	SC 20	
Rated Voltage	12V	24V
Equalize Charging Voltage	14.8V	29.6V
Boost Charging Voltage	14.6V	29.2V
Float Charging Voltage	13.8V	27.6V
Low Voltage Disconnect Voltage	11.1V	22.2V
Load Current	20A	
Working Temperature	-35°C ~ +55°C	
Self Consumption	6mA (MAX)	
Net Weight	0.3kg	
Size	14.4x7.5x4.5cm	

Features

- 12/24V auto work
- High efficient Series PWM charging
- Use MOSFET as electronic switch
- Gel, Sealed and Flooded battery type option
- Temperature compensation
- Electronic protection: over charging, over discharging, overload, short circuit, and overheating
- Reserve protection: any combination of solar module and battery

Applications

- Solar traffic system
- Solar home system
- Solar billboard
- Solar detection equipment, etc.

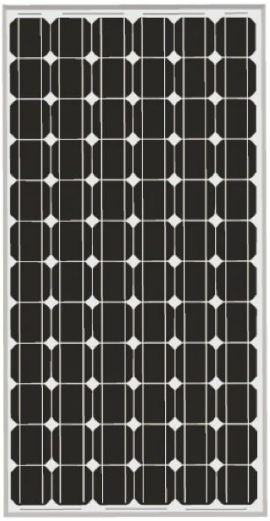
Connection Diagram

Specifications of monocrystalline module

MONO CRYSTALLINE MODULE

SPECIFICATIONS

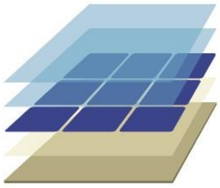
Module Type	SPU-180M	SPU-180M	SPU-180M
Maximum Power (Pmax)	180 Wp	190 Wp	200 Wp
Maximum Power Voltage (Vmp)	36.0 V	36.6 V	38.7 V
Maximum Power Current (Imp)	5.0 A	5.19 A	5.17 A
Open-circuit Voltage (Voc)	44.8 V	45.2 V	45.9 V
Short-circuit Current (Isc)	5.29 A	5.56 A	5.50 A
Dimensions (mm)		1580x808x35	
Operating Temperature		-40°C - 85°C	
Maximum system voltage		1000V	
Maximum rated current series		10 A	
Power Tolerance		±3%	
Temperature coefficient of Pmax		-0.48%/°C	
Temperature coefficient of Voc		-0.33%/°C	
Temperature coefficient of Isc		0.04%/°C	
Nominal operating cell temperature (NOCT)		48±2°C	
Bypass Diode		3	
Junction Box IP Rating		IP 65 (dust & water protection)	
Netto Weight		14.36kg	
Package		2 pcs / box	
Gross Weigth		33.4 kg	
Lifetime		20 years	
Solar Cell Type		Monocrystalline	
Efficiency	14,10%	14,88%	15,67%



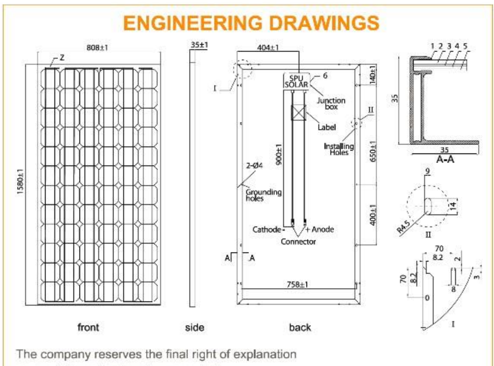
Certified

SNI 04 - 3850.2 -1995 By **BPPT**
Characteristic Current And
Voltage of Photovoltaic

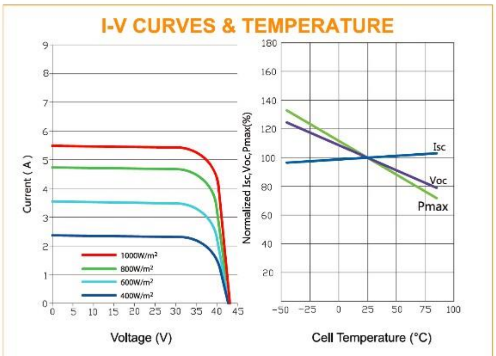
SNI 04-6298-2000
Salt Resistance



STC: Irradiance 1000W/m² | Module Temperature 25°C | AM=1.5



The company reserves the final right of explanation on any information hereby presented



I V Curves & Temperature Dependence of Isc,Voc,Pmax

Specifications of inverter

Model	**FPC-1000A**
Peak Power	2000W
Maximum input voltage	750 V
Output Waveform	pure sine wave
Harmonic Distortion	＜3%
Output Frequency	50Hz
Standby Current	＜0.9A
Conversion Efficiency	maximum 94%
MPP voltage range	180 V to 500 V
Rated input voltage	400 V
Minimum input voltage	125 V
Initial input voltage	150 V
Maximum input current	15 A
Maximum input current per string	15 A
Number of independent MPP inputs	1
Strings per MPP input	2
Rated power at 230 V, 50 Hz	2500 W
Maximum apparent AC power cos φ = 1	2500 VA
Rated grid voltage	230 V
AC nominal voltage	220 V / 230 V / 240 V
AC voltage range	180 V to 280 V
Nominal AC current at 230 V	230 V 10.9 A
Maximum output current	12.4 A
Maximum output current in the case of faults	12.4 A
Total harmonic factor of output current at AC total harmonic factor < 2 %	≤ 4 %
AC power > 0.5 nominal AC power	
Output Short Circuit Protection	Buzzer/ LED warning
Output Overload	smart control
Load Power Factor	0.98
USB Output	5V1000Ma
Battery Reverse Protection	fuse protection
Cooling Way	temperature control
Working Temperature	-20～60℃
Storage Temperature	-20～80℃
Working Humidity	10～90%

Specifications of outdoor unit

MODEL			AER318SH3	
Power source			380 - 400 V - 3N ~ 50 Hz	
Control circuit			220 - 240 V ~ 50 Hz	
CONTROLLER PCB			**POW-C186GH**	
COMPRESSOR				
Type			Rotary (Hermetic)	
Compressor model			C-2RN173H8A 80242088	
Source			380 - 400 V - 3N ~ 50 Hz	
Nominal output		W	1700	
Compressor oil ... Amount		cc	FV68S ... 800	
Coil resistance (Ambient temp. 25°C)	C - R	Ω	5,62	
	C - S	Ω	5,51	
	R - S	Ω	5,62	
Safety devices: Type			Internal protector	External protector
Overload relay			//	HOE-10TB TH-7A
Operating temp.	Open	°C	120 ± 5	//
	Close	°C	Automatic reclosing	//
Operating amp. (Ambient temp. 25°C)			//	0
Run capacitor		µF	//	
		VAC	//	
Crank case heater			240 V - 30 W	
FAN AND FAN MOTOR				
Type			Propeller	
Number ... Dia.		mm	1 ... Ø400	
Fan motor model ... Number			SG6S-51B5P ... 1	
Source			220 - 240 V ~ 50 Hz	
No. of poles ... rpm (220 V)			6 ... 900	
Nominal output		W	50	
Coil resistance (Ambient temp. 20°C)	WHT - BRN	Ω	89,1	
	WHT - YEL	Ω	111,8	
	YEL - PNK	Ω	55,9	
Safety devices: Type			Internal protector	
Operating temp.	Open	°C	130 ± 8	
	Close		Automatic reclosing	
Run capacitor		µF	2	
		VAC	440	
HEAT EXCH. COIL				
Coil			Aluminum plate fin / Copper tube	
Rows			2	
Fin pitch		mm	1,6	
Face area		m^2	0,453	
EXTERNAL FINISH			Acrylic baked-on enamel finish	

Specifications of auxiliary heat pump

OPERATING TEMPERATURE LIMIT

In heating mode:
- Water: + 18°C/+ 60°C,
- Outside air: - 20°C/+ 35°C

In cooling mode:
- Water: + 18°C/+ 25°C,
- Outside air: +7°C/+ 46°C

In air conditioning mode (with options EH811 and HK25):
- Water: + 7°C/+ 25°C,
- Outside air: +7°C/+ 46°C

Heating circuit:
Max. operating pressure: 3 bar
Max. operating temp.:
- 95°C with (.../H)
- 75°C with (.../E)

MODEL	HPI-M	6 MR	8 MR	11 MR
SEASONAL PERFORMANCES				
Energy class in heating ERP (35°C)		A+++	A++	A++
Energy class in heating ERP (55°C)		A++	A++	A++
SCOP (35°C/55°C)		4.67/3.30	4.35/3.50	4.34/3.40
Seasonal space heating energy efficiency under average temperature (35°C/55°C) *	%	184/129	171/137	170/133
Seasonal space heating energy efficiency under average temperature (35°C/55°C) (with outdoor sensor supplied as standard)	%	186/131	173/139	172/135
CERTIFIED THERMAL PERFORMANCE				
Heating output at +7°C/+35°C (1)	kW	6.00	9.00	11.20
Heating COP at +7°C/+35°C (1)		4.83	4.51	4.54
Heating output at -7°C/+35°C (1)	kW	6.00	7.50	9.00
Heating COP at -7°C/+35°C (1)		3.11	2.69	3.27
Outdoor module sound power (3)	dB(A)	58	58	60
TECHNICAL SPECIFICATIONS				
Outdoor module perceived sound level(4)	dB(A)	36	36	38
Indoor module perceived sound level(4)	dB(A)	35	43	43
Cooling output at +35°C/+18°C (5)	kW	6.00	7.50	10.00
Cooling COP at +35°C/+18°C (5)		4.26	4.42	4.74
Nominal water flow rate at $\Delta T = 5$ K	m^3/h	1.03	1.55	1.93
Total pressure head at nominal flow rate at $\Delta T = 5$ K	mbar	750	650	500
Maximum hydraulic connection distance	m	20	20	20
Connection diameter	pouce	1"	1"	1"
Power supply voltage of the outdoor unit	V	230 V single-phase	230 V single-phase	230 V single-phase
Maximum electrical power	kW	5.06	5.06	6.44
Start-up amperage	A	9	9	12
Curved circuit breaker protection C outdoor unit*	A	16	25	32
Power regulation mode (compressor)		variable speed	variable speed	variable speed
Soft starter		No	No	No
Refrigerant fluid R410A	kg	2.4	2.4	3.3
CO_2 equivalent	tonne	5.01	5.01	6.89
Weight of outdoor unit without charge	kg	97	97	118
Weight of indoor module without charge (tank) (version /H - Version /E)	kg	50 - 57	50 - 57	50 - 57

* Values certified according directives n°813/2013
(1) Heating mode: outside air temperature/water temperature at outlet, performance in accordance with EN 14511-2
(3) Test performed in accordance with standard EN 12102-1
(4) At 1 m in a free field (5 m for the outdoor unit)
(5) Air conditioning mode: outdoor air temperature/water temperature at the outlet, performance according to EN 14511-2.

Specifications of hot water tank

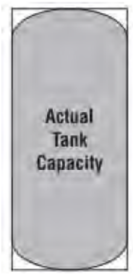
A	B	C	D	E	F	G	H	I	J	K	L	M	N
SPP-JS30-063	193	175	71"	41"	67"	18"	2"	19.5"	34"	2.5"	1"	3"	548
SPP-JS30-075	229	210	83	41	79	24	2	19.5	34	2.5	1	3	613
SPP-JS30-085	260	240	93	41	89	29	2	19.5	34	2.5	1	3	700
SPP-JS30-099	303	280	107	41	103	36	2	19.5	34	2.5	1	3	673
SPP-JS30-111	340	320	119	41	115	42	2	19.5	34	2.5	1	3	730
SPP-J36-072	318	285	80"	47"	76"	21"	2"	21"	40"	2.5"	1"	3"	714
SPP-J36-078	344	310	86	47	82	24	2	21	40	2.5	1	3	782
SPP-J36-085	375	340	93	47	89	27.5	2	21	40	2.5	1	3	845
SPP-J36-090	397	360	98	47	94	30	2	21	40	2.5	1	3	894
SPP-J36-102	449	415	110	47	106	36	2	21	40	2.5	1	3	982
SPP-J36-114	502	465	122	47	118	42	2	21	40	2.5	1	3	1106
SPP-J36-126	555	515	134	47	130	48	2	21	40	2.5	1	3	1194
SPP-J42-081	486	435	89"	53"	85"	24"	2"	22.5"	46"	3"	1"	3"	1024
SPP-J42-084	504	453	92	53	88	25.5	2	22.5	46	3	1	3	1074
SPP-J42-093	558	505	101	53	97	30	2	22.5	46	3	1	3	1168
SPP-J42-105	630	575	113	53	109	36	2	22.5	46	3	1	3	1292
SPP-J42-117	702	645	125	53	121	42	2	22.5	46	3	1	3	1392
SPP-J42-129	774	720	137	53	133	48	2	22.5	46	3	1	3	1498
SPP-J42-139	846	790	147	53	143	53	2	22.5	46	3	1	3	1587
SPP-J48-073	572	500	81"	59"	77"	18.5"	2"	24"	52"	3"	1"	3"	1381
SPP-J48-084	658	580	92	59	88	24	2	24	52	3	1	3	1539
SPP-J48-096	752	675	104	59	100	30	2	24	52	3	1	3	1653
SPP-J48-108	846	765	116	59	112	36	2	24	52	3	1	3	1803
SPP-J48-120	940	840	128	59	124	42	2	24	52	3	1	3	1947
SPP-J48-141	1128	1040	149	59	145	52.5	2	24	52	3	1	3	2216

A – Tank Part Number
*B – Nominal Gallon Capacity**
*C – Actual Capacity**
D – Vertical Height
E – Horizontal Height
F – "L"
G – "D"

H – Base Clearance
I – "H"
J – Diameter
K – Tapping "A"
L – Tapping "B"
M – Tapping "C"
N – Weight

*Nominal gallon capacity is listed for comparison purposes . Nominal gallon capacity refers to a hypothetical measurement in a case where overall tank length remains the same but instead of an elliptical head and base , the gallons are calculated as if it was built with at heads and base. – See diagram

*Nominal capacity includes the white area in addition to actual tank capacity.



Specifications of cold storage

Outside Temperature	+45°C maximum DB, +30°C WB (1130 F/860 F)
Product Loading Temperature	20 °C - 25 °C maximum
Weight of each bag	50 kg
Total Storage Capacity	5000 metric ton
Chamber Size	100ft Lx45ft Wx 45ft H (3 Chambers) 80ft Lx45ft Wx 45ft H(1 chamber) (Total Volume = 769500 ft3 , Total Floor Area = 17100 sq ft)
Loading Rate	50 ton for 1 chamber (maximum)
Pull Down Time	15 °C in 24 hrs
Compressor Running Hours	20 hrs/day during pull down
Ventilation Requirements	2 to 6 air changes per day
Heat of Respiration	1350-1870 J/kg per 24 hours
Specific Heat above freezing	3.433 kJ/kg.K
Refrigeration System	Vapour Compression System
Refrigerant	R 22
Suction Pressure	1.5 bar
Discharge Pressure	19 bar
Storage Temperature	2°C
Number of Compressor	15
Compressor Capacity	23 horsepower (hp) (i.e. 1 hp = 745.5 Watts)

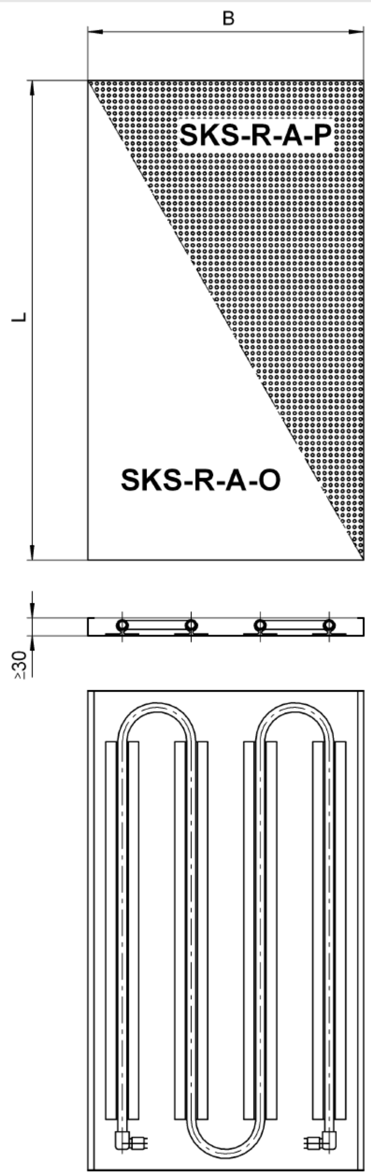
Specifications of pipe

PIPE SPEC 1-CS-1-P	Description
Class 150	3 = class 300 6 = class 600 9 = class 900 15 = class 1500 25 = class 2500
Carbon Steel	CA = Carbon Steel Alloy Low-Temp (Killed Steel) SA = Austenitic Stainless Steel 304SS SD = Austenitic Stainless Steel 316SS
Corrosion Allowance (1 x factor)	0 = Stainless steel or other Austenitic Stainless Steels
General Process Non-Corrosive	FW = Fire Water V = High Process Vacuum A = Alloy 20 valves

Specifications of Pump

Maximum output capacity (L/min)	500
Inlet/outlet diameter thread type (mm/inches)	50/2-PF
Total head (m)	50
Suction head (m)	8
Pressure (bars)	5
Debris size capacity (mm)	3

Specifications of cold circulation



Alpety-SKS-R:

Rectangular shaped ceiling panel
L= from 800 to 2500 mm
W= from 200 to 800 mm
(in intervals of 100 mm)
Other dimensions on request

Alpety-SKS-Q:

Square ceiling panels
Length x Width
600x600
625x625
700x700
800x800
900x900
Other dimensions on request

The panel thickness and bevel depend on the selected ceiling system.

Output

Cooling power to DIN 4715: up to 90 W/m²
The cooling power of the cooling ceiling elements depends on the type of air supply as well as the covered %, i.e., percentage of the activated surface area, relative to the overall surface area of the ceiling.

Weight 7 - 11 kg/m² including water (depending on model)
Normally the interface for each water circuit is the ball valve at the start of the air conditioned zone.

Appendix F

The yearly operating profit of the system can be systematically calculated as follows:

Year 1

Income generated **= (0.149 × 6917.60) + (0.0464 × 6917.60)**

= 1030.72 + 320.98 = £1351.70

Annual maintenance cost **= £100.00**

Yearly inflation rate is **4% (0.04)**

Operating profit **= 1351.70 – 100.00**

= **£1251.70**

Year 2

Income generated **= (0.149 × 6883.01) + (0.0464 × 6883.01)**

= 1025.57 + 319.37 = £1344.94

Income generated **= 1344.94 + (0.04 × 1344.94)**

= £1398.74

Operating profit **= 1398.74 – 103.00**

= **£1295.73**

Year 3

Income generated **= (0.149 × 6848.42) + (0.0464 × 6848.42)**

= 1020.41 + 317.77 = £1338.18

Income generated **= 1338.18 + (0.04 × 1338.18)**

= **£1391.71**

Operating profit **= 1391.71 – 106.09**

=£1285.62

Year 4

Income generated **= (0.149 × 6813.84) + (0.0464 × 6813.84)**

= 1015.26 + 316.16 = £1331.42

Income generated **= 1331.42+ (0.04 × 1331.42)**

= £1384.68

Operating profit **= 1384.68 – 109.27**

= £1275.41

Year 5

Income generated **= (0.149 × 6779.23) + (0.0464 × 6779.23)**

= 1010.11 + 314.56 = £1324.67

Income generated **= 1324.67 + (0.04 × 1324.67)**

= £1377.66

Operating profit **= 1377.66 – 112.55**

= £1265.11

Year 6

Income generated **= (0.149 × 6744.66) + (0.0464 × 6744.66)**

= 1004.95 + 312.95 = £1317.90

Income generated **= 1317.90 + (0.04 × 1317.90)**

= £1370.61

Operating profit **= 1370.61 – 115.93**

= £1254.69

Year 7

Income generated **= (0.149 × 6710.07) + (0.0464 × 6710.07)**

= 999.80 + 311.35 = £1311.15

Income generated **= 1311.15 + (0.04 × 1311.15)**

= £1363.50

Operating profit **= £1363.50 – 119.41**

= £1244.19

Year 8

Income generated **= (0.149 × 6675.48) + (0.0464 × 6675.48)**

= 994.65 + 309.74 = £1304.39

Income generated **= 1304.39 + (0.04 × 1304.39)**

= £1356.57

Operating profit **= 1356.57 – 122.99**

= £1233.58

Year 9

Income generated **= (0.149 × 6640.80) + (0.0464 × 6640.80)**

= 989.48 + 308.13 = £1297.61

Income generated **= 1297.61 + (0.04 × 1297.61)**

= £1349.51

Operating profit **= 1349.51 – 126.68**

= £1222.83

Year 10

Income generated **= (0.149 × 6606.31) + (0.0464 × 6606.31)**

= 984.34 + 306.53 = £1290.87

Income generated **= 1290.87 + (0.04 × 1290.87)**

= £1342.50

Operating profit **= 1342.50 – 130.48**

= £1212.02

Year 11

Income generated **= (0.149 × 6571.72) + (0.0464 × 6571.72)**

= 979.19 + 304.93 = £1284.12

Income generated **= 1284.12 + (0.04 × 1284.12)**

= £1335.48

Operating profit **= 1335.48 – 134.40**

= £1201.08

Year 12

Income generated **= (0.149 × 6537.13) + (0.0464 × 6537.13)**

= 974.03 + 303.32 = £1277.35

Income generated **= 1277.35 + (0.04 × 1277.35)**

= £1328.44

Operating profit **= £1328.44 – £138.43**

= **£1190.01**

Year 13

Income generated **= (0.149 × 6502.54) + (0.0464 × 6502.54)**

= 968.88 + 301.72 = £1270.50

Income generated **= 1270.50 + (0.04 × 1270.50)**

= **£1321.32**

Operating profit **= 1321.32 – 142.58**

=£1178.74

Year 14

Income generated **= (0.149 × 6467.96) + (0.0464 × 6467.96)**

= 963.73 + 300.11 = £1263.84

Income generated **= 1263.84 + (0.04 × 1263.84)**

= £1314.39

Operating profit **= 1314.39 – 146.86**

= £1167.53

Year 15

Income generated **= (0.149 × 6433.37) + (0.0464 × 6433.37)**

= 958.57 + 139.29 = £1257.08

Income generated **= 1257.08 + (0.04 × 1257.08)**

= £1307.36

Operating profit **= 1307.36 – 151.27**

= £1156.09

Year 16

Income generated **= (0.149 × 6398.78) + (0.0464 × 6398.78)**

= 953.42 + 296.90 = £1250.32

Income generated **= 1250.32 + (0.04 × 1250.32)**

= £1300.33

Operating profit **= 1300.33 – 155.81**

= £1144.52

Year 17

Income generated **= (0.149 × 6364.19) + (0.0464 × 6364.19)**

= 948.26 + 295.20 = £1243.56

Income generated **= 1243.56 + (0.04 × 1243.56)**

= £1293.30

Operating profit **= £1293.30 – 160.48**

= £1132.82

Year 18

Income generated **= (0.149 × 6329.60) + (0.0464 × 6329.60)**

= 943.11 + 293.69 = £1236.80

Income generated **= 1236.80 + (0.04 × 1236.80)**

= £1286.27

Operating profit **= 1286.27 – 165.29**

= £1120.98

Year 19

Income generated **= (0.149 × 6295.02) + (0.0464 × 6295.02)**

= 937.96 + 292.09 = £1230.05

Income generated **= 1230.05 + (0.04 × 1230.05)**

= £1279.25

Operating profit **= 1279.25 – 170.23**

= £1109.02

Year 20

Income generated **= (0.149 × 6260.43) + (0.0464 × 6260.43)**

= 932.80 + 290.48 = £1223.30

Income generated **= 1223.30 + (0.04 × 1223.30)**

= £1272.23

Operating profit **= 1272.23 – 175.34**

= £1096.89

Appendix G

The yearly cash flow of the system can be systematically calculated as follows:

Year 1

1351.70 – 100.00 **= £1251.70**

Year 2

$1398.74 \times (1.04)^1 = 1454.69$

1454.69 – 103.00 **= £1351.69**

Year 3

$1391.71 \times (1.04)^2 = 1505.27$

1505.27 – 106.09 **= £1399.18**

Year 4

$1384.68 \times (1.04)^3 = 1557.58$

1557.58 – 109.27 **= £1448.31**

Year 5

$1377.66 \times (1.04)^4 = 1611.67$

1611.67 – 112.55 **= £1499.12**

Year 6

$1370.61 \times (1.04)^5 = 1667.56$

1667.56 – 115.93 **= £1551.63**

Year 7

$1363.50 \times (1.04)^6 = 1725.26$

1725.26 – 119.41 **= £1605.85**

Year 8

$1356.57 \times (1.04)^7 = 1785.15$

1785.15 – 122.99 **= £1662.16**

Year 9

$1349.51 \times (1.04)^8 = 1846.80$

1846.80 – 126.68 **= £1720.22**

Year 10

$1342.50 \times (1.04)^9 = 1910.70$

1910.70 – 130.48 **= £1780.32**

Year 11

$1335.48 \times (1.04)^{10} = 1976.84$

1976.84 – 134.40 **= £1842.44**

Year 12

$1328.44 \times (1.04)^{11} = 2045.07$

2045.07 – 138.43 **= £1906.64**

Year 13

$1321.32 \times (1.04)^{12} = 2115{,}48$

2115,48 – 142.58 **= £1972.80**

Year 14

$1314.39 \times (1.04)^{13} = 2188.56$

2188.56 – 146.86 **= £2041.60**

Year 15

$1307.36 \times (1.04)^{14} = 2263.92$

2263.92 – 151.27 **= £2112.65**

Year 16

$1300.33 \times (1.04)^{15} = 2341.82$

2341.82 – 155.81 **= £2186.01**

Year 17

$1293.30 \times (1.04)^{16} = 2422.33$

2422.33 – 160.48 **= £2261.85**

Year 18

$1286.27 \times (1.04)^{17} = 2505.53$

2505.53 – 165.29 **= £2340.24**

Year 19

$1279.25 \times (1.04)^{18} = 2591.53$

2591.53 – 170.23 **= £2421.20**

Year 20

$1272.23 \times (1.04)^{19} = 2680.30$

2680.30 – 175.34 **= £2505.06**

Appendix H

External Validation of Sustainable Smart Air-Conditioning

Letter of Introduction

Tosin Oye
PhD Researcher
School of Engineering and the Built Environment
Edinburgh Napier University
Merchiston Campus.
Edinburgh EH10 5DT
3rd February 2020

Name of Interviewee
Role of Interviewee in the Industry
Address

Dear Sir/Madam,

Sustainable Theoretical Framework for Renewable Smart Air-Conditioning

In the course of my PhD research study at Edinburgh Napier University, I have developed a sustainable theoretical framework for smart air-conditioning using the principles of sustainability namely environment, social and economic.

I would be grateful if you would permit me to interview you (through the telephone or in-person) to seek your opinion on the feasibility and performance of the system models.

The estimated time for the interview will not exceed twenty minutes (20 minutes).

I undertake that I will not reveal the identities of the interviewees that participate in these exercises and will observe good and professional ethical conduct throughout the investigation and afterwards. Your participation in this study is completely voluntary. There is no foreseeable risk associated with this investigation. However, if you feel uncomfortable answering my questions, you can withdraw from the interview at any point.

If you wish, I will keep you informed of the progress throughout, and I will be happy to share my findings with you. My thesis will also be available at the university library.

Yours sincerely,

Tosin Oye

Interview Schedule

Section (I)

1. Do you know if sustainability planning of air-conditioning was conducted by means of considering the sustainability principles? If yes, what model/ technique was employed?
2. What will you consider as the major impact of air-conditioning in recent times?
    A. Energy consumption
    B. Carbon emission
    C. Climate change
    D. Health effects
    E. All the above

Section (II)

A sustainable theoretical framework has been developed for the smart air-conditioning using the principles of sustainability namely environment, social and economic. The environment and the social address renewable and advanced smart options while the economy addresses the profitability measures of the system.

3. How do you assess the inclusion of sustainability principles in the developed theoretical framework of air-conditioning?
4. Do you think the sustainable theoretical framework of smart air-conditioning will be beneficial for tackling the associated health effects and combatting climate change?
5. Which aspect do you think the developed framework can be improved for further sustainability planning of the system?

Psalm 91; 121