Viability of Trombe Wall Promotion through Utility Demand-Side Management

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ABSTRACT

The present study explores the feasibility of developing a demand-side management (DSM) strategy with the purpose of making advantage of the shifted solar energy use of Trombe wall (TW) systems to the evening hours while both the electric utility and its customers enjoy economic benefits. In many countries the winter peak hours coincide with the early evening hours and therefore replacing the electric heaters with TW systems during these hours would facilitate the peak clipping strategy in DSM. The aim of the current work is to offer means of overcoming the difficulties concerned with the implementation of such a DSM program and developing a comprehensive method to determine whether the outlined DSM program can be economically justifiable. The proposed method is examined under three different case studies including North Cyprus (NC), Erbil, and San Diego for single and two storey buildings. According to the simulations performed in Design Builder software (Eastern Mediterranean University license 2019-2021); in the case of single storey building, for a 35 m^2 room, integrated with a TW, an estimated 11.2, 12.48, and 4.37 kWh_e/m^2 is saved for NC, Erbil, and San Diego, respectively in each house participating in the program during the peak hours in winter. On the other hand, in the case of two storey building 9.22, 10.77, and, 3.03 kWh_e/m^2 is saved for NC, Erbil, and San Diego, respectively. A peak clipping of 17.5-MW is targeted in all programs to be achieved with the participation of 6842 houses in a DSM program. The utility rebates estimated per house are 1588.25, 1058.75, and 2543.9 EUR for the cases of NC, Erbil and San Diego respectively.

The net present values (*NPV*s) for applying such a DSM program for single-storey buildings over a life-time of 20 years in NC, Erbil and San Diego are estimated to be 4,824,090, 29,597,585 and 1,575,901 EUR respectively. In the case of two-storey buildings, the *NPV*s are slightly different; for NC, Erbil and San Diego the *NPV*s are computed to be 4,866,525, 29,502,686, and 3,608,460 EUR, respectively. The life cycle cost indicators under different conditions and risks that might befall during the project implementation are also investigated. In all considered possibilities the savings-to-investment ratio of the DSM program for the case of NC and Erbil is greater than 1.0, implying that TW implementation is economically feasible in these locations. However, in the case of San Diego the economic viability of the proposed DSM program under unforeseen conditions is under risk, implying that its implementation should be carried out with utmost carefulness.

Keywords: Solar Energy, Demand-Side Management, Trombe Wall, Economic Feasibility Analysis, Design Builder, Simulation

ÖZ

Sunulan çalışmada, Trombe Duvarı (TD) kullanılarak güneş enerjisinden akşam saatlerinde yararlanmaya imkan veren ve bu yolla hem elektrik enerjisi sağlayıcılarının hem de tüketicilerin ekonomik fayda sağlamasını mümkün kılan bir talep tarafı yönetim (TTY) stratejisi geliştirilmesinin uygunluğu incelemiştir. Birçok ülkede kış dönemi elektrik tüketimi pik periyodu akşamın ilk saatlerinde meydana gelmekte dolayısı ile bu saatlerde kullanılan elektrikli ısıtıcıların yerine TD kullanımı, TTY amacıyla pik kırpma stratejisinden yararlanılmasına olanak vermektedir. Sunulan çalışmanın amacı, böyle bir TTY programının uygulanmasında ortaya çıkabilecek zorlukluklara çözüm stratejileri sunmak ve belirtilen TTY programının ekonomik fizibilitesini değerlendirebilmek amacıyla detaylı bir yöntem geliştirmektir. Amaçlanan yöntem, Kuzey Kıbrıs, Erbil ve San Diego'da bulunan tek ve çift katlı binalar olmak üzere üç farklı örnek bölge için incelenmiştir. Design Builder programında (Doğu Akdeniz Üniversitesi lisans 2019-2021) gerçekleştirilen simülasyon sonuçlarına göre, tek katlı bir binanın 35 m^2'lik bir odasına Trombe Duvarı entegre edilmesi ile, programda yer alan Kuzey Kıbrıs, Erbil ve San Diego koşullarındaki herbir konutta, kış dönemi pik yük saatlerinde, sırasıyla 11.2, 12.48, and 4.37 kWh_e/m^2 enerji tasarrufu elde edileceği belirlenmiştir. İki katlı bina uygulamalarında ise elde edilebilecek enerji tasarruf miktarı Kuzey Kıbrıs, Erbil ve San Diego koşulları için 9.22, 10.77 ve 3.03 kWh_e/m^2 olarak bulunmuştur. Bu stratejinin, TTY programına katılacak 6842 adet konuta uygulanması ile, amaçlanan 17.5 MW'lık pik yük düşüşünün elde edilebileceği tespit edilmiştir. Kuzey Kıbrıs, Erbil ve San Diego koşullarında yapılacak yatırım için elektrik sağlayıcı tarafından her bir konut için verilecek destek miktarları sırasıyla 1588.25, 1058.75, ve 2543.9 Euro olarak belirlenmiştir.

Amaçalanan TTY programı ile, Kuzey Kıbrıs, Erbil ve San Diego'da bulunan tek katlı bina koşulu için, 20 yıllık periyotta elde edilebilecek tasarruf miktarının bugünkü değeri sırasıyla 4,824,090, 29,597,585 ve 1,575,901 Euro olarak hesaplanmıştır. Aynı koşullardaki iki katlı bir bina için tasarruf miktarının bugünkü değerinin tek katlı binaya göre biraz farklılık göstereceği ve Kuzey Kıbrıs, Erbil ve San Diego koşulları için sırasıyla 4,866,525, 29,502,686, ve 3,608,460 Euro olacağı öngörülmektedir. Çalışma kapsamında amaçlanan stratejinin çeşitli koşullar altında uygulanmasında ortaya çıkabilecek farklı yaşam döngüsü maaliyet göstergeleri ve riskler göz ününde bulundurulmuştur. İncelenen tüm durumlarda Kuzey Kıbrıs ve Erbil bölgeleri için tasarruf-yatırım oranı 1'den büyük olarak belirlenmiş dolayısı ile TD uygulamasının bu bölgelerde ekonomik olarak uygulanabilir olduğu belirlenmiştir. Ancak amaçlanan stratejinin San Diego için öngörülemeyen durumlarda uygulanmasının ekonomik olarak riskli olduğu, dolayısı ile, bu bölgede gerçekleştirilecek uygulamalarda büyük bir titizlik gösterilmesi gerektiği sonucuna ulaşılmıştır

Anahtar Kelimeler: Güneş Enerjisi, Talep Tarafı Yönetimi, Trombe Duvarı, Ekonomik Fizibilite Analizi, Design Builder, Simülasyon

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A	Area Element of the Interior Node
C_{DS}	Cost of Decreased Sales (EUR)
C_{DSM}	Cost of the Demand-Side Management Program (EUR)
C_{DW}	Cost of Knocking Down the Outer Wall
C_{Filter}	Costs of the Filter (EUR)
C_{Fuel}	Total Cost of the Avoided Fuel Consumption (EUR)
C_{Ins}	Cost of Insurance (EUR)
$C_{O\&M}$	Operation and Maintenance Cost During the Lifetime of the Demand-Side Management Program (EUR)
$C_{O\&M,Filter}$	Operation and Maintenance Costs of the Filter (EUR)
$C_{O\&M,PP}$	Operation and Maintenance Costs of the Power Plant (EUR)
$C_{O\&M,PP(fixed)}$	Fixed Operation and Maintenance Cost During the Lifetime of the Demand-Side Management Program (EUR)
$C_{O\&M,PP(variable)}$	Variable Operation and Maintenance Cost During the Lifetime of the Demand-Side Management Program (EUR)
C_P	Specific Heat Capacity (J/(K.kg))
C_{PP}	Cost of Power Plant (EUR)
$C_{Subsidizing}$	Cost of Electricity Subsidizing
$C_{T\&D}$	Cost of Transmission and Distribution Network Expansion
C_{TW}	Cost of Trombe Wall
$E_{Site,sav}$	Electric Energy Saving at the Site (kWh)
$\dot{g}$	Heat Generation

H_v	Heating Value (kWh/m^3)
I_{Ret}	Investment Required to Replace an Outer Wall with a New Trombe Wall
k	Thermal Conductivity (W/(m·K))
L	Thickness
L_{Grid}	Grid Loss-Ratio
m	Air Flow Rate Through the Channel
$m_{Fuel,sav}$	Fuel Savings Due to Energy Savings (tons)
$Q_{L,g}$	Heat Loss from Ground
$Q_{L,TW}$	Heat Loss from TW
$Q_{L,r}$	Heat Loss from Roof
$Q_{L,w}$	Heat loss from walls
Q_o	Energy Gained by the Air Flows Through the Air Channel
Q_r	Radiation Heat Gain by the Glass
Q_{stored}	Heat Gain by TW
Q_{TW}	Heat Transfer from TW to the Room
Q_t	Total Heat Gain
Q_{Vent}	Heat Loss from Air Ventilation
R_{diff}	Diffuse Solar Radiation
R_{dir}	Direct Solar Radiation
T_{amb}	Outdoor Temperature
T_i	Air Inlet Temperature
T_{in}	Indoor Temperature
T_o	Air Outlet Temperature
V	Volume Element of the Interior Node

α	Thermal Diffusivity (m^2/s)
η_{PP}	Efficiency of the Power Plant
ρ_{Fuel}	Density of the Fuel ($tons/m^3$)
τ	Dimensionless Mesh Fourier
Δt	Time Interval
CECW	Ceramic Evaporative Cooling Wall
COP	Coefficient of Performance
CTW	Classic Trombe Wall
DR	Demand Response
DSM	Demand Side Management
EU	European Union
FTW	Fluidized Trombe Wall
KIB-TEK	Cyprus Turkish Electricity Authority
LCC	Life Cycle Cost
NC	North Cyprus
NPI	Net Present Investments
NPS	Net Present Savings
NPV	Net Present Value
PV	Photovoltaic
PVTW	Photovoltaic Trombe Wall
RM	Malaysian Ringgit
SIR	Saving to Investment Ratio
SCTW	Solar Chimney Trombe Wall
STW	Solar Trans-Wall
Std	Standard

TES	Thermal Energy Storage
TL	Turkish Lira
TRNSYS	Transient System Simulation Program
TMW	Trombe-Michel Wall
TW	Trombe Wall
WTW	Water Trombe Wall
ZTW	Zigzag Trombe Wall

Chapter 1

INTRODUCTION

1.1 Background

Increasing environmental pollution and energy demand are some of the collateral effects of the human population growth. It is observed that total energy usage in buildings are responsible for 30-to-40% of the worldwide energy consumption (Omrany et al., 2016; Zeng et al., 2011; Bellos et al., 2016) 50% of which is utilized only for meeting the heating and cooling demand of buildings (Omrany et al., 2016). For instance, 50% of energy usage in service sector is consumed for heating in United Kingdom in 2004 (IEA, 2007; IEA, 2008).

It would be possible to reduce the fossil fuel consumption in power plants by using renewable sources for on-site heat generation together with thermal energy storage while giving consideration to sustainability. More importantly, if the energy is stored and used during the peak hours, the peak load of power plants could be reduced (Saffari et al., 2018). By this way, both the fossil fuel sourced electricity consumption in buildings and the necessity of installing new power plants or increasing capacity of existing power plants are lessened. Consequently, considerable reduction in emissions and environmental pollution could also be achieved (Giglio et al., 2019). In this context, promoting passive solar heating systems could be considered as a promising policy to adopt.

In passive solar heating systems thermal energy can be exploited devoid of any mechanical and electrical systems. This is how they are distinguished from active solar heating systems. Trombe wall (TW) is one example of passive solar heating systems which is basically built from a solid block of concrete and painted dark color from external side and is covered by a layer of glass (Moore, 1992). It is essentially a thermal storage wall that stores solar energy when it is available to be transmitted to the room in the evening. It does not only enable solar energy use when it is not available–e.g. night time- but also allows reducing evening peak. The mechanism of TW is based on creating greenhouse effect between a wall and a glazing for capturing and storing solar energy in the form of heat. Heat is conducted through the wall to the inner surface. The stored heat in the wall is mainly transferred to the room by convection and radiation. Figure 1 illustrates the cross-section of a building space integrated with an unvented TW and the heat transfer mechanisms. Thermal properties of concrete such as density, thermal conductivity and specific heat are the reasons which makes it the most appropriate material for the purpose of storing and transferring heat. Thermal diffusivity expresses the behavior of concrete in terms of heat transfer. In fact, it is a parameter in the transient heat conduction analysis, which demonstrate how fast heat diffuses through the material. Thermal diffusivity is the ratio of thermal conductivity *(k)* with the unit of W/m.K, and heat capacity (ρC_p), where ρ is density (kg/m^3) and C_p is specific heat (J/kg.K). Thermal diffusivity (m^2/s) is defined as:

$$\alpha = \frac{k}{\rho C_p} \tag{1}$$

A material that has a high thermal diffusivity, means heat can propagate faster into the medium. On the other hand, a material with small thermal diffusivity demonstrates that material is absorbing the major amount of heat and just a small portion of heat will be conducted. It is noticeable to mention that thermal diffusivity varieties from $\alpha =$

0.14×10^{-6} m^2/s for water to 174×10^{-6} m^2/s for silver. Thermal diffusivity of concrete and brick at 20^o C is 0.75×10^{-6} and 0.52×10^{-6} m^2/s, respectively. This shows that, heat can propagation faster through concrete than brick.

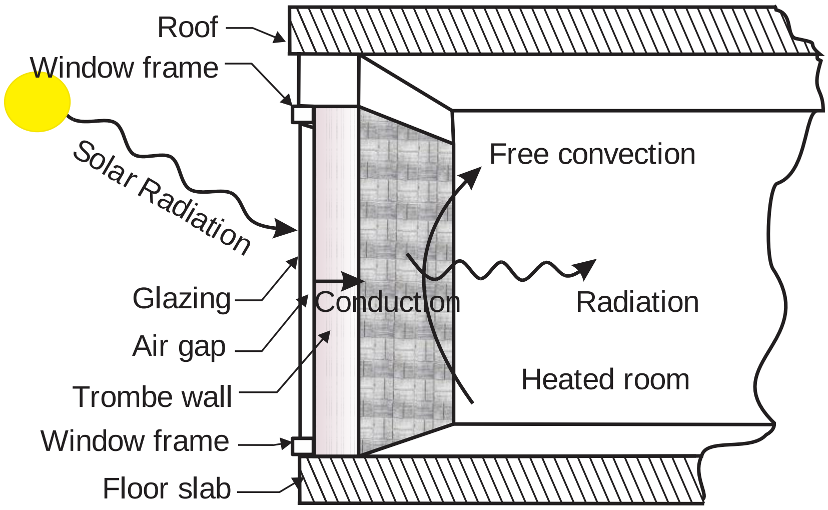


Figure 1: Cross-section of a building space utilizing a TW and the heat transfer mechanisms

Due to the simple configuration of the TW, building a TW is not very complicated and expensive. The complexity of TW arises due to the construction details such as its front framework and the glazing placed on the external part. In financial terms, for a house which is under construction, only the surplus expenditures of constructing a TW instead of normal wall needs to be considered. Despite this, TW is not usually considered by the home builders as part of their houses. Initial construction cost of TW, having low aesthetic value and lack of social awareness are the main reasons that TW is not opted by home owners.

1.2 Demand Side Management

Providing electric energy to end users is a difficult task, whereas handling the peak time is another challenging issue, which requires scrupulous management of resources. In this context, Demand side management (DSM) could be a promising tool that can be used by the utilities to manage the peak load. When Gellings (1985) introduced DSM in USA, he defined it as the utility activities planned on the consumer side of electric meter. Ever since, it has been a common practice to pay rebate to the consumers to affect their decisions on how to use electricity during the peak times. Not only developing incentives to shift the peak to off-peak hours, but also promoting the use of non-electric devices for clipping the peak has been a common strategy. Figure 2 demonstrates the six techniques applied to modify the peak with DSM. Six techniques are peak shifting, peak clipping, strategic conservation, strategic growth, flexible load shape and valley filling (Gellings, 1985). For instance, cool storage and thermal energy storage are some examples for load shifting and valley filling DSM techniques, respectively. According to Warren (2014), DSM comprises the policy objectives for emissions reduction, energy security and affordability, and encompasses energy efficiency, demand response (DR), and on-site back-up generation and storage. On the other hand, Arteconi et al. (2012) stated that, thermal energy storage (TES) systems have the capacity of being a powerful instrument in DSM programs. In line with these statements, TES systems demonstrate a capacity of shifting electrical loads from on-peak to off-peak hours, which is a well-aligning approach with DSM peak shifting strategy. Nowadays, those TES systems which assist in dealing with the mismatch between the renewable electricity and the peak hours are of particular interest. Using solar thermal technologies with storage capability to provide heat during the peak hours, eliminating the need for electricity usage, is also becoming attractive for the policy makers (Azeez and Atikol, 2019). Indeed, TW as a kind of passive TES, has significant impact on reduction of electricity usage particularly for the regions, where the peak demand occurs in the evening. Due to sluggish behavior of TW in releasing absorbed energy, it can contribute significantly to balancing the mismatch between the solar energy availability and the peak hours. As a matter of fact, it can be utilized as a DSM strategy to reduce the evening peak in winter (peak clipping).

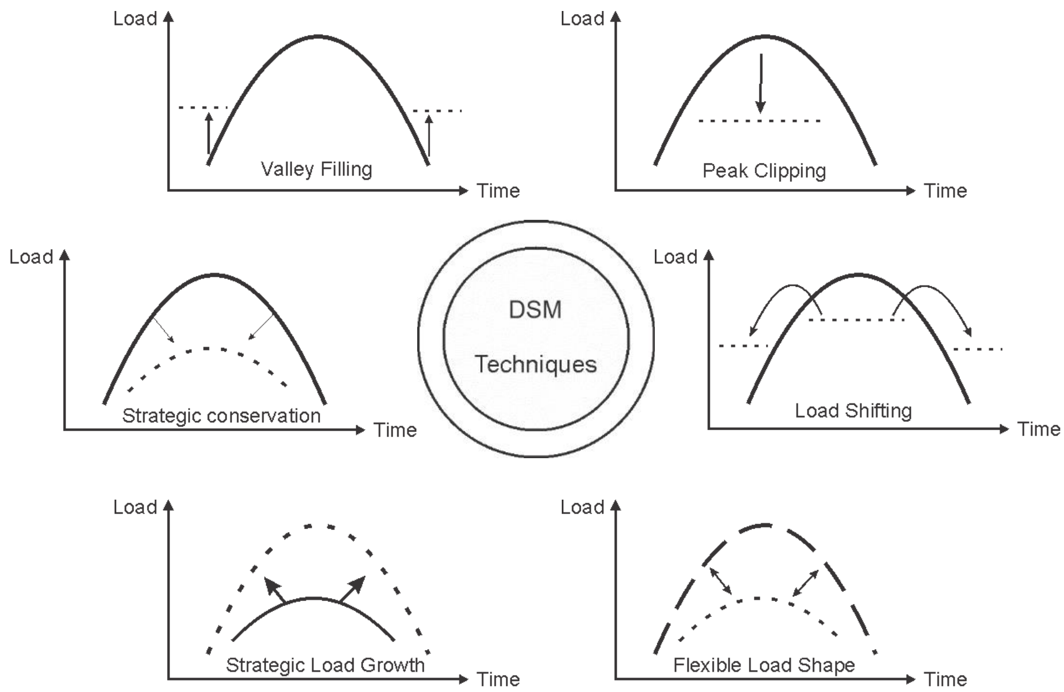


Figure 2: Six techniques of DSM. Adapted from Gellings (1985)

1.3 Scope and Objectives of the study

Although, TW is a well-known application due to some benefits such as simple configuration and low running cost, its construction is not very popular among the homeowners. There can be several reasons for this; such as lack of technical expertise and the obscure economic benefits. One of the advantages of the TW is the fact that it is a construction element, replacing another building component and its cost will be in the order of such a component. As a matter of fact, if the consumers decide to build a TW during the design stages of their homes, then it is the surplus expenditures (difference between the cost of TW and the building element it is replacing) that determine the cost of the TW. Reduction in non-renewable energy consumption and CO_2 emissions are the extra benefits.

It is clear from the literature (Nowzari 2009; Atikol et al. 2013; Ozdenefe et al. 2018) that TW applications in buildings can be considered to be economically viable (from customer point of view) under specific conditions. In another study by Ozdenefe et al. (2018) it was observed that it is worth building TWs for the newly built houses which are thermally insulated. It is also mentioned that for existing houses that are not thermally insulated it is not worth carrying out a modification to add a TW. As it is mentioned previously, in real life applications, due to the initial construction cost and low aesthetic value of TW, together with the lack of social awareness, its construction is not opted by the home owners as much as desired. Therefore, it is sought to develop a comprehensive method to make TW construction economically viable and attractive especially when it is not affordable for homeowners. This could also serve as one way to increase the homeowners' awareness for integrating TW in the building envelop as a preferred heating application. Amongst many different inducements, financial incentive is one of the most promising approaches to encourage homeowners. Since, the spread of TW can assist reducing the evening peak which in return enables the utility to avoid utilization of peak generators; it would be advised to investigate utilizing DSM as a tool for promoting TW in buildings. In order to do that, economic feasibility analysis of promoting TW construction with the utility resources needs to be performed. It is clear from literature that, there is no study by any researcher analyzing the feasibility of utilizing DSM to encourage the societal acceptance and wider usage of TWs. By and enlarge, there has not been any attempt to develop an inclusive methodology in which not only the promotive activities are devised for increased use of TW but also the economic anxieties are taken care of both for the utility and its customers. Therefore, the present study focuses on developing a DSM strategy through which TW construction in buildings is facilitated with economic feasibility in mind. In this regard, the main contributions of the present study are to (a) outline a novel DSM program for promoting the TW that is most appropriate for countries with different conditions and (b) determine a method of analyzing the economic feasibility of the suggested rebate programs with possible risks from the utility perspective.

1.4 Organization of Thesis

A comprehensive literature review on TW and DSM is provided in chapter 2. The DSM methodology together with mathematical model utilized in simulation and a general theory of economic viability suitable for promoting the TW system in residences are disclosed in chapter 3. Building features and envelops used in the simulation together with utilized parameters and the results of energy simulations for the representative hypothetical buildings for different case studies are presented in section 4. In section 5, based on the simulations performed, economic feasibility of promoting the TW through a rebate program is studied. Furthermore, a sensitivity analysis is conducted to investigate the effects of unpredictable changes in conditions on the feasibility indicators. Finally, a discussion is presented together with conclusive comments in section 6.

Chapter 2

LITERATURE REVIEW

2.1 Trombe Wall

2.1.1 Mechanism of Operation

The original idea of Trombe wall (TW) was pioneered by E.S. Morse in the 19th century which was then improved in 1957 by Félix Trombe and Jacques Michel. The first TW was built in 1967, in Odeillo, France. It was built in a simple structure to store and transfer the heat in a delayed manner to the room space (Zhongting et al., 2017; Saadatian et al., 2012; Shen et al., 2007a; Shen et al., 2007b). This configuration of TW is now known as classic or standard TW.

The mechanism of classic TW is based on creating greenhouse effect between a wall and a glazing for capturing and storing solar energy in the form of heat. Heat is conducted to the other side of the wall and transferred from the wall to the room by means of convection and radiation. One of the disadvantages of TW is that it is "sluggish" and needs time to heat up in the morning. By opening vents at the top and bottom of the TW, hot air, which is trapped between the glazing and wall, can be transferred to the room from top vents by natural convection. In this setup, heat exchange of TW with room takes place by heat transfer through the wall and air circulation through the vents (Zhongting et al., 2017). Some main disadvantages of classic TW can be expressed as follows:

1) Low thermal resistance can cause great amounts of heat losses when the sun is

not available (during night time or prolonged cloudy days) (Shen et al., 2007a).

2) Inverse thermo-siphon phenomena in vented TWs can cause cooling of the heated space when the temperature of the air gap between the glazing and the wall decreases due to low outdoor temperature. The warm air leaves the room through the top vents cooling down as it sinks through the gap and re-enters through the lower vents. This can only be prevented if the vents are closed under such circumstances (Zalewski et al., 2002).

3) Appearance of the TW is not appealing to many designers and home owners (Ji et al., 2007).

Based on the operation of TWs, they are categorized into two types: heating- based usage of TW and cooling-based usage of TW. There are seven different constructions of TW in heating based types such as: (1) classic Trombe wall (CTW); (2) composite Trombe wall or Trombe–Michel wall (TMW); (3) water Trombe wall (WTW); (4) zigzag Trombe wall (ZTW); (5) solar trans-wall (STW); (6) fluidized Trombe wall (FTW); and (7) photovoltaic Trombe wall (PVTW). Three different configurations of cooling-based types of TW are: (1) ceramic evaporative cooling wall (CECW); (2) classic TW and photovoltaic TW for cooling operation mode; and (3) new designed TW in combination with solar chimney (SCTW).

2.1.2 Modification of TW

Composite Trombe wall or Trombe–Michel wall (TMW) is a heating based type of TW, which has a higher thermal resistance and control supplies (Shen et al., 2007a). It includes more than one layer such as: glazing, storage wall, insulation layer, enclosed and ventilated air layers (see Figure 3). The main solar radiation dispatches by the first layer. Like the classic type of TW, the wall heats up with greenhouse effect by solar energy after which the heat is conducted to the interior air layer. At this stage, thermal energy is mainly transferred to the room by the flow of heated air through the vents. Simultaneously a small portion of the energy conduct into the room through the wall. Here, it should be noted that, in composite TW applications, majority of the supplied heat to the building is provided by the ventilated air layer as depicted in Figure 3. The amount of thermal flux from indoor to outdoor is far less compared to the classic type of TW, due to existence of the air and insulated layer in the design. Another advantage of TWM is that it provides an opportunity for the users to control the air circulation rate. However, still the reverse thermos-circulation is taking place in this type of TW.

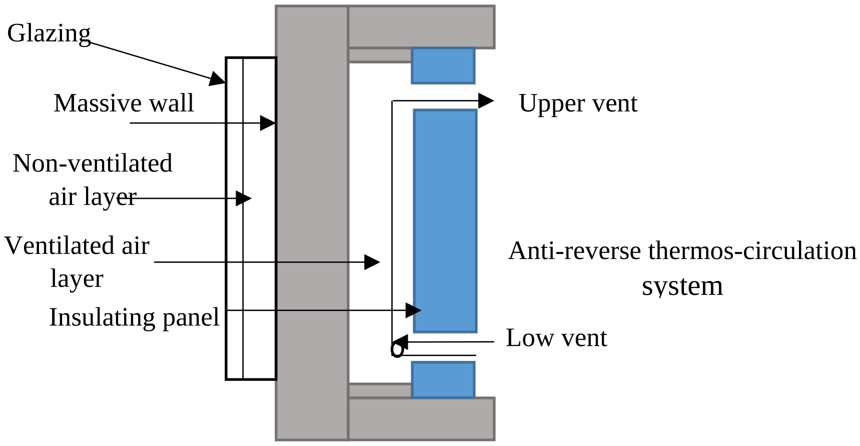


Figure 3: A composite TW. Adapted from Shen et al. (2007a)

Replacing concrete with water is another solution for reducing heat loss from the TW. With this purpose water TW is developed as an alternative to concrete based TW configuration (Adam et al., 2010; Wang et al., 2013). In water TW application, the surface temperature of water does not increase as much as that of the concrete due to having higher specific heat. As a result, heat loss through the glazing is reduced and higher percentage of solar energy is utilized as useful heat. On the other hand, the main disadvantage of using water TW instead of concrete TW is the regular maintenance requirement of it, which is the main barrier on wider usage of water TW applications.

Zigzag TW, as another modified TW configuration, is constructed from three sections; in section one a window is utilized for morning time and for obtaining the direct heat and light. The other two sections are designed in a zig-zag manner with classic TW configuration for storing solar energy and providing heat to the building for night time (see Figure 4). This type of TW provides the advantages of decreasing unnecessary heat gain and preventing the glare of sun (Saadatian et al., 2012).

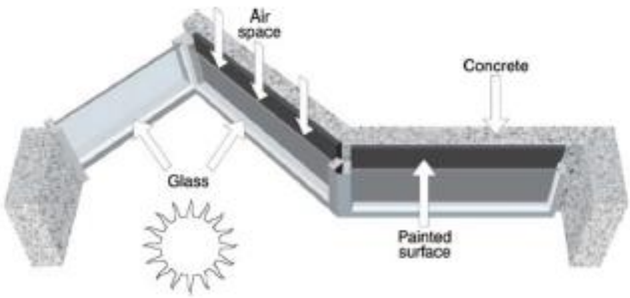


Figure 4: A zigzag TW. This figure is previously used by Saadatian et al. (2012)

As it is mentioned, one of the disadvantages of classic TW is its aesthetic value. In this regard, trans-wall type TW serves as an innovative solution to this problem by providing both solar heating and enabling visual contact with the building's exterior (Garge et al., 2000). Consequently, trans-wall type TW while enables solar energy gain of the building, it also contributes to the building aesthetics thereby enhances the chance of usage of passive heating in the buildings. In trans-wall type TW configuration, water is surrounded by two parallel glass panes. The difference between trans-wall and water wall is the existence of a semitransparent absorbing plate inside the wall which increases the absorption of solar radiation (as shown in Figure 5). On the other hand, transmitted radiation provides required heating and light to the indoor area. Since this type of TW can provide direct (day time) and indirect (night time) heating, it is more appropriate for places with high daytime temperature (Al-

Karaghouli et al., 2010).

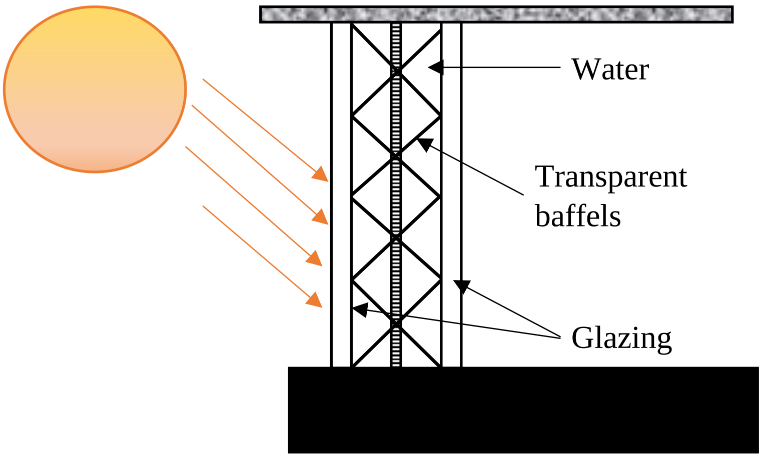


Figure 5: Across-sectional view of Trans-wall system. This figure is adopted from Saadatian et al. (2012)

A fluidized TW is very similar to classic TW, in spite the air gap between glazing and the massive wall is filled with particles with low-density and high absorbing properties (Tunç et al., 1991). There is a fan at the bottom of the wall to circulate heat which is absorbed by particles from daily solar radiation to the room space. In order to avoid entrance of the fluidized particles to the room space, air channels are covered with filters (Sadineni et al., 2011). Due to the direct contact of air with fluidized particles, the efficiency of this type of TW is higher than classic TW.

Photovoltaic (PV) TW is another type of TW which is integrated with solar cells as its name suggests. Simultaneous electric and heat production is the main advantage of this type of TW. On the other hand, this type of TW provides more aesthetic value compared to the classic type of TW. Another positive aspect of having PV on the glazing is providing partial shading, which decreases the undesired heat gain, particularly in summer (Sun et al., 2011; Jie et al., 2007a; Jie et al., 2007b).

2.1.3 Significant Factors for Designing a TW

TWs are considered as a sustainable architectural technology that utilizes clean solar energy (Zamora et al., 2009). There are some factors those need to be considered in design stage of TW in order to increase the efficiency. These influencing factors can be mentioned as: Trombe wall design parameters (TW's area, properties of the glazing and massive wall, air gap depth), building parameters (used materials, window effects) and site parameters (orientation and radiation, speed and direction of wind).

2.1.3.1 Glazing Properties

Glazing properties, including type of material and number of glazing layers affect the absorbance of solar radiation, reflection and heat loss (Stazi et al., 2012a). For this reason, careful evaluation and proper selection of glazing properties is important in design stage of TW. Based on the weather conditions, the type and number of glazing layers can be decided. For instance, Koyunbaba et al. (2012) found that utilizing single glass for glazing improves the performance of TW in Izmir weather conditions. Whereas, based on the studies of Stazie et al. (2012a) and Stazi et al. (2012b) for Italy climate conditions, applying double glazing decreases heat loss while having limited impact on enhancing solar heat gain.

Richman and Pressnail (2009) presented a low-e covering to be applied on the glazing in order to reduce the radiative heat losses to the outside in heating season. Zalewski et al. (2002) investigated the effects of materials on the TW efficiency by conducting simulation for Trappes and Carpentras weather conditions. It is obtained that, installation of low-e double glazing absorbs more solar energy compared to a standard double glazing.

2.1.3.2 TW Area

The effect of TW area on the energetic efficiency of a TW system is evaluated by Abbassi et al. (2014) in Tunisia. Based on the performed simulation, required amount of auxiliary heating demand shows a decreasing trend with the increase of the TW area. However, the TW area is restricted due to limited space in the south part of the building. Figure 6 demonstrates potential annual heating energy savings based on the size of TW.

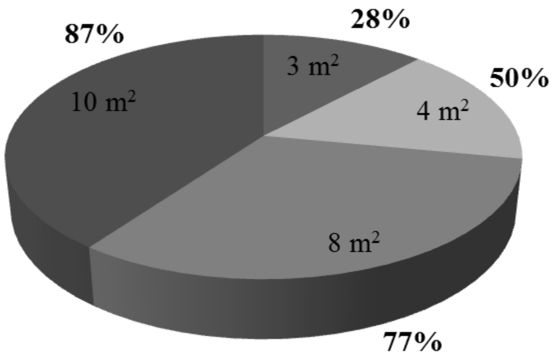


Figure 6: TW area effect on annual heating energy saving. Adapted from Abbassi et al. (2014)

2.1.3.3 Massive Wall Properties

Investigated TW parameters in this section including thickness, materials and insulation level. The effect of different thickness on the TW heating gain is calculated based on ISO 13790:2008(E), by Briga-Sá et al. (2014) for ventilated and unventilated TW. In case of ventilated TW, by increasing the TW thickness, heat gain is increasing as well, whereas when the TW is non-ventilated, by increasing the TW thickness heat gain is decreasing (see Figure 7). Therefore, it could be concluded that in non-ventilated TW applications the wall thickness should be carefully determined to optimize the wall heat storage capacity and the building heat gain. In ventilated TW applications, as the heat is mostly carried with the air flow, increases of the wall thickness do not have negative impact on the heat gain of the building.

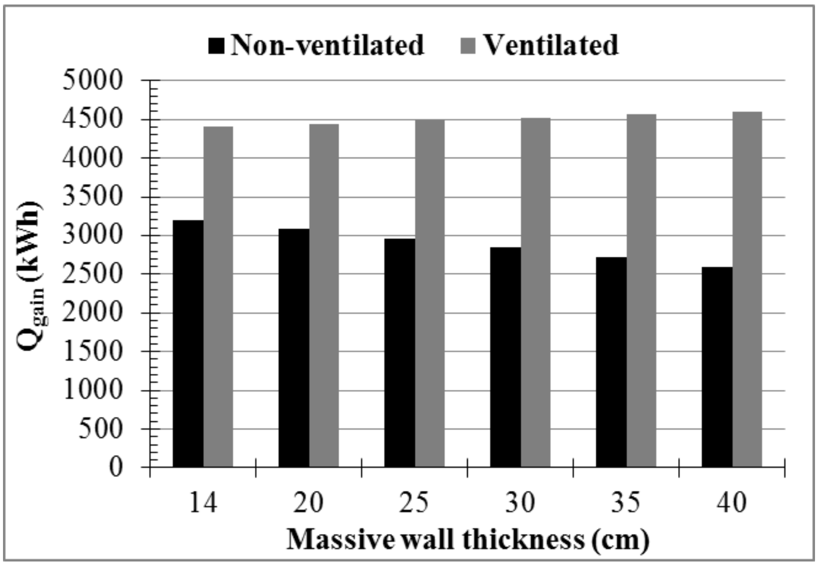


Figure 7: TW global heat gains depending on the thickness of the concrete massive wall. Adapted from Briga-Sa et al. (2014)

2.1.3.4 Shading Devices

Extreme heat gains in summer and heat loss in winter night are the two major weaknesses of TW which limited the application of it. Applying appropriate shading devices can be counted as one simple solution to overcome these unfavorable shortcomings (Ngô et al., 2012), for instance over hangs (Stazi et al., 2012c; Soussi et al., 2013) roller shutter [Stazi et al., 2012b; Stazi et al., 2012c, Chel et al., 2008), shading curtain (Ji et al., 2007; Chen et al., 1961) and venetian blinds (Hong et al., 2015). Utilizing a TW without solar screening during summer is not advised based on Stazi et al. (2012b). Regarding this, the optimal TW performance for summer is presented by applying a combined use of overhang and roller shutter (Stazi et al., 2012c). Not only in the summer, but also in winter night, based on experimental study of Chen et al. (1961), installation of shading in the channel is improving thermal efficiency of the TW. In fact, adjusting shading devices for different periods of the year should be considered.

Martinez at al. (2021) has reduced the solar gain of TW in summer by applying a thermochromic mortar to a prototype TW. It is observed that the thermal transfer performance of the thermochromic TW is improved which can be utilized for energy renewal in the existing building.

It is noticeable to mention that, shading devices are appropriate for summer season, however, they should be removed from TW in winter season specially during day. Regarding this, a simulation study is conducted by Soussi et al. (2013). A 1.5 m movable overhang is installed for TW, means that it can be removed in winter season and applied for summer. The results are demonstrated in Figure 8 and illustrated that the annual cooling energy required is decreased by installing the solar over hang.

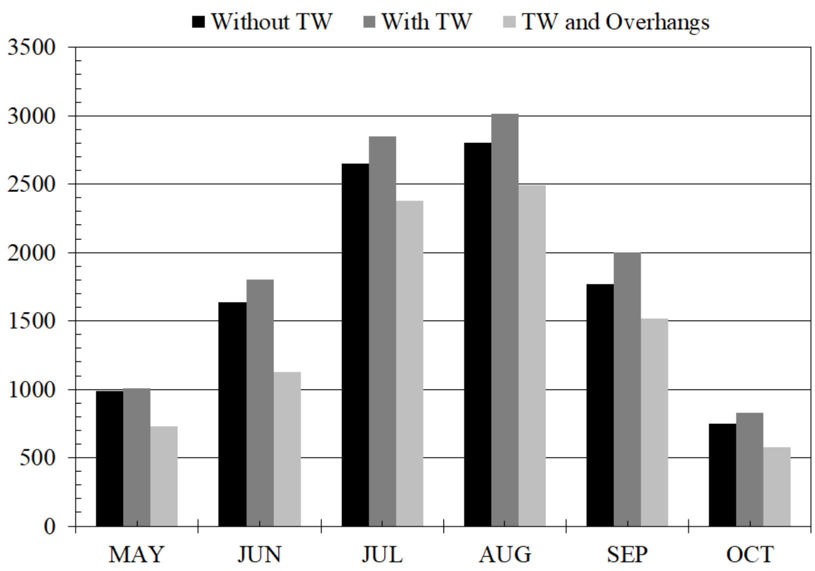


Figure 8: Cooling energy savings using solar overhangs. This figure is adapted from Soussi et al. (2013)

A simulation study conducted by He et al. (2015) indicated that if TW is applied for building which are occupied daytime (offices, shopping malls and schools), venetian blind is more appropriate to install during winter season.

2.1.3.5 Channel Depth

Another parameter which can be considered is the channel depth or air gap between glazing and the TW. In fact, Dragcevic et al. (2011) found that this parameter is unavoidable. Chen et al. (2003) the air flow rate is increasing if the channel depth increases. By increasing the air gap to a specific amount, air flow change to a limitless space flow, at the same time, due to this the average air temperature in the channel is reducing and backflow is happening around the exit of TW. On the other hand, an excessive air gap, required thicker TW which causes structural security problem (Hong et al., 2015). A study for a building with unvented TW and direct solar gain is conducted by Yilmaz et al. (2008) and it is found that in case of unvented TW the effect of channel depth is insignificant on TW performance. This result is obtained by applying three different air gap as 0.05, 0.10 and 0.15 m. It is found that different air gap distances neither affect the temperature of the inner surface of TW or room.

2.1.4 Building Parameters

2.1.4.1 Construction Materials

Implemented materials in the building envelope effect the thermal behavior of structure with TW. It is common to use insulation level and high thermal inertia materials for construction envelope. The impact of different building envelope on the efficiency of TW is evaluated by conducting a simulation by Abbassi et al. (2014). The results illustrate that insulation assisted TW significantly for decreasing the required heating in the building. Regarding building insulation impact on the TW performance, a numerical study investigated by Stazi et al. (2012b) in Italy. It is found that, if the insulation level increases, the overall energy performance also increase as the overall required heating and cooling was 38 (kWh/m^2) for conventional envelope, whereas it is decreased to 29 (kWh/m^2) for the super-insulated envelope.

2.1.4.2 Window Effects

The indoor air flow circulates due to thermos-siphon. Besides that, in the existence of window, solar radiation can transmit and heat the floor and walls which cause circulating warm air flow from the top down. In this section the impact of window on the south façade of the building on the TW is investigated. Regarding that, Ji et al. (2007) investigated the effects of a window on the PV-TW performance in China, which is placed on the south façade of the building. The results show that the average daily efficiency for the PVTW is reduce by 5.7% in the result of having window. An experimental and dynamic numerical model study is conducted by Sun et al. (2011). It is found that the thermal performance of the PVTW is reduced by 27% in case of having window on the south façade. Based on the literature, the thermal efficiency of TW is reducing in case of having TW, however, they did not investigate the size and position of window in detail. Hence, it is suggested that the effect of window on the TW efficiency need to be investigated in more details.

2.1.5 Site Parameters

2.1.5.1 Solar Radiation and Orientation

Based on the study of Li and Liu (2014) and Dragicevic et al. (2009), solar radiation is one of the significant factors in circulating air flow through the TW channel. Li and Liu (2014) have been studied the impact of solar radiation on the air flow rate. It is found that the air flow rate slightly increases by increasing in the heat flux. Regarding this, Burek and Habeb (2007) have been conducted an experiment by considering different heat inputs for a TW. It is obtained that; the mass flow rate is proportion to heat input. In fact, the thermal performance of the TW depends on the solar radiation level and increases proportionally with solar radiation increment.

Another parameter which affects the efficiency of TW is the orientation of TW. Generally, in the north hemisphere, the most appropriate direction for building a TW is south, southeast and southwest. However, in the southern hemisphere, north, northeast and northwest are the most favorable orientation for constructing a TW Krüger et al. (2013). Three orientations for TW construction has been simulated by Soussi et al. (2013) at Borj Cedria, Tunisia. The results demonstrated that the total required heating has the lowest value in the southwest orientation (469.6 kWh), whereas for the northwest and west the total required heating value for the building increase significantly.

2.1.5.2 Wind Speed and Direction

Another natural parameter which affects the thermal efficiency of TW is the speed and direction of wind. Normally, heat loss thorough glazing which affects TW thermal performance and air flow depends on the speed and direction of the wind. Dragicevic et al. (2011) has been investigated the impact of wind speed on the thermal performance of TW when the solar radiation is constant. They found out, the thermal performance of TW increased with wind speed increases. It is noticeable to mention that the obtained result is close to the study which has been done by Bhandari and Bansal (1994). The impact of ambient air speed on the efficiency of TW (solar chimney) is investigated by Tan and Wong (2014). It is obtained that when the ambient air speed is zero, the solar chimney had better performance.

2.1.6 Evaluation Indicators

In general, the TW efficiency can be investigated under three point of view: thermal efficiency, energy and economic. From energy point of view, the TW has higher thermal efficiency when the value of room temperature is higher which causes more energy savings. However, there are variety of description for TW performance in the literatures. For instance, Rabani et al. (2015) and Li and Liu (2014), described the performance of TW as the effective energy gained by the air flows through the vents. Based on the Li and Liu (2014) study, the thermal efficiency can be estimated as follows:

$$Q_o = mC_p(T_o - T_i) \tag{2}$$

where T_o and T_i are the temperature rise, m is the flow rate through the inlet and outlet of air channel, and *Cp* is air specific heat (J/kg °C).

where the total heat input and thermal efficiency are as follows:

$$Q_i = Q_o + Q_r \tag{3}$$

$$\eta = \frac{Q_0}{Q_0 + Q_r} \tag{4}$$

where Q_r is radiation heat gained by the glass and η is the thermal efficiency.

2.1.7 Economic Perspective

Considering any additional construction in buildings can be costlier than its benefits (Zhao et al., 2012). For instance, extra expense of building a TW to the homeowners denotes a cost, and the energy savings and reduction in CO_2 are considered as profits. An experimental study has been conducted by Llovera et al. (2010) in Andorra. It is mentioned that, 20% of the required heating in the house can be delivered by TW. Furthermore, by constructing TWs, clients can benefit economically in long term period.

The environmental, economic and thermal impacts of building TWs in residences have been investigated by Jaber et al. (2011) for the Mediterranean region. They concluded that the economic optimum point is achieved when the ratio of TW area to that of the southern wall is 37%. This required an extra investment of 1260 EUR resulting in a life-cycle saving of 1169 EUR. The performance of TW in this study is analyzed by conducting a simulation in TRNSYS software. A hypothetical honey-storage building with TW is simulated by Chel et al. (2008) in TRNSYS for India weather conditions. It is found that 3312 kWh/year could be saved by constructing a TW. Moreover, reduction in about 33 tons CO_2 emissions is achieved. On the other hand, the authors found that for an existing house, building a TW is economically viable since the payback period is about seven months. Kashif Irshad et al. (2014) investigated the integration of different types of photovoltaic (PV) with TW in Malaysia. The results showed that the annual energy consumption of a typical house with PV-TW is approximately 1302 kWh less than a house without PV-TW and around RM 3044.4 savings are achieved over 20 years. A comparison of energy and environmental performance of two buildings with and without TW which are placed in Lyon, France is carried out by Bojic et al. (2014). It is found that, the annual energy savings in case of having TW is about 20%. A hypothetical two story building (with 5cm thermal insulation) integrated with a TW is simulated with TRNSYS by Nowzari (2009) for Larnaca's weather conditions. The results showed that a vented 15 m^2 TW, can meet approximately 95% of the heating energy required by the zone. In this study the Life Cycle Cost analysis revealed that building a TW is economically feasible compared to installing a 3-kW gas heater. An integrated economic viability study of a one storey solar house in NC is carried out by Atikol et al. (2013). In this work, the solar building is integrated with a TW and a direct gain solar window. The economic viability analysis results demonstrated that building a TW is economically viable. Ozdenefe et al. (2018) also investigated the economic feasibility of constructing a TW from the customers' point of view and found that it is worth building TWs for the new houses which are thermally insulated.

Kostikov et al. (2020) has presented an algorithm regarding technical and economic analysis of TW application together with the most appropriate climate for its construction. The results demonstrated that the most effective TW in terms of heating supply is in the latitude range of 40° to 55° N with the payback period of 3.5 to 10 years.

2.2 Demand Side Management

Demand side management (DSM) includes any arrangement, performance, and monitoring of the utility activities devised in order to rectification the electricity usage patterns of customer match to the preferred utility's load shape, i.e., shifting in the time usage and utility's load. These activities include: load management, new uses, strategic conservation, electrification, customer generation, and adjustments in market share (Gellings 1985). Six techniques applied to modify the peak with DSM are peak shifting, peak clipping, strategic conservation, strategic growth, flexible load shape and valley filling (see Figure 2).

One of the classic forms of the managing load is peak clipping. Mostly, it reduces the peak load by direct load control utilization or direct monitoring of customer's usage (Gellings 1985). In developing countries or places with economic difficulties of building new power plants peak clipping is very convenient solution.

Valley Filling is another type of load management which encompasses creating off-peak loads. In fact, it changes load curve in such a way that increases load factors in off-peak hours due to encouraging customers to spend energy during off-peak hours and change their time schedule of usage during day. Offering lower electricity tariff is one way to encourage them. In region where the loads are generated by fossil fuels, promoting thermal energy storage is another way of accomplishing valley filling.

Load shifting is another type of classic load management which shift loads from on-peak to off-peak periods (Gellings 1985) generally by using of storage devices (e.g., ice thermal storage, storage space heating).

It is noticeable to mention that, energy storage probably will play a significant role, while at the moment storage technologies are under research and testing level. For instance, pump hydro is one of the only technologies which improved commercially and utilized extensively. However, the disadvantage is geographical restriction (Deane et al., 2010). Flywheels, compressed air energy storage, large thermal storage tanks, electric vehicle and batteries are another storage options (Evans et al., 2012).

Strategic Conservation defined as a change in load shape as a result of designated program from utility which concentrated on the customers' side consumptions. In fact, strategic conservation reveals a rectification for the load shape by changing the usage pattern which cause less electricity sales as well. It is essential to assess those conservation actions which might arise naturally to estimate the cost effectiveness of the chance of future utility programs in order to hasten and incite those activities (Alto 1984). For instance, weatherization and efficiency improvement appliances.

Strategic Load Growth is the load shape modification which applied with the purpose of general increasing in sales, implemented by utility and it is different from valley filling. There is a possibility of including electrification in load growth in the future. One definition of the term electrification is to explain the new developing electric technologies including electric vehicles, automation and heating process in industrial which increase the electric energy consumption in industrial sector (Gellings 1985).

Flexible load shape is an impression regarding dependability and planning limitation. In flexible load shape customers have the chance of different incentives based on the quality of service (Gellings 1985).

Atikol et al. (1999) indicated that investing a$100 million for a new power plant in NC can be postponed for 19 years, by applying the proposed DSM program costing $12.15 million. A survey had been conducted in order to obtain a trend of hourly power consumption of home appliances, to be used in the DSM analysis. The offered DSM programs in this study contributed in peak shifting and strategic conservation strategies.

Atikol et al. (2003) proposed a methodology in order to facilitate the DSM technologies enter to the market of developing countries. In this study, by utilizing existing economic indicators and some end-use information, the appropriate technologies for the defined developing country had been determined. NC and Turkey are selected as the case studies to corroborate the theory. It is found that, DSM-technology transfer in NC in the residential and commercial sectors are more successful, however in Turkey the industrial sector was a better choice.

Saffari et al. (2018) examined implementing DSM in industrial sector to decrease demand by off-grid solar PV and shift peak electricity demand by the usage of cold thermal energy storage. It is obtained that the annual electricity savings is higher in case of coupling solar PV and cold thermal energy storage compared to utilizing them individually. Moreover, by integrating thermal energy storage with off-grid solar PV, electricity power demand is reduced significantly.

The relation between the usage of thermal energy storage, solar energy, and DSM strategies to increase energy flexibility in buildings has been investigated by Ren et al. (2021). Energy performance of a net-zero energy house is simulated by using TRNSYS. It is found that, by utilizing DSM strategies, contribution of solar energy to run the heat pump (i.e. the ratio of the energy usage delivered by PV to its total energy usage) was 0.79.

Campos et al. (2020) proposed promotion of heat pumps through DSM. The authors concluded that cleaner residential heating can be achieved with an additional potential for flexibility in electricity demand due to proposed usage of hot water storage tank.

Reducing the power peak at grid level by controlling the operation of a pool of heat pumps has been investigated by Vivian et al. (2020). In the study, heat pumps are integrated with heat storage tanks for space heating and producing hot water. The results show that the proposed DSM allows reducing daily peaks up to 21% if only utilized for space heating.

Bechtel et al. (2020) has investigated the influence of different sizes of heat storage and heat pumps on cost savings and shifting energy consumption from the consumer side, under Luxembourgish conditions. The suitability of heat pump DSM strategies for net zero energy buildings is obtained. However, cost savings is not sufficiently encouraging the consumers to invest in optimizing the heating system for DSM dedications.

The impacts of adsorption thermal storage and storage of sensible heat in hot water tanks on peak shaving has been investigated by Hutty et al. (2020). The utilization of these technologies along with DSM is simulated in a residential building. It is obtained that by employing both technologies peak is reduced by 14%. However, due to high cost and complexity of adsorption storage, this technology is not attractive for consumers for peak shaving application.

Chapter 3

METHODOLOGY

3.1 Overview

In many countries where smart grid is not available, the six strategies of DSM can be applied by introducing rebate programs or introducing multi-tariff electricity pricing. Multi-tariff pricing of electricity can be effective in achieving demand response, urging the consumers to shift their activities to off-peak hours. In the current work, the promotion of TW is considered to be a potential strategy in matching the use of solar energy with the demand for heating a space. This strategy may also help the utility reduce its costs. The process is summarized in Figure 9. It is proposed that the utility not only generates electricity for meeting the demand, but also conducts a rebate program funding the installation of TW in residences in order to reduce the peak demand and make its activities more profitable. Due to the fact that TWs utilize solar energy to provide heat in winter, it is anticipated that non-renewable energy consumption and CO_2 emissions would be reduced due to their promotion.

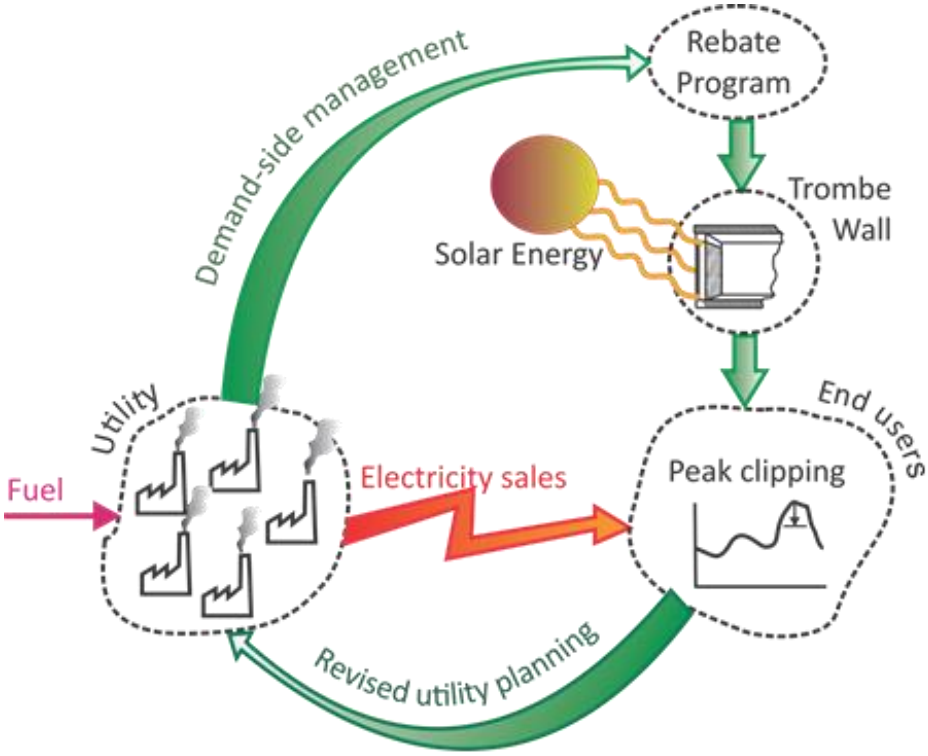


Figure 9: The simplified utility activities integrated with promotion of TW with DSM (Rezaei et al. 2020)

The methodology can be broken down into three main steps; development of DSM approach, energy simulation of buildings and, economic feasibility analysis. These steps are explained in detail in the following sections.

3.2 Proposed DSM Methodology for Promotion of TW

3.2.1 Introduction

Typically, the annual usage of maximum peak generators is limited to a few weeks. Therefore, avoidance of the purchase of these generators is most desirable since their economic justification is uncertain. In the proposed approach, the extent of desired peak reduction is determined first. It would be appropriate to consider this reduction to be equivalent to a deferred power unit of known capacity and cost. By promoting the TWs in houses, it is targeted to make the end-users terminate the use of electric heating devices during peak hours. In many countries winter peak hours coincide with the maximum thermal performance of the TWs, which is usually in the early evening.

Figure 10 shows a simplified setup of the DSM approach adopted in the present work. A carefully designed implementation program, including the criteria for selection of houses and assessment of economic feasibility from the points of view of the utility and the consumers is required.

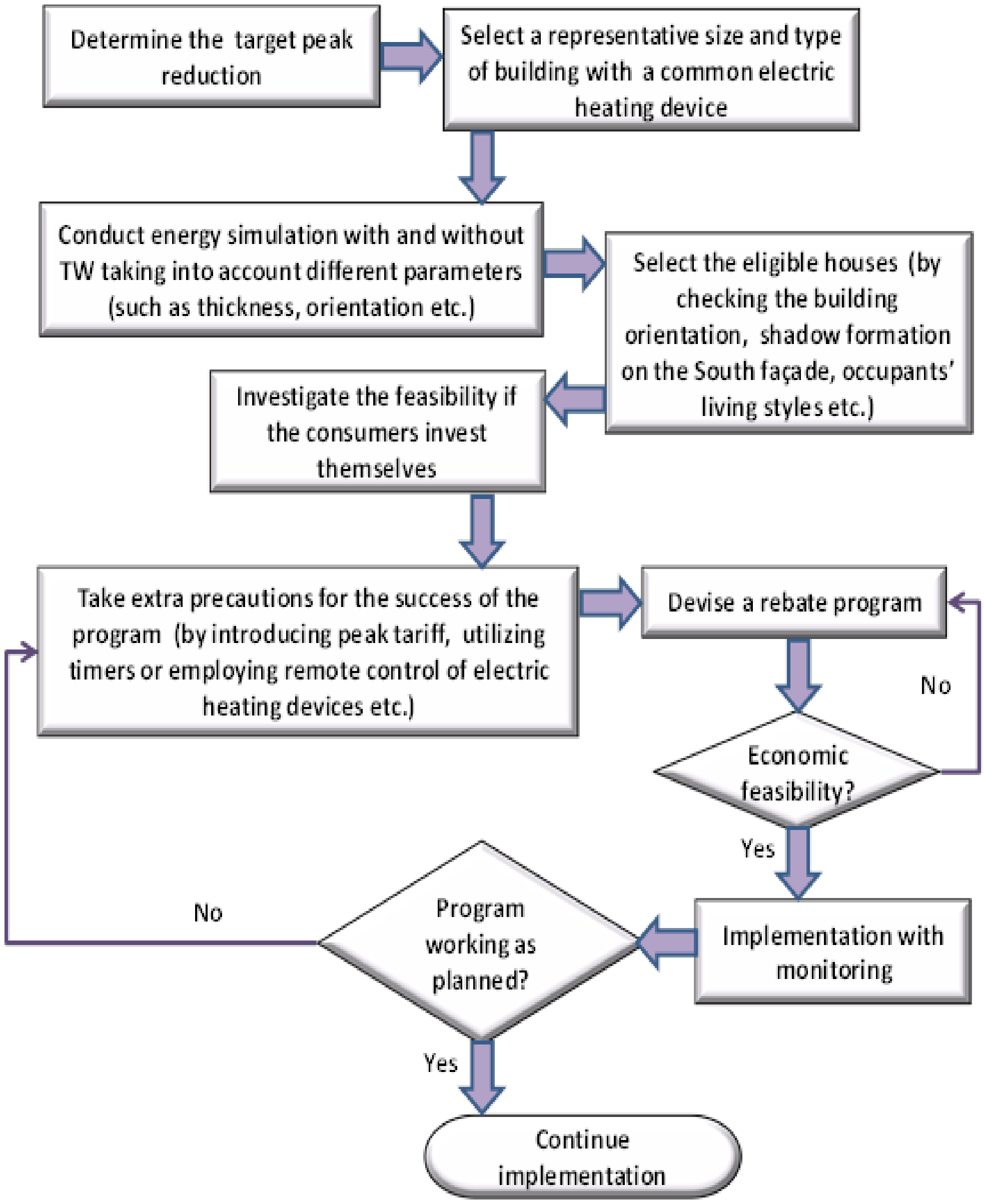


Figure 10: Proposed approach for enhancing the economic feasibility of TW construction in residences

3.2.2 Determining the Suitability of Participating Houses

As the peak reduction target needs to be satisfied it is required to understand the power rating of the heating devices that are to be switched off during the peak hours. Moreover, a representative house model needs to be determined for carrying out energy simulations. A representative house could be selected based on the average size of living rooms, common materials used in building constructions and if there are any enforced construction rules in the considered region. The simulation results would allow assessing the room temperature deviations, economic costs of not selling electricity during these hours and savings achieved due to power unit deferral when applied to a number of houses. It would also be required to optimize the area of the TW in order to store enough energy for providing heating even in the coldest days. The eligibility of the houses that can be accepted to participate in a DSM program for construction of a TW can be set as follows:

i. The room where the TW is to be built should face to South in the northern hemisphere and to North in the southern hemisphere. There may be slight off-sets from the orientation, the limits of which can be determined in the simulations.

ii. There should not be any trees or other objects casting shadow on the TW.

iii. The living style of the occupants should be in line with the DSM program requirements. In other words, the heat provided with the TW should be satisfactory for them at all times.

iv. The selected houses should preferably be participating in a multi-tariff system, in which the cost of electricity is considerably higher during the peak hours compared to off-peak hours.

v. Those houses fitted with electric resistant heaters and low-*COP* air conditioners (specifically those without inverter feature) should be preferred as they would contribute more to the peak reduction when they are switched off during the peak hours.

vi. Low-income consumers should be given priority to participate in the DSM program since they would prefer to avoid using electricity during peak hours.

If an expensive tariff is applied by the utility during peak hours, it would be easier to convince house owners to take part in the DSM program. It is also highly likely that they will not turn on their electric heating devices at that time once they have a TW in their houses. However, it should be remembered that TW is essentially a passive solar system and may not perform at its best on some days. In order to make sure that the electric heating devices are not used during peak hours when the temperature is relatively low, several extra precautions can be taken. These can be listed as follows:

i. In places where multi-tariff system is in force, the DSM program can be applied to more houses than required to eliminate the effect of unexpected usage of electric heaters during peak hours.

ii. Gas space heaters can be offered within the DSM package so that the participants can get extra heating if they wish so during the peak hours.

iii. Timers can be introduced as an integrated part of the DSM contract which would not allow the usage of electric heating devices during the peak hours.

iv. In places where the infrastructure allows, remote cyclic control of electric heating devices can be integrated as a part of the DSM program to ensure that they are not turned on during the peak hours.

The transient energy simulation in a representative hypothetical building carried out for the whole year round would reveal the following information:

i. The electricity consumption of the electric heating device for a room that does not have a TW will be estimated. This will help to evaluate the lost income of the utility, the equivalent operation and maintenance (O&M) savings of the avoided peak generator in winter in case of having TW. In summer, the TW causes extra cooling requirement in which case the extra income and the extra O&M expenditures can be evaluated.

ii. The indoor temperature profile in the room will be obtained throughout the peak hours. This will be useful in determining the thermal comfort level.

iii. The simulation plays an important role in determining the economic feasibility.

3.3 Mathematical Model

The energy flow across the control volume of a room integrated with TW is demonstrated in Figure 11. During day time, solar radiation (Q_S) is gained and stored (Q_{Stored}) by the TW. Heat loss from TW to the surroundings are denoted by ($Q_{L,\ TW}$). Moreover, heat losses from the roof, ground, walls, and due to ventilation are denoted by $Q_{L,\ r}$, $Q_{L,\ g}$, $Q_{L,\ w}$, and Q_{Vent}. During evening time (when solar radiation is not available), some portion of stored heat in TW is transferred to the room (Q_{TW}). By this way, integration of TW to the building enables gaining solar heat during the daytime and releasing it to the building in the evening.

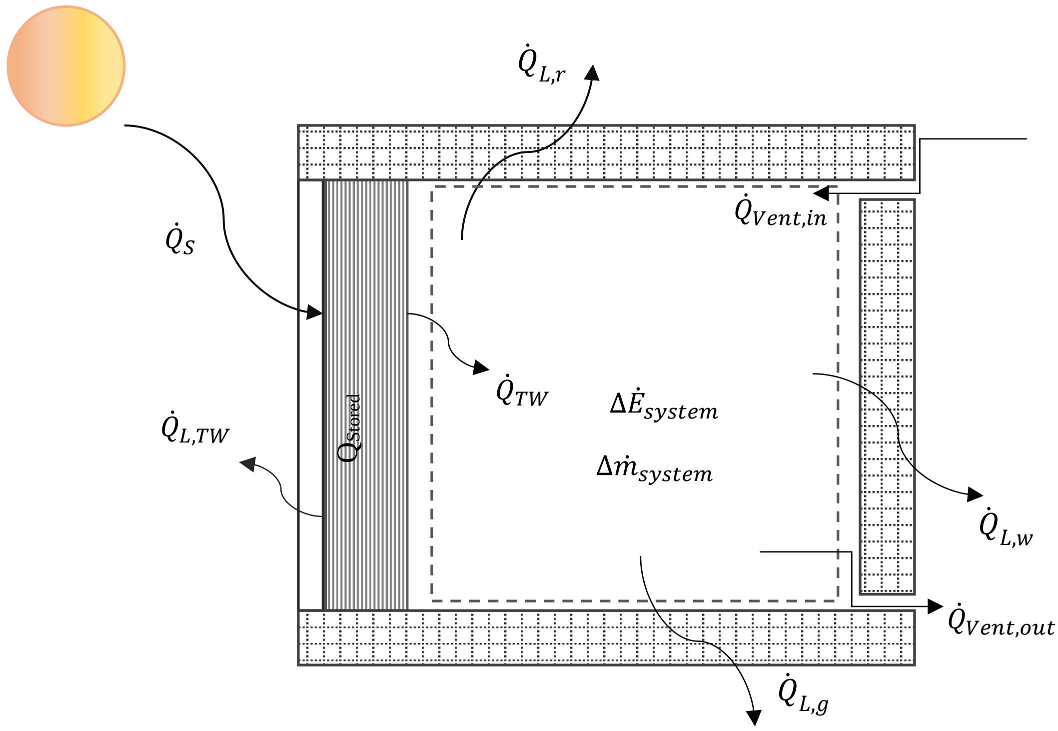


Figure 11: Control volume across a room integrated with TW

The energy balance equation, in the rate form, based on the selected control volume in figure 11, can be calculated as follows:

$$\dot{Q}_{TW} + \dot{Q}_{Vent,in} - \dot{Q}_{Vent,out} - \dot{Q}_{L,r} - \dot{Q}_{L,w} - \dot{Q}_{L,g} = \Delta\dot{E}_{system} \quad (5)$$

The simulation conducted in the current study is based on a numerical solution of transient heat conduction through the walls. In general, transient heat conduction considers the variation of temperature with time and position through the wall. One way of obtaining the numerical formulation of a heat conduction under transient condition is finite difference method, which involves clustering in time as well as space, as illustrated in Figure 12. This requires an appropriate time step Δt selection which solving for the indefinite nodal temperature. This needs to be done for each Δt until the result at the preferred time is obtained.

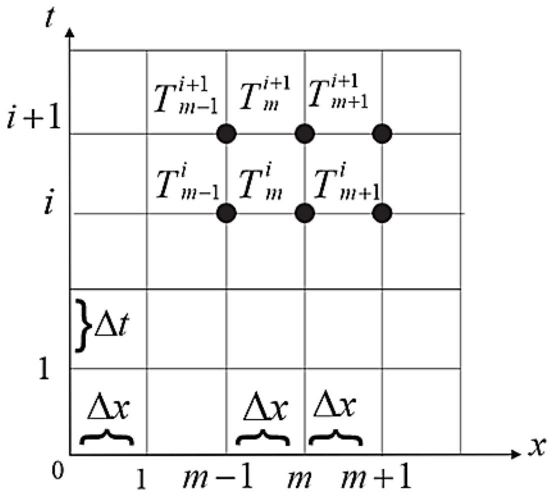


Figure 12: Finite difference formulation of time dependent condition includes discrete points in time and space. Adopted from Cengel (2003)

3.3.1 Transient Finite Difference Formulation of One-Dimensional Conduction in a Plane Wall

A plane wall with the thickness and heat generation of L and $\dot{g}$(x,t) is considered as shown in Figure 13. The transient one-dimensional heat conduction of the wall with heat generation $\dot{g}$(x, t) which might vary with time and position, and constant thermal conductivity k with a mesh size of Δx and nodes 0,1, 2…, M is demonstrated in Figure 13 (Cengle, 2003).

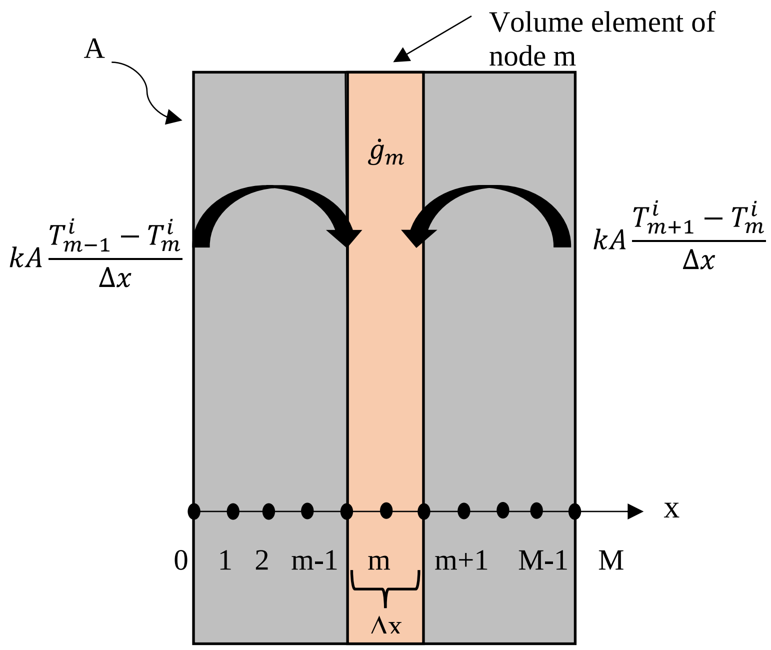


Figure 13: The nodal points and volume elements for the transient finite difference of one-dimensional conduction. Adapted from Cengel (2003)

If the volume element of the interior node of m be *V=A*Δ*x* and considering that it includes heat conduction from two sides, the transient finite difference formulation for node can be calculated by writing the energy balance on a volume element during a time interval Δt:

$$\begin{pmatrix} \textit{Heat transferred into} \\ \textit{the volume element} \\ \textit{from} \\ \textit{all of its surfaces} \\ \textit{during } \Delta t \end{pmatrix} + \begin{pmatrix} \textit{Heat generated} \\ \textit{within the volume} \\ \textit{element} \\ \textit{during } \Delta t \end{pmatrix} = \begin{pmatrix} \textit{The change in the} \\ \textit{energy content of} \\ \textit{the volume element} \\ \textit{during } \Delta t \end{pmatrix}$$

$$\sum_{All\ sides} \dot{Q} + \dot{G}_{element} = \rho V_{element}\ C\ \frac{T_m^{i+1} - T_m^i}{\Delta t} \tag{6}$$

where T_m^i and T_m^{i+1} are the node (m) temperatures at times i and i+1, respectively.

$$kA\frac{T_{m-1} - T_m}{\Delta x} + kA\frac{T_{m+1} - T_m}{\Delta x} + \dot{g}_m A\Delta x = \rho A\Delta x C\frac{T_m^{i+1} - T_m^i}{\Delta t} \tag{7}$$

Withdrawing the surface area, A and multiplying by Δx/k, it shortens to

$$T_{m-1} - 2T_m + T_{m+1} + \frac{\dot{g}_m \Delta x^2}{k} = \frac{(T_m^{i+1} - T_m^i)}{\tau} \tag{8}$$

where α is thermal diffusivity of the wall material and τ is a dimensionless mesh Fourier number.

3.4 General Methodology of Economic Feasibility Calculations

In this section the general economic feasibility calculations of a TW construction from customer and utility point of view are presented. In energy projects, total savings during the life time of the project is required to be more than the investments in order to have economic feasibility.

3.4.1 Economic Feasibility from the Customer Point of View

Estimating the viability of TW construction from customer point of view indicates if the customers can invest in this construction themselves. On the other hand, clarifying the advantages of integrating a TW to the building structure, could encourage the homeowners more to participant in the DSM program. Therefore, before analyzing the economic viability of the proposed DSM program, the economic feasibility of TW construction from customer point of view should be conducted. Net present value (*NPV*), savings- to-investment ratio (*SIR*), and present value of cash flow are the economic factors that can be employed to evaluate economic analysis. *NPV* can be calculated as the difference of total annual savings and total annual investments. However, *SIR* is the ratio of total annual savings to total annual investments. A project is economically viable if the value of *NPV* is greater than zero and *SIR* is greater than one (Ozdenefe et al., 2018). These can be represented mathematically as follows:

$$NPV = \sum_1^n AS_{PV} - \sum_1^n LCI_{PV} \quad (9)$$

$$SIR = \frac{\sum_1^n AS_{PV}}{\sum_1^n LCI_{PV}} \quad (10)$$

$$Present\ Value\ of\ Cash\ Flow = \frac{Cash\ flow\ in\ year\ zero}{(1+discount\ rate)^n} \quad (11)$$

where, AS_{PV} is the present value annual savings, LCI_{PV} is the present value life cycle investments and n is the number of years taken for economic lifetime of the project. This is a widely accepted method and has been utilized in many studies (Agboola et al., 2015; Atikol et al., 2013). Time is a significant parameter for the value of money. It means that the value of money for today is different from the value of same amount of money tomorrow. The fundamental method to obtain cash flow at different times properly is defined discounted cash flow analysis. The value of cash flow at different time is calculated from Eq. (11), where n is equal to the corresponding year. For instance, In the current study, the period of the project is 20 years, therefore, the value of n is varied from 0 to 20. Thereby, the cash flow of value for each year during the period of project is taken to the account. The value of discount rate demonstrates the lowest rate of return which is appropriate for any investment and it is assumed to be 2% in the current study. The project is economically feasible if *SIR* is greater than 1.

In the evaluation of the required investment of a TW, the cost of the reinforced concrete wall and glazing should be taken into account. It should be mentioned that since the current study is targeting existing houses, the demolition of the existing standard wall cost, where the TW is to be built, should be added on the cost of TW, such that:

$$I_{Ret} = C_{TW} + C_{DW} \tag{12}$$

where I_{Ret} is investment required to replace an outer wall with a new TW, C_{TW} is the cost of building a TW and C_{DW} is the cost of removing the outer wall.

3.4.2 Economic Feasibility from the Utility Point of View

Economic feasibility is determined by comparing the net present savings with the net present investments and the lost net income in electricity sales. It was shown by previous studies (Kalogirou et al., 2002 & Ozdenefe et al., 2018) that the presence of a TW in a room causes extra cooling requirement in summer. Therefore, there will be a lost income in winter and a gained income in summer as far as the electricity sales are concerned. In general, if the savings are greater than the losses during the lifetime of the DSM program, then the program is feasible from the utility point of view.

The net present savings can be evaluated as follows:

$$NPS = C_{PP} + C_{Fuel} + C_{Ins} + C_{O\&M} \tag{13}$$

where C_{PP} is the cost of the avoided power plant, C_{Fuel} is the total cost of the avoided fuel consumption, C_{Ins} is the insurance cost and $C_{O\&M}$ is the operation and maintenance cost during the lifetime of the DSM program.

The net present investments for a DSM program can be expressed as:

$$NPI = C_{DSM} + C_{DS} \tag{14}$$

where C_{DSM} is the cost of the DSM program. This is usually comprised of the rebate given to the participants and any other service purchased specifically for the DSM program. C_{DS} is the cost of decreased sales that may take place during the implementation of the program. C_{DS} is the difference between lost income in winter and gained income in summer. *NPV* and *SIR* can be used as the life-cycle indicators for determining the feasibility of any considered DSM program, such that:

$$NPV = NPS - NPI \tag{15}$$

$$SIR = NPS/NPI \tag{16}$$

NPV should be greater than zero and *SIR* should be more than one at the end of the project period for achieving economic feasibility.

As a general perspective, the value of *SIR* can be estimated as follows:

$$SIR = \frac{C_{Fuel}+C_{Filter}+C_{PP}+C_{O\&M,PP}+C_{O\&M,Filter}+C_{ins}}{C_{DSM}+C_{DS}} \qquad (17)$$

where C_{Filter} is the capital and $C_{O\&M,Filter}$ is the *O&M* costs of the filter. There will be cash flows due to savings in fuel consumption, *O&M*, insurance payments, and decreased sales of electricity which should be discounted each year due to time value of money by applying Eq. (11).

Fuel savings due to energy savings can be estimated as follows:

$$m_{Fuel,sav} = \frac{E_{Site,sav} \times \rho_{Fuel}}{\eta_{PP} \times (1-L_{Grid}) \times H_v} \qquad (18)$$

where $E_{Site,sav}$ is the electric energy saving at the site (i.e., houses), ρ_{Fuel} is the density of the fuel, η_{PP} is the efficiency of the power plant, L_{Grid} is the grid loss-ratio and H_v is the heating value of the fuel. Here it is assumed that L_{Grid} and ρ_{Fuel} are constant in the regions of analysis. The assumed values for all parameters are described separately for each case studies in chapter five. The fuel cost savings ($C_{fuel,sav}$) eventually can be estimated as follows:

$$C_{Fuel,sav} = m_{Fuel,sav} \times C_{Fuel} \qquad (19)$$

Chapter 4

PERFORMANCE OF TW IN ONE AND TWO-STOREY BUILDINGS UNDER THE CLIMATE CONDITIONS OF FAMAGUSTA, ERBIL AND SAN DIEGO

4.1 Introduction

In this chapter information regarding energy simulations of two hypothetical buildings located in North Cyprus (NC), Erbil and San Diego which utilized in the study are provided. Design builder software is applied to run the energy simulation. The two different hypothetical buildings used in the study, are one and two storey buildings. The simulations are conducted for each building with and without TW. The TW is placed in the living room. It is assumed that in winter during peak hours the living room is occupied and it is unoccupied during daytime hours on the working days. Due to the assumption that the living room is unoccupied during daytime hours and no heating is required the type of TW considered in this study is an unvented classic type one. Another reason of selecting this type of TW is that it is also in line with the purpose of this study. Since the aim of this study is to reveal the feasibility analysis of DSM program for construction of TW in the residential sector, energy consumption of the building needs to be estimated that will be utilized in economic analysis section.

4.2 Design Builder Simulation Tool

Design Builder is an Energy Plus based program tool mostly employed for energy measurement and control. It is established to make the building simulation easer. It is considered as a unique program for creating and estimating the designs of building as it is confederating three-dimensional building modeling with dynamic energy simulations. Design Builder is a user friendly software and suitable for non-professional users since it includes advanced modules to be utilized effectually at any stage of simulation by just a limited number of parameters (Altensis Department, 2015). Design Builder has been utilized not only by engineers, but also by architects, and a wide range of professionals. Design Builder utilizes the latest version of Energy Plus simulation engine (Energy Plus is an energy and thermal load estimation program). In order to evaluate the heating and cooling load of the building, there are different available heat balance algorithms in the Energy Plus program such as Conduction Transfer Function (CTF), and Conduction Finite Difference (CFD). The applied algorithm in the current study for heat transfer calculations within the building structure is CFD model which is based on time series solutions of conduction heat transfer through the walls.

4.3 Validation of simulation setup

The accuracy of the simulation is investigated by conducting experiments in a test building integrated with TW. The building (shown in Figure 14) is built for research on passive and active solar energy methods, which is located in the campus of Eastern Mediterranean University in Famagusta (Lat. 35.1^{o}, Lon. 33.9^{o}), NC.

Figure 14:Test building integrated with TW

The monitoring of the test building was performed by employing measurements for the indoor and outdoor temperatures together with the TW surfaces and the global solar irradiation. A schematic diagram displayed in Figure 15 shows how the experiment was set up. A data acquisition system with a computer was used to collect the data. The details of the experiment can be found in Ozdenefe et al. (2017).

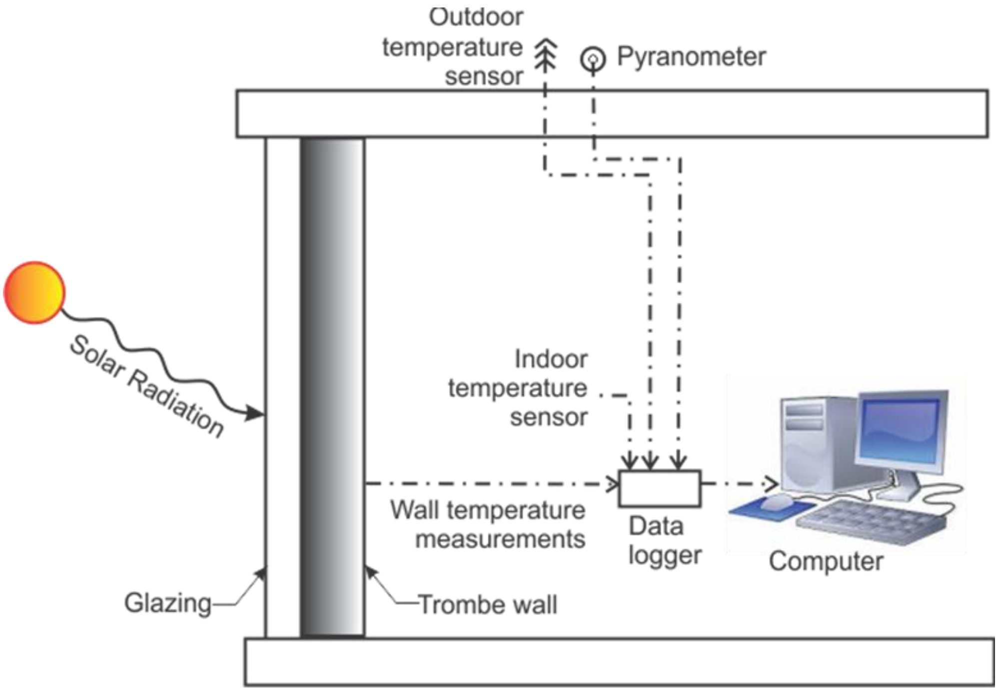


Figure 15: Schematic diagram showing the experimental setup

The hourly values of solar radiation, indoor and outdoor air temperatures acquired from the simulations performed in Design Builder for a similar building and the experimental data were compared. After carefully screening through the simulation results, it was found that between 8th February and 11th February there was a similarity in the outdoor air temperature and solar radiation in four consecutive days. It was realized that the room temperature obtained in the simulations agreed well with that of the experimental observations (see Figure 16). It is clearly seen that, the experimental and simulation results are very close to each other on 8th and 9th February. However, on 10th and 11th February due to incompatibility of solar radiation values in experimental and simulation, the difference in the measured and computed room temperatures during the early evening hours diverge from each other. The same simulation setup was used for the hypothetical buildings described in Chapter four.

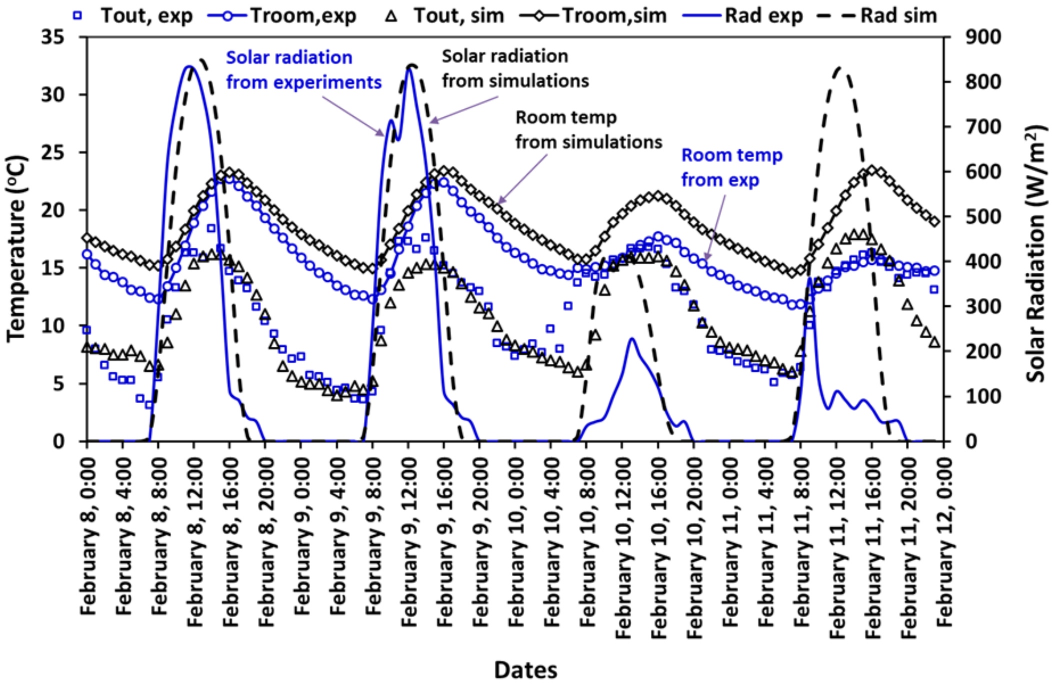


Figure 16: Hourly values of solar radiation and outdoor air temperature acquired from simulations and monitoring

4.4 Building Features and Envelops

4.4.1 Building Characteristics

In this study due to the available conditions for the selected case studies, two different hypothetical buildings (single and two storey building) are considered. The single storey building used in the simulation has a 140 m^2 total floor area with a 35 m^2 living room area within. The virtual two storey residential building has 280 m^2 floor area with a 35 m^2 floor area living room. For both single and two storey buildings, the TW which is faced to the south is resides in the living room. Figures 17 and 18 show the three dimensional of the single and two storey hypothetical buildings, respectively. For daytime illumination in the living room where the TW is placed, a 2.6 m^2 area window is placed in the West wall. The plan view of single and two storey buildings are demonstrated in Figures 19 and 20.

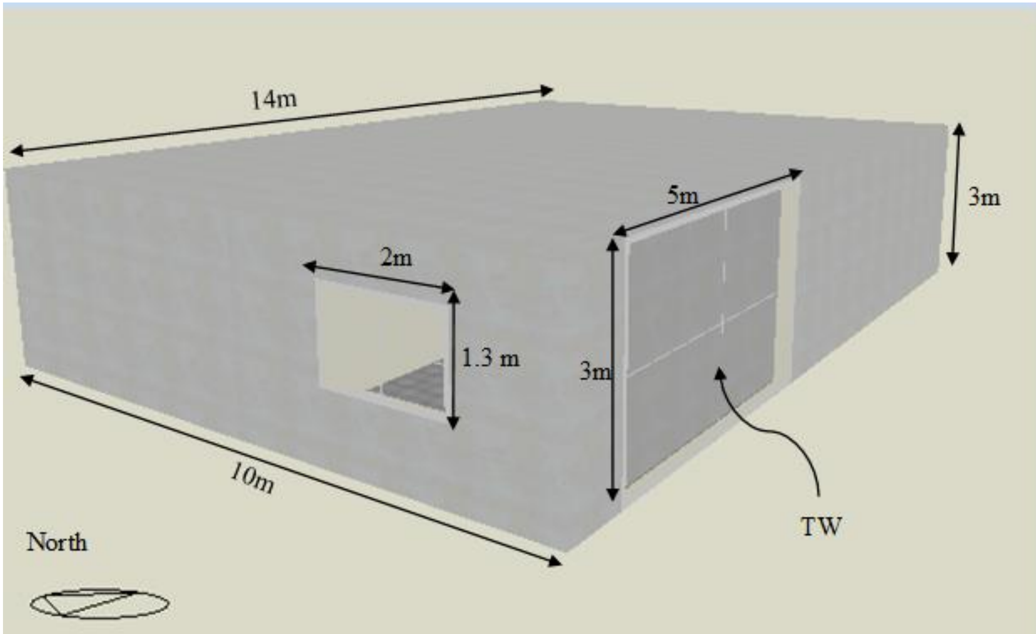


Figure 17: Single hypothetical building

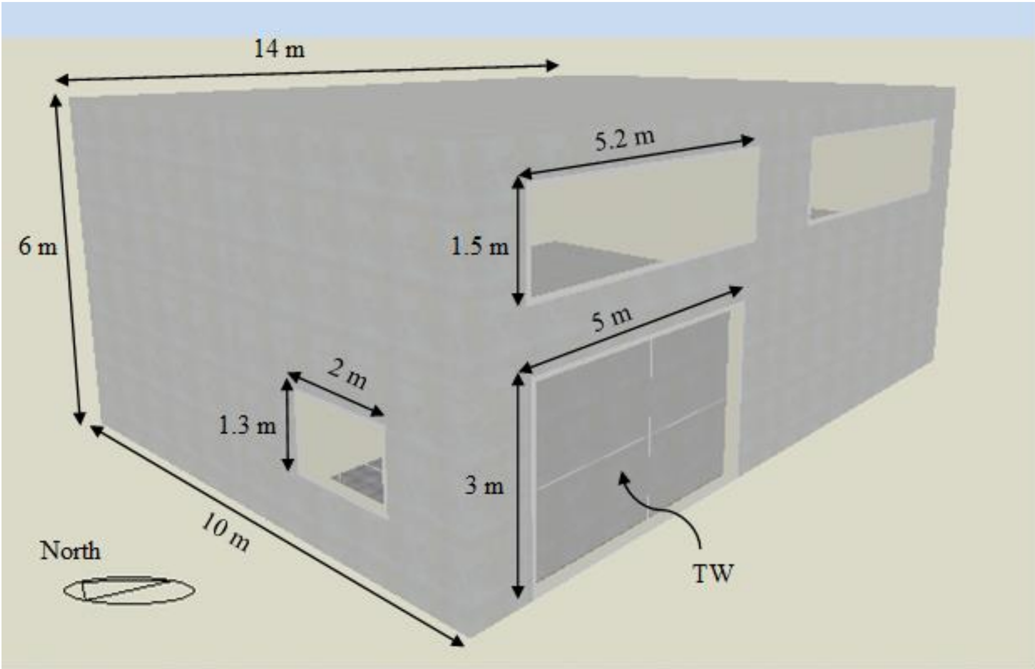


Figure 18: Two storey hypothetical building

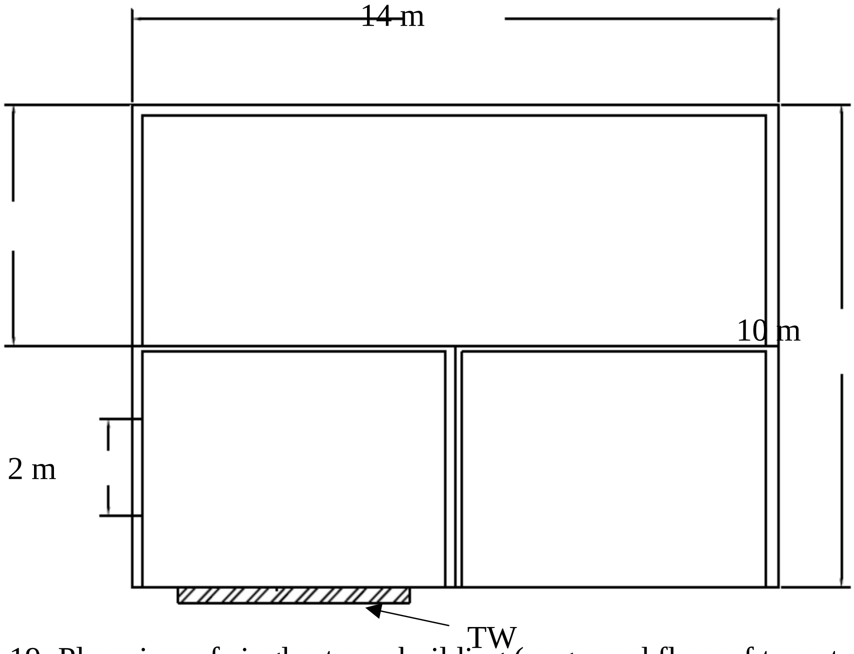


Figure 19: Plan view of single storey building (or ground floor of two storey building)

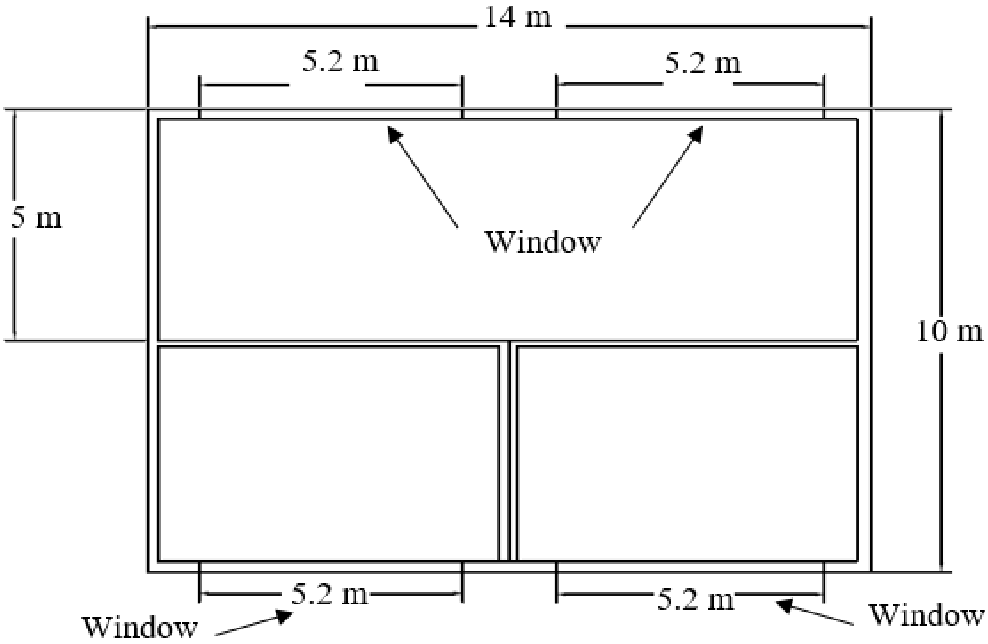


Figure 20: Plan view of the upper floor of the two storey building

The construction materials and dimensions of the building materials which are used in the simulation are presented in details in Figure 21 for case studies of NC and Erbil, and Figure 22 for the case study of San Diego, respectively.

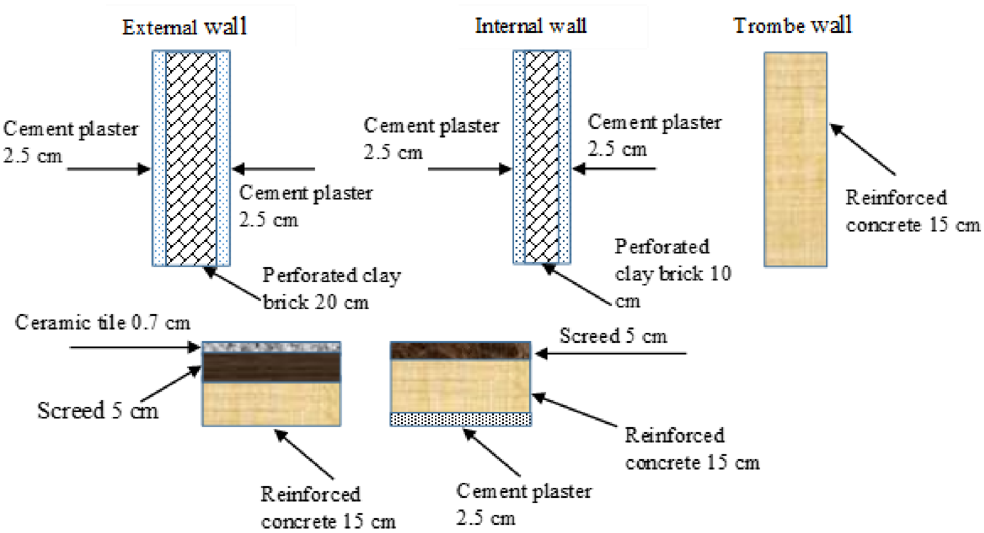


Figure 21: Construction configurations and fabric thicknesses of the hypothetical building used in case study of NC and Erbil

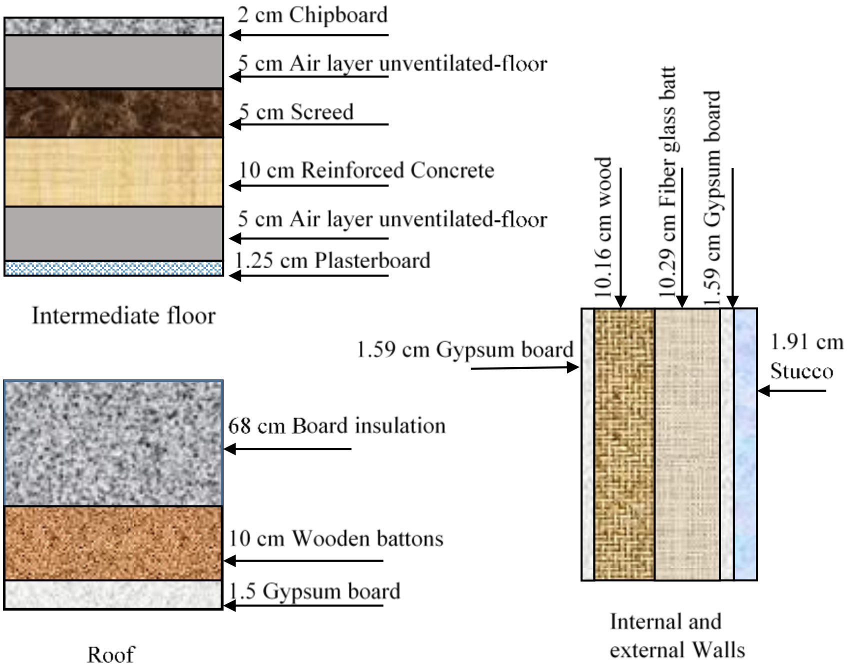


Figure 22: Construction configurations and fabric thicknesses of the hypothetical building used in San Diego case study

In the simulation, in case studies of NC and Erbil, both external and internal wall are built from perforated clay brick and covered from inner and outer surface from cement plaster. Floor is constructed from 15 cm reinforced concrete and 5 cm screed and covered with tile. The main material used for the roof is reinforced concrete with 15 cm thickness and covered by 2.5 cm cement plaster from inner surface and 5 cm screed from outer surface. The TW used in the simulation is constructed from reinforced concrete with 15 cm thickness. For case study of San Diego, walls are built from 10.16 cm wood and insulated with a 10.29 cm fiber glass bath insulation. Roof is constructed from 10 cm wooden battons and covered with 68 cm board insulation. The intermediate floor is built from 10 cm reinforced concrete and covered with 1.25 cm plaster board and 2 cm chipboard from outer and inner surface. It is worth mentioning to mention that the allowed U value for building structures in San Diego are considered in the simulation parameters. The integrated TW to the building is constructed from reinforced concrete with 15 cm thickness.

Thermal properties of the materials used in the building structures are presented in Table 1. k, ρ, and c_p define thermal conductivity, density, and specific heat, respectively. It is worth mentioning that the solar absorptivity value considered for the black paint is 0.96. In addition the U-value for the windows are considered as 3.058 $W/m^2.K$.

Table 1: Thermophysical properties of the hypothetical buildings

Material	Properties		
	k (W/m.K)	ρ (kg/m^3)	c_p (J/kg.K)
Reinforced concrete	1.9	2300	840
Perforated clay brick	0.4	700	840
Cement plaster	1.4	2000	650
Ceramic tiles	0.8	1700	850
Screed	1.4	2100	650
Chipboard	0.13	500	1600
Stucco	1.35	1858	840
Plasterboard	0.21	700	1000
Board insulation	0.036	160	840
Wooden battons	0.13	2800	896
Gypsum board	0.16	640	1150
Wood	1	1000	1000
Fiber glass batt	0.043	12	840

Windows used for the buildings are constructed from two glasses with an air layer in between. The utilized frame for the window is from PVC.

4.4.2 Trombe Wall Characteristics

The TW used in this study is faced to the south and built from reinforced concrete. The variation of zone temperature under various TW thickness under Larnaca weather condition has been investigated by Kalogirou et al. (2002). It is found that there is no significant change in zone temperature for different thickness of 15, 25 and 34 cm. Due to this, in the current study, 15 cm thickness is considered for TW, which helps to decrease the cost of TW construction as well. The thermal properties of the reinforced concrete are provided in Table 1. The TW used in this study is an unvented classic TW (CTW) which is painted with black in its outer surface and glazed. The glazing is a single clear glass with 6mm thickness. In order to provide the greenhouse effect there is an air gap between the TW and the glazing which is considered as a separate zone and called TW zone. As previously has been studied by Kalogirou et al. (2002) the air gap thickness and type of glazing has no significant impact on total heating or cooling load.

4.5 Other Simulation Parameters

In this study in order to provide the real condition regarding with supply fresh air to the room by occupants, in the simulation mechanical ventilation during occupied hours is included. This is due to this fact that, as the fresh air is supplied by occupants by opening the windows and doors from time to time. The electricity consumption of mechanical ventilation is excluded from energy analysis.

Table 2 demonstrates parameters to be entered to Design Builder. These parameters together with weather data for each case study are necessary for energy calculations.

Table 2: Heating and cooling parameters for the auxiliary heat pump

Parameter	Value
Heating set point(during heating season)	22 ^{o}C
Cooling set point(during cooling season)	24 ^{o}C
Heating set point(during cooling season)	50 ^{o}C
Cooling set point(during heating season)	60 ^{o}C
COP (during cooling season)	3
COP (during heating season)	2.75

It is worth mentioning that the unitary air to air heat pump (air conditioning system) used in the simulation is auto sized which depends on the load during the heating and cooling design days. In addition, heating and cooling will be supplied when the indoor air temperature, falls below or rises above 22 ^{o}C and 24 ^{o}C respectively (see Table 2).

4.6 Simulation Results

4.6.1 Case of NC

Famagusta has abundant supplies of solar energy, since it is located at 35.1^{o} N, 33.9^{o} E. In Design Builder, weather data of Larnaca (another city which is approximately 50 km away from Famagusta) located at 34.9^{o} N and 33.6^{o} E is available. In the present study, Larnaca weather data is utilized for simulation. Figure 23 demonstrates the room temperature for single and two storey buildings with TW together with ambient temperature variation during heating season for the case of NC. As it is clear, the ambient temperature never dropped below zero degree Celsius. Starting from November 1, outside temperature start decreasing. On February 4 which is the coldest day of the year it dropped to 1 ^{o}C at 7 o'clock in the morning. Until the end of March while the outside temperature is increasing during day, night times are cold and the temperature is below 20 ^{o}C. On April 25, at 11 o'clock, the outside temperature hit the peak with 30.26 ^{o}C, which even it is above the room temperature with TW. The reason of this, is the sluggish behavior of TW to absorb heat, and needs time to warm up during day, and could not reach the outside temperature. Direct normal and diffuse horizontal solar radiations of Famagusta during heating season which are used in the simulation are demonstrated in Figure 24.

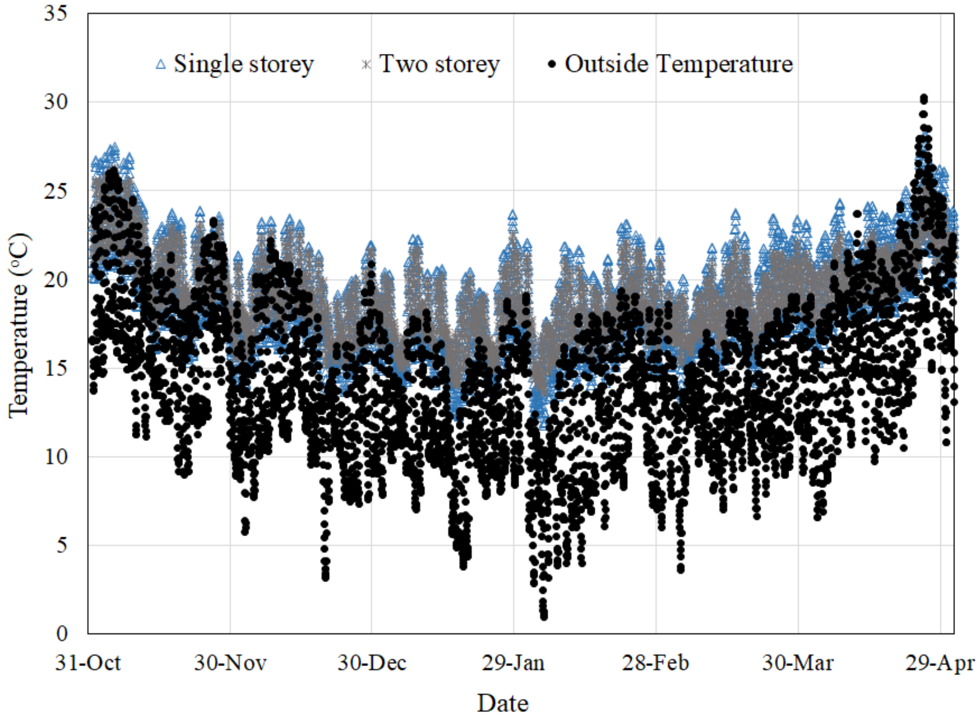


Figure 23: Indoor and outdoor temperature profiles for a south-facing 35 m^2 room integrated with 15 m^2 TW in a single and two storey buildings located in Famagusta during heating season

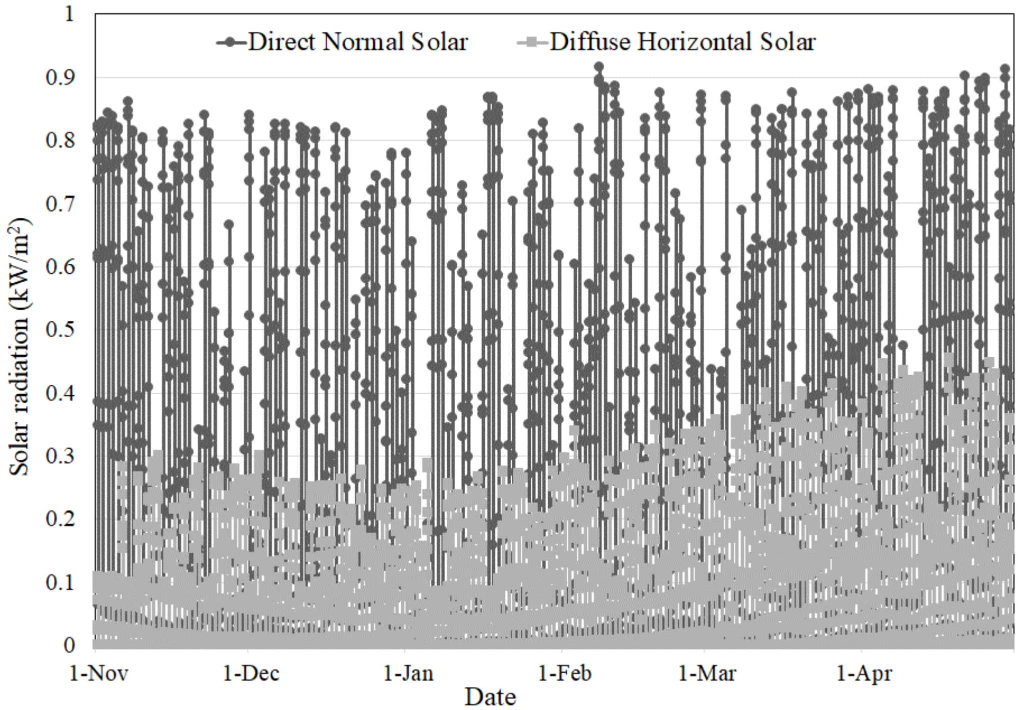


Figure 24: Direct normal and diffuse horizontal solar radiation profiles for Famagusta during heating season

In NC thermal insulation is not very common and the majority of the houses are not insulated. Thereby, in energy simulation the hypothetical building is not insulated and configurations introduced in Figure 21 are utilized in the construction. The energy simulations for heating and cooling seasons are carried out from November 1 to May 31, and Jun 1 to October 31, respectively. In fact, the air conditioning system is set to provide heating during November 1 to May 31 once the living room temperature falls below 22 ^{o}C, and supply cooling during Jun 1 to October 31 once the living room temperature rises above 24 ^{o}C. In addition, the time schedules for occupancy and air conditioning system working during weekdays and weekend are set to be from 17 to 22 pm and 14 to 23 pm for winter and summer, respectively. The design builder models were set to obtain the essential electrical energy to run the AC during mentioned time schedules. The ratio of total electrical energy required to floor area during heating season with TW for single and two storey buildings are 5.54 and 4.2 kWh_e/m^2, while in the case of no TW for single and two storey buildings are 11.2 and 9.2 kWh_e/m^2, respectively. In addition, in this study the burden put on the AC due to TW during cooling season is investigated. It is found that during cooling season the ratio of total electrical energy required to floor area for the living room integrated with TW for single and two storey buildings are 20.65 and 13.11 kWh_e/m^2. This ratio for single and two storey buildings with no TW are 13.4 and 7.6 kWh_e/m^2, respectively.

Figure 25 demonstrates the profile indoor temperature of the living room of the two storey building with and without TW for the coldest days of the winter starting from February 1 to February 5. As it can be seen from Figure 25 except February 5, for the other mentioned days the solar radiation is very low. On the 2nd February, between 17 to 22 pm the living room temperature having TW varies from 15.3 ^{o}C to 14.74 ^{o}C while in case of no TW it varies from 13.9 to 13.65 °C. On the 5th February between 17 to 22 pm while the solar radiation is increased after four consecutive cold days, the living room temperature having TW varies from 17.4 °C to 16.6 °C while in case of no TW it varies from 15.3 to 14.9 °C.

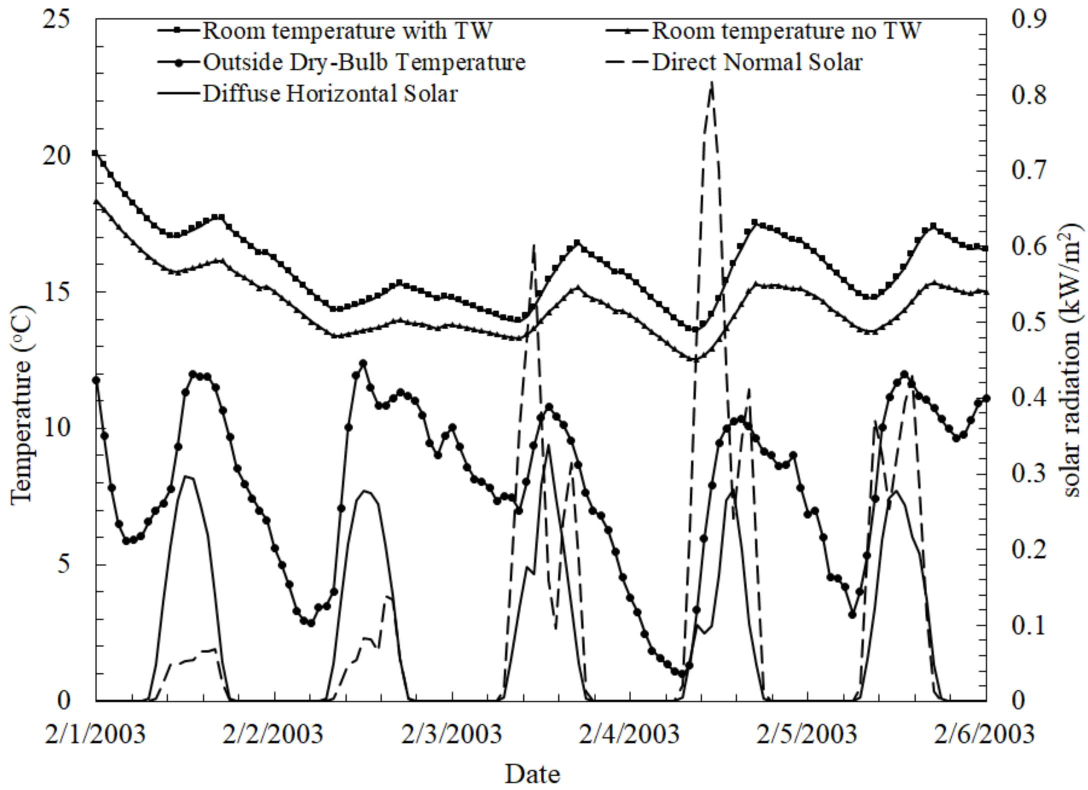


Figure 25: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 15 m^2 TW area in a two storey building located in Famagusta

Figure 26 demonstrates the profile indoor temperature of the living room of the single storey building with and without TW for the coldest days of the winter starting from February 1 to February 5. As it can be seen from Figure 26 except February 5, for the other mentioned days the solar radiation is very low. On the 2nd February, between 17 to 22 pm the living room temperature having TW varies from 13.9 °C to 13.64 °C while in case of no TW it varies from 12.55 to 12.53 °C. The solar radiation has increased after four consecutive cold days on 5th February, which increased the performance of

TW. On this day the living room temperature between 17 to 22 pm having TW varies from 17.2 °C to 16.1 °C while in case of no TW it varies from 14.57 to 14.13 °C.

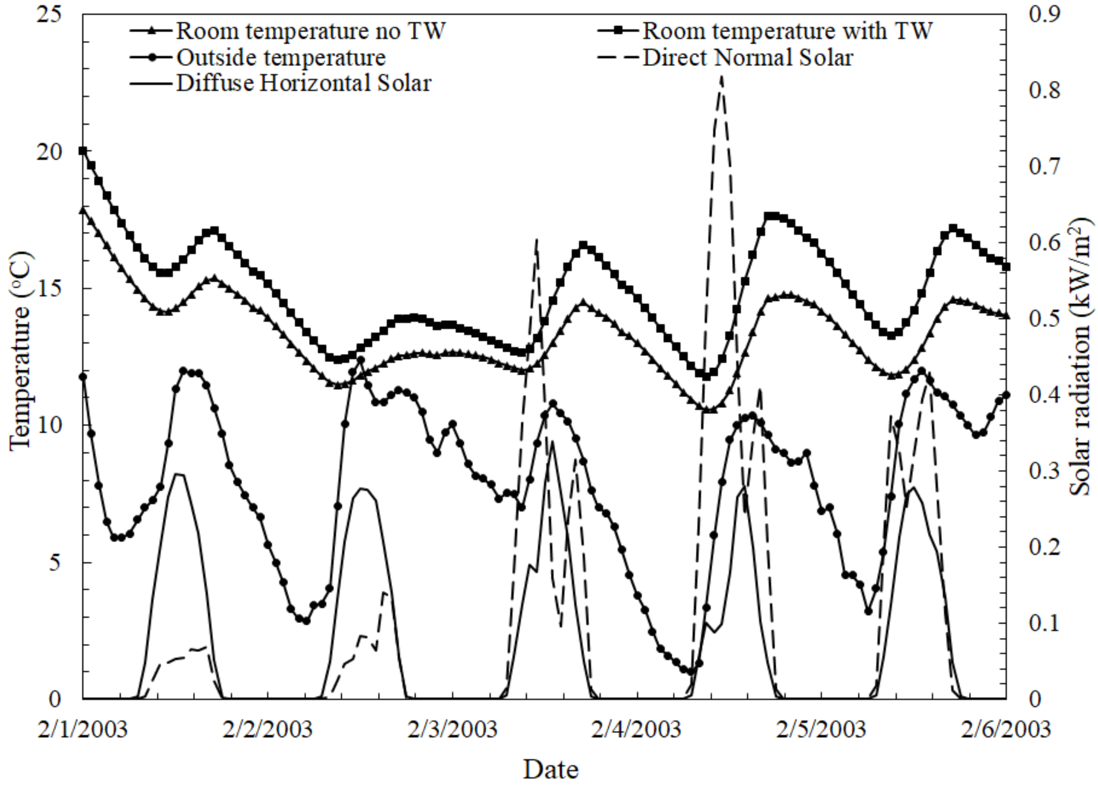


Figure 26: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 15 m^2 TW area in a single storey building located in Famagusta

Tables 3 and 4 Provide some more information regarding some selected days with higher solar radiations and ambient temperatures between 17 to 22 pm for single and two storey buildings, respectively.

Table 3: Single storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
1st November	0.55	22-17	26-24	22-21
3rd December	0.133	14-11	18-17	16-15
27th February	0.206	14-10	19.5-18	16.9-15.8

Table 4: Two storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
1st November	0.55	22-17	25.6-24	22.67-21.88
3rd December	0.133	14-11	18-17.29	16.47-16
27th February	0.206	14-10	19.56-18	17.5-16.5

Obviously, solar radiation has a big impact on the performance of the TW. On the 3rd December and 27th February although the ambient temperature range is almost same but the TW performed better on 27th February due to higher average direct normal solar radiation than the other day.

4.6.2 Case of Erbil

Erbil has cold and partially cloudy winters and arid and sweltering summers. The temperature usually fluctuates from 4 to 42 ^oC and hardly falls below 0 ^oC or rises above 45 ^oC. The hot season starts from June to September 16 lasts for 3.4 months with an average daily high temperature approximately 36 ^oC. The cool season starts from November to March lasts for approximately 4 months. The length of the day fluctuates considerably over the year. The shortest and longest days are December 21, with 9 hours, 42 minutes of daylight and, June 21, with 14 hours, 38 minutes of daylight, respectively (weatherspark, 2020).

Figure 27 illustrates the indoor temperature of single and two storey buildings integrated with TW together with the outside temperature of Erbil which is utilized as the weather data in the simulation. It is worth mentioning that since thermal insulation is not popular in Erbil, the simulated building is not insulated and configuration illustrated in Figure 21 are utilized in the building construction. On November 1, between 17-21 o'clock while the outside temperature is dropping from 14.9 to 9.4 ^{o}C the room temperature which is integrated with TW, is varied from 19.55 to 19.27 ^{o}C for single storey and 19.81 to 19.55 ^{o}C for two storey building. The outside temperature hit a low of -5.91 ^{o}C on January 12 at 23 o'clock. From February 14, the ambient temperature is started increasing and never fell down below zero. Since the performance of TW is based on the solar radiation, direct normal and diffuse horizontal solar radiations of Erbil during heating season which are used in the simulation is demonstrated in Figure 28.

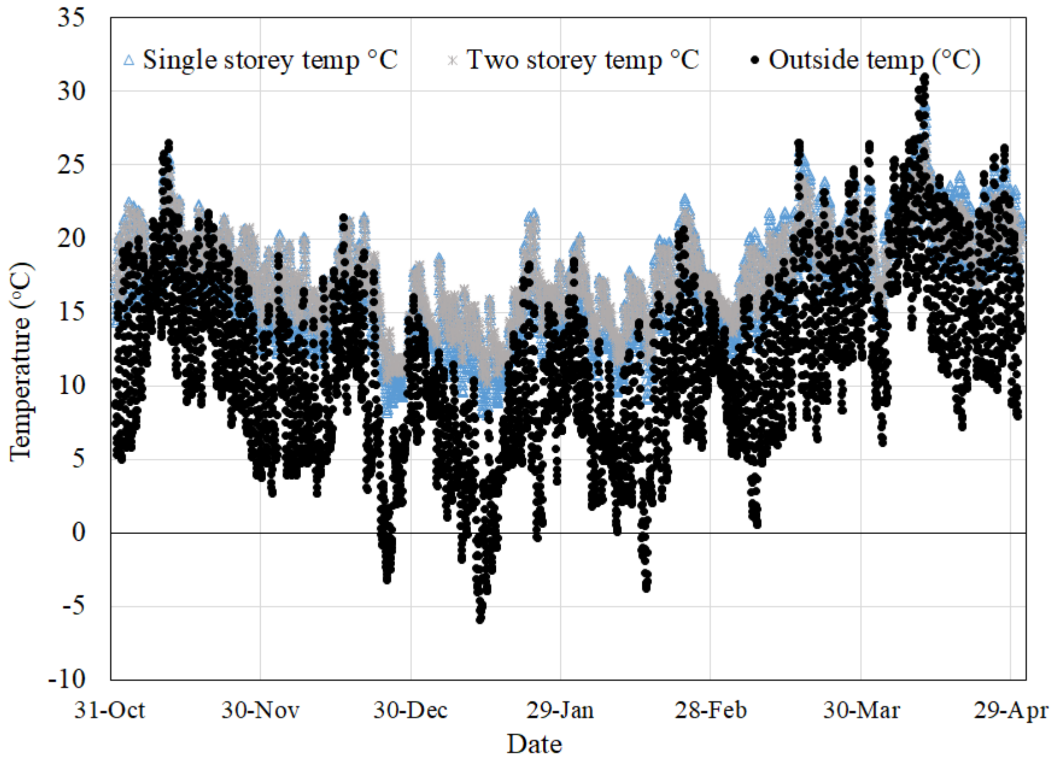


Figure 27: Indoor and outdoor temperature profiles for a south-facing 35 m^2 room integrated with 15 m^2 TW in a single and two storey buildings located in Erbil during heating season

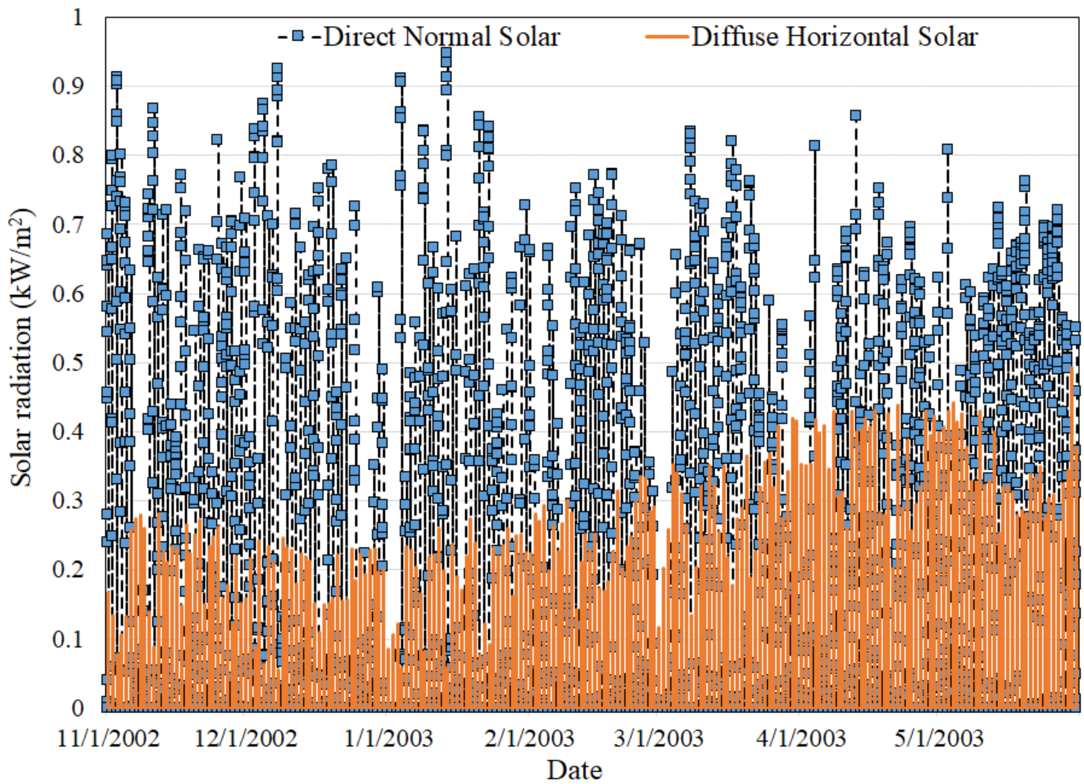


Figure 28: Direct normal and diffuse horizontal solar radiation profiles for Erbil during heating season

The energy simulations for heating and cooling seasons are carried out for the whole year for both seasons. Similar to the NC case study, the air conditioning system is set to provide heating when the living room temperature falls below 22 ^{o}C, and supply cooling once the living room temperature rises above 24 ^{o}C. In addition, the time schedules for occupancy and air conditioning system working during weekdays and weekend are set to be from 17 to 21 pm and 14 to 23 pm for winter and summer, respectively. The design builder models were set to obtain the essential electrical energy to run the AC during mentioned time schedules. The obtained simulation results indicate that in case of having TW, the ratio of total electrical energy required to floor area for the living room during heating season for single and two storey buildings are 8.6 and 6.71 kWh_e/m^2, while in case of no TW these results increased to 12.48 and 10.77 kWh_e/m^2 for single and two storey building, respectively. In addition, during cooling season, the ratio of extra cooling electrical energy required to floor area in order to overcome the extra heating loaded by TW are 6.4 and 7 kWh_e/m^2 for one and two storey buildings, respectively.

Figures 29 and 30 demonstrate the profile indoor temperature of the living room of the two and single storey buildings with and without TW for the coldest days of the winter under Erbil weather condition, starting from December 24th to December 27th. On the December 27th between 17-21 pm, when the TW had experienced a few consecutive cold days with almost zero direct normal solar radiation, which prevents storing heat in the wall, the living room temperature ranges in case of having TW and no TW varies from 12-11.5 ^{o}C and 11.33-10.9 ^{o}C, respectively. On the same day and hours of the day, for a single storey building, the living room temperature ranges with and without TW varies from 10.99-10.7 and 10.21 to 10.03 ^{o}C.

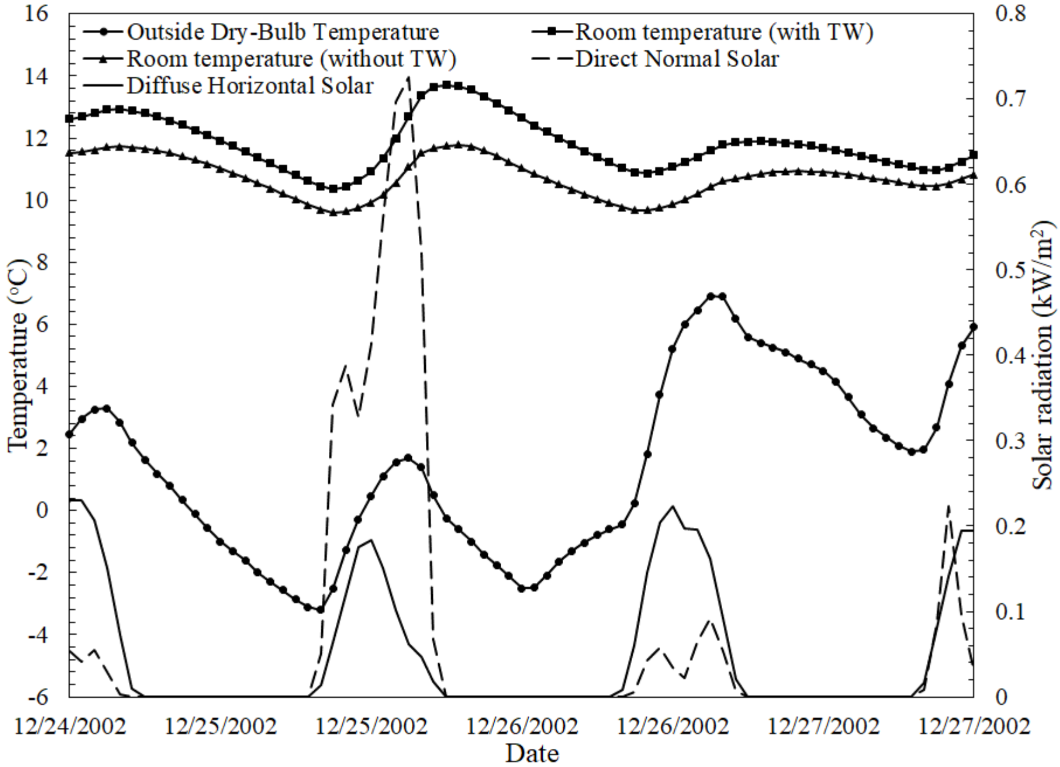


Figure 29: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 15m^2 TW area in a two storey building located in Erbil

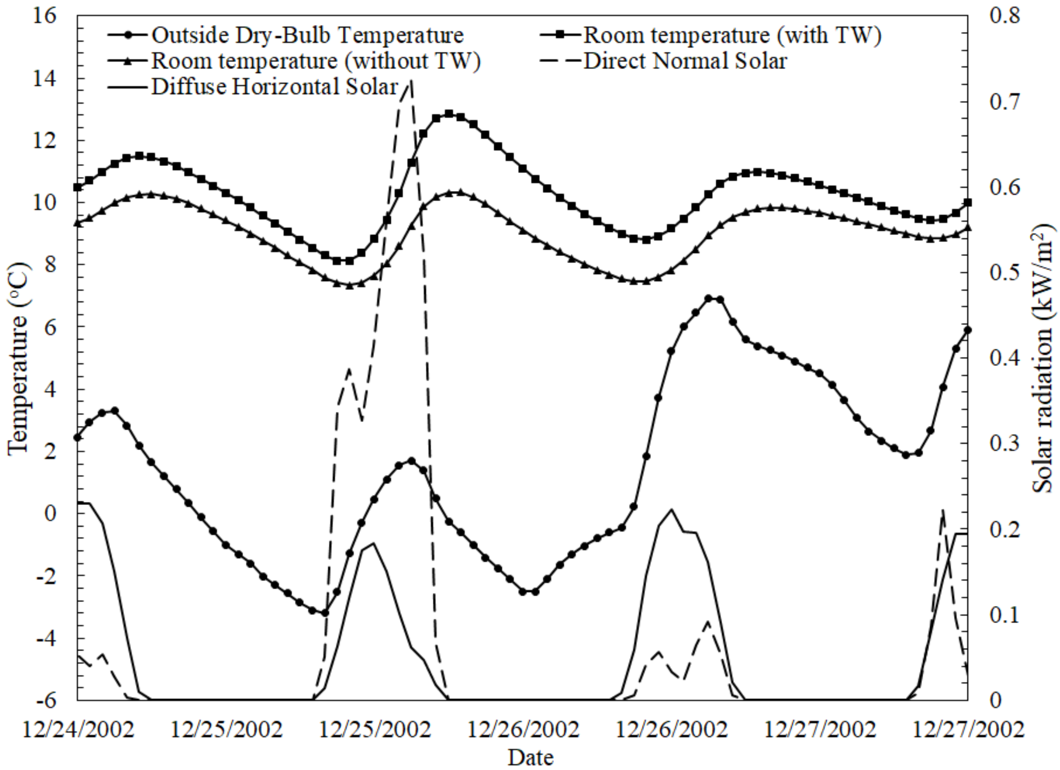


Figure 30: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 15 m^2 TW area in a single storey building located in Erbil

Tables 5 and 6 provide some more information regarding some selected random days during heating season with higher solar radiations and ambient temperatures between 17 to 21 pm for single and two storey buildings, respectively.

Table 5: Single storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
31st January	0.275	17-14.24	19.42-18.95	17.32-17.29
18th February	0.52	12-8	19.41-18.98	16-16.08
27th March	0.145	23-18.5	21.94-22.1	20.29-20.75

Table 6: Two storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
31st January	0.275	17-14.24	18.93-18.7	17.39-17.45
18th February	0.52	12-8	19.19-18.83	16.71-16.63
27th March	0.145	23-18.5	20.98-21.1	19.64-19.96

4.6.3 Case of San Diego

San Diego has a semi-arid climate with warm and sunny summers, and cold and wet winters. Summers are short lasts for 2.8 months starting from July 9 to October 3. The average temperatures vary between 16.7°C and 24.4°C from June to September and weather is warm and arid. The cool season is longer and lasts for 4.1 months, beginning from November 28 to April 1, with the average temperatures between 8.9 ^oC to 18.3 °C. San Diego has a nice weather for more than half of the year, with 3050 hours of sunshine and average humidity range of 63% to 75%. The highest temperature recorded for San Diego is 43.9 ^{o}C on September 26, 1963, while the lowest recorded temperature is -3.9 ^{o}C set on January 7, 1913 (weather-us, 2020).

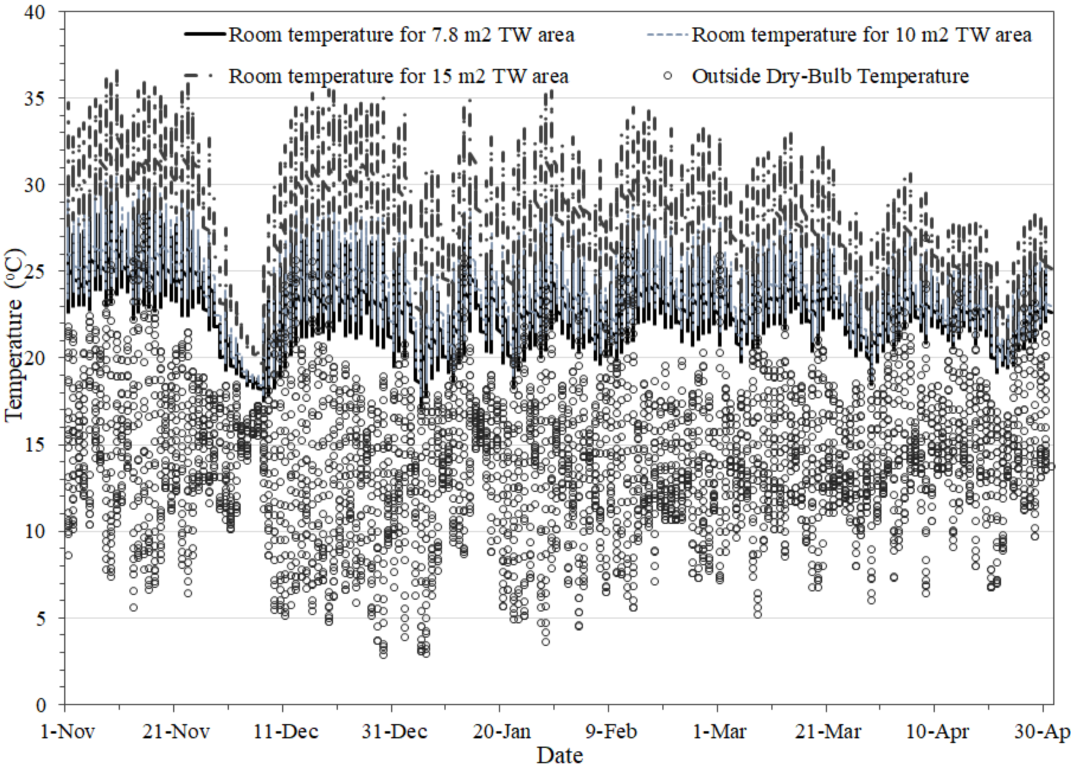


Figure 31: Temperature profiles during heating season for a south-facing 35 m^2 room integrated with 15, 10, and 7.8 m^2 TW area in a single storey building located in San Diego

Despite of the other case studies, thermal insulation is very common in San Diego. Thereby, the utilized building in the simulation under San Diego weather conditions has different configurations from the other two case studies (see Figure 22). Since the weather climate of San Diego and building constructions are different from the other case studies, the appropriate TW area under these conditions needs to be investigated. Figure 31 demonstrates the indoor temperature profiles of a living room integrated with 15,10, and 7.8 m^2 TW area during heating season. It is found that, a 15 m^2 TW area is not appropriate for San Diego since during heating season most of the time, room temperature exceeds 30 ^{o}C and cooling is required. When the TW area decreases to 10 m^2 only a few days' room temperature reached to 30 ^oC. However, with the 7.8 m^2 TW area, the living room temperature never exceeds 30 ^oC. It is observed that on the hottest day of the winter which is November 10, between 16-21 pm the living room temperature hit a peak of 30.5 and 29 ^oC for 10 and 7.8 m^2 TW area, respectively. On the other hand, during heating season, the living room temperature with 7.8 m^2 TW area never dropped below 18 ^oC. For instance, the living room temperature between 16-21 pm hit a low temperature of 18.6 ^oC in case of 7.8 m^2 TW area size on December 5. The effect of aforementioned TW size area on the living room temperature during cooling season under San Diego weather climate and building structures are illustrated in Figure 32. On October 30 which is the hottest day of summer, between 16 to 21 pm, while the ambient temperature fluctuating between 31-20 ^oC, the living room temperature for 15, 10, and 7.8 m^2 TW area without overhang hit a peak of 39, 33.5, and 32 ^oC, respectively. Therefore, based on the mentioned results, TW with 7.8 m^2 area is more appropriate one for the case of San Diego. Smaller size than 7.8 m^2 TW area might create discomfort condition during heating season.

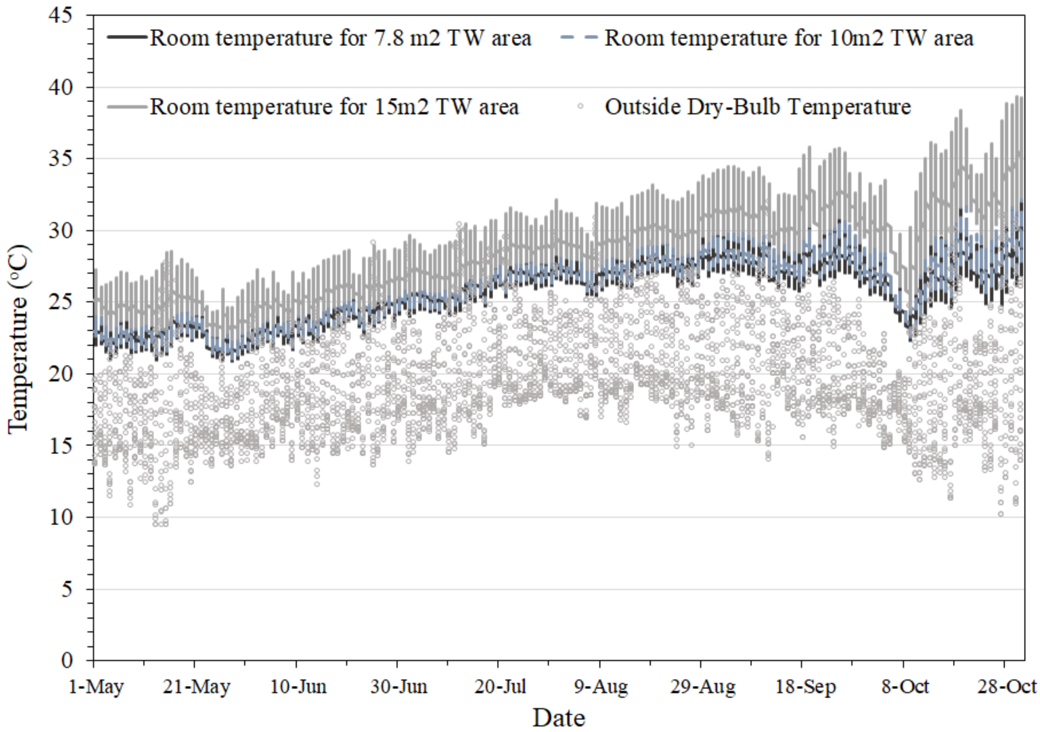


Figure 32: Temperature profiles during cooling season for a south-facing 35 m^2 room integrated with 15, 10, and 7.8 m^2 TW area in a single storey building located in San Diego

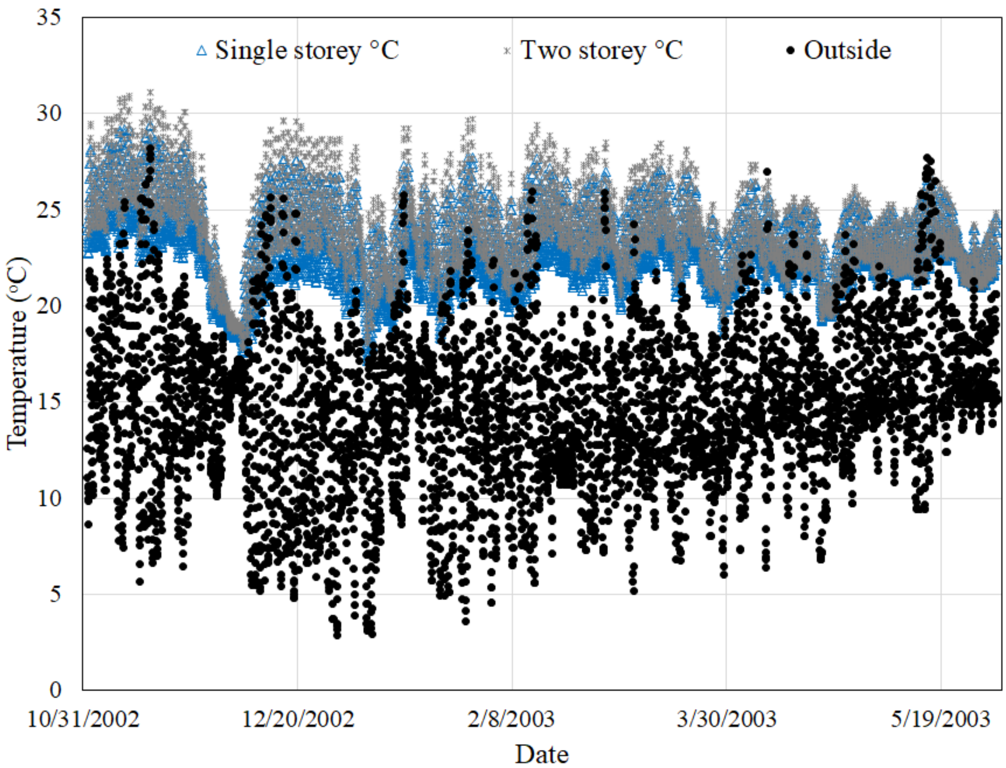


Figure 33: Indoor and outdoor temperature profiles for a south-facing 35 m^2 room integrated with 7.8 m^2 TW in a single and two storey buildings located in San Diego during heating season

Figure 33 demonstrates the outdoor and indoor temperature profiles of a living room integrated with TW for single and two storey buildings under San Diego weather condition. It is obvious from figure that the coldest months of year are December and January.

The direct normal and diffuse horizontal solar radiation during heating season obtained from simulation are illustrated in Figure 34. On the January 3, 4 and 5 the average daily direct normal solar radiations are 0.0575, 0.08828, and 0.6538 kW/m^2, respectively. These days are selected as the coldest consecutive days.

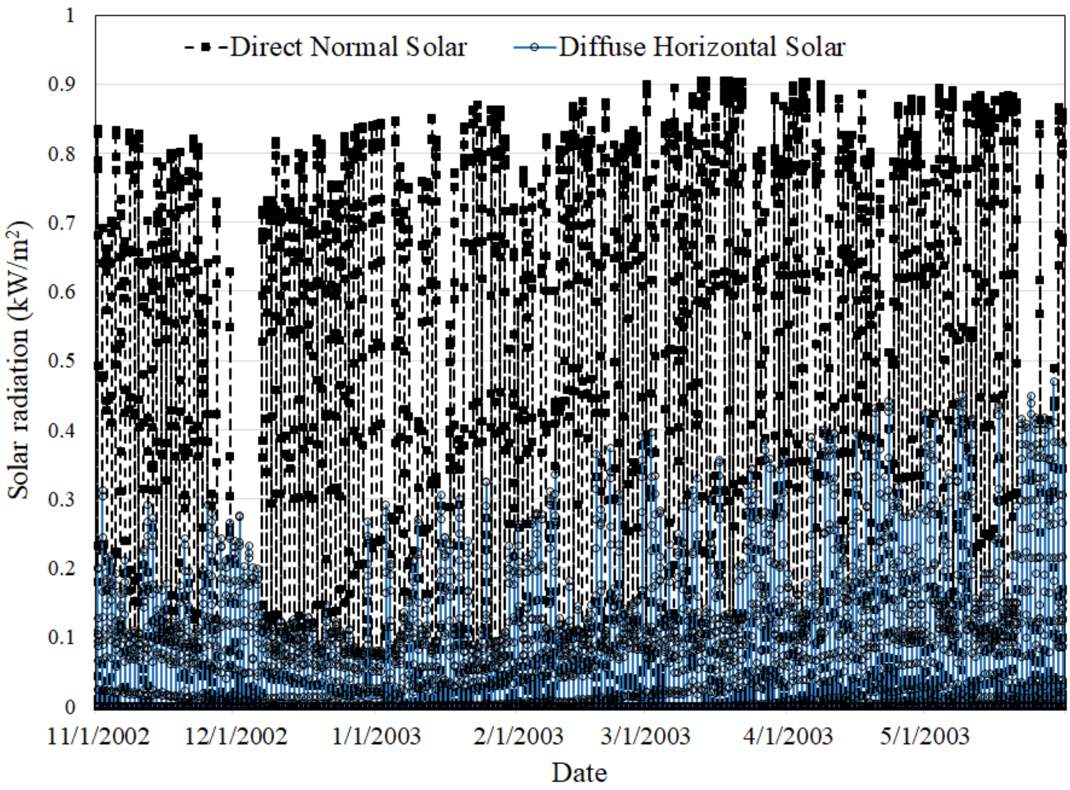


Figure 34: Direct normal and diffuse horizontal solar radiation profiles for San Diego during season

The energy simulations for heating and cooling seasons are carried out from November 30 to May 1, and May 1 to November 30, respectively. In fact, the air conditioning system is set to provide heating during November 30 to May 1 once the temperature of the room falls below 22 ^{o}C, and supply cooling during May 1 to November 30 once the temperature of the room rises above 24 ^{o}C. In addition, the time schedules for occupancy and air conditioning system working during weekdays and weekend are from 16 to 21 pm and 14 to 23 pm for winter and summer, respectively. During heating season, the ratio of total electrical energy required to floor area in order to maintain the room at the desired temperature which is integrated with 7.8 m^2 TW area for single and two storey buildings are 0.4 and 0.3 kWh_e/m^2. This ratio for the room with no TW in case of one and two storey building are 4.37 and 3 kWh_e/m^2, respectively. During cooling season, the ratio of extra electrical energy required to floor area for single and two storey buildings are 8.4 and 8.65 kWh_e/m^2, respectively. If a 1.5 m overhang utilized during cooling season over TW, the ratio of extra electrical energy required to floor area is reduced to 2.68 and 3 kWh_e/m^2, for single and two storey buildings, respectively.

Figures 35 and 36, demonstrate the profile indoor temperature of the living room of the two and single storey buildings with and without TW for the coldest days of the winter under San Diego weather condition, starting from January 3 to January 6. For both single and two storey buildings, on January 4 which is the coldest day amongst the mentioned days, the living room temperature during 16-21 pm hit a low and rising gradually the day after when the ambient temperature and direct solar radiation is increased compare to previous days. In case of two storey building, on the January 4 during 16-21 pm the living room temperature having TW and no TW is fluctuating between 22.23-21 and 18.43-17.4 ^{o}C, respectively. However, on the same day and hours of the day, for a single storey building, the living room temperature ranges with and without TW is 20.95-19.85 and 15.35-14.43 ^{o}C, respectively.

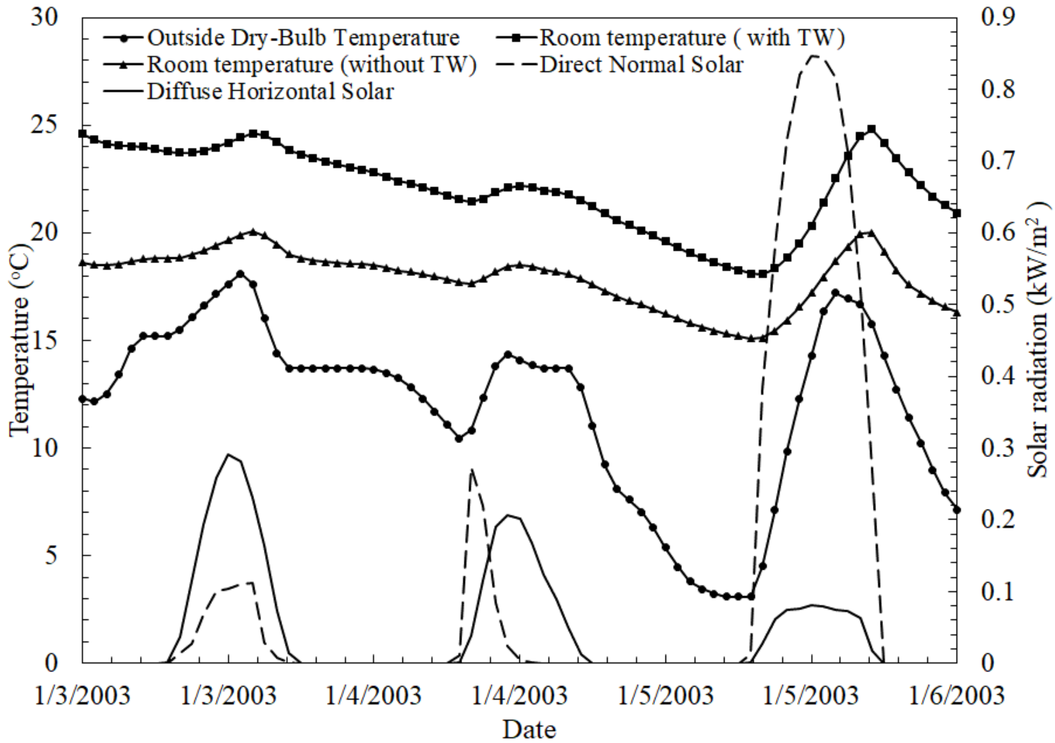


Figure 35: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 7.8 m^2 TW area in a two storey building located in San Diego

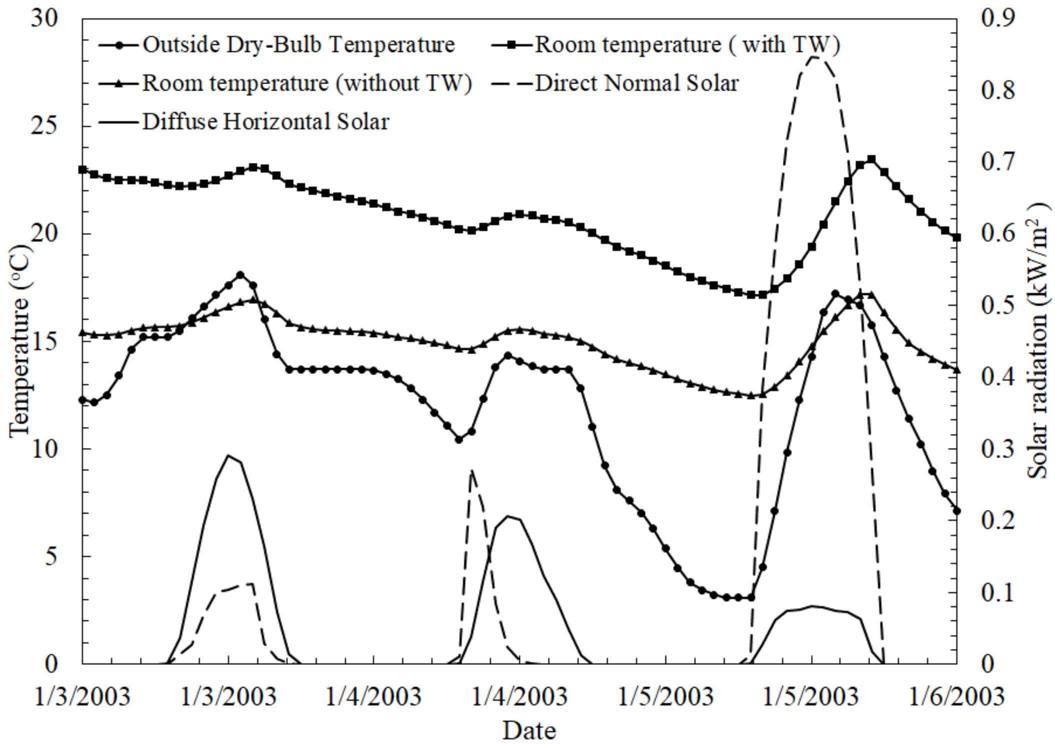


Figure 36: Temperature and solar radiation profiles during the coldest days in winter for a south-facing 35 m^2 room integrated with and without 7.8 m^2 TW area in a single storey building located in San Diego

Tables 7 and 8 provide some more information regarding some selected random days with higher solar radiations and ambient temperatures between 16 to 21 pm for single and two storey buildings, respectively.

Table 7: Single storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
1st November	0.487	21.29-15.59	28-26	22.43-20.17
15th January	0.106	17-16.3	24.75-23.7	18.2-17
17th February	0.597	15.1-13.4	27-25.33	19.3-17.8

Table 8: Two storey building

Date	Average direct normal solar radiation (kW/m^2)	Ambient temperature range (^oC)	Living room with TW temperature range (^oC)	Living room no TW temperature range (^oC)
1st November	0.487	21.29-15.59	29.5-27.4	23-21
15th January	0.106	17-16.3	26-25	20-19
17th February	0.597	15.1-13.4	27-26	22-20

Chapter 5

DSM FEASIBILITY UNDER DIFFERENT CONDITIONS OF FAMAGUSTA, ERBIL AND SAN DIEGO

5.1 Economic Justification of Promoting TWs Through DSM

The economic feasibility of applying a DSM program, promoting TW-implementation in residences, in exchange of avoiding the usage of peak power generating units during the peak time of winter season for different case studies is investigated in this chapter.

5.1.1 Case of NC

It is the interest of this section to determine the economic feasibility of applying a DSM program, promoting TW-implementation in residences, under NC conditions. Figure 37 shows the difference between the measured highest peaks in winter and summer in 2019. The difference was 12-MW. It would be desirable to shave the maximum winter peak to the same level as that of summer in order to avoid sparing a power unit for winter.

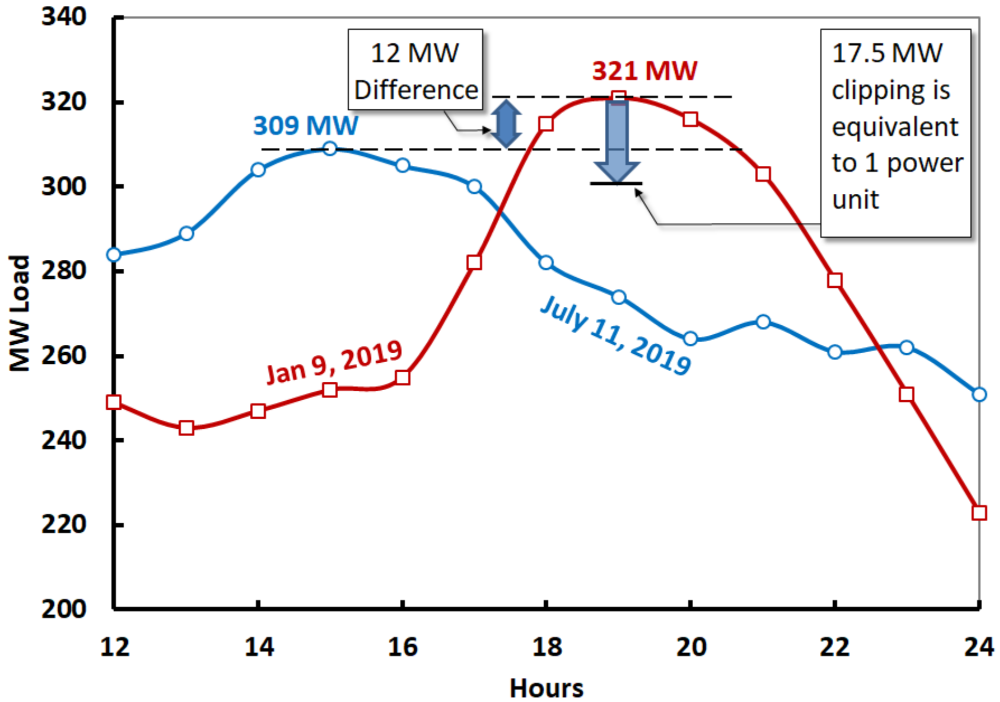


Figure 37: Maximum demand curves observed in NC for winter and summer in 2019 (Rezaei et al., 2020)

It is accustomed to assume that the capacity of the power unit is equivalent to the reduction achieved by the DSM program. The lowest capacity thermal power units in NC are 17.5-MW diesel generators.

In NC, the most popular system used for heating living rooms is split unit heat pump. For a room of the size considered in the present study, heat pumps with a heating capacity of 24,000 Btu/h (7.032 kW) is commonly installed. The power requirement for such a heat pump would be approximately 2.56 kW assuming a *COP* of 2.75. The aim is to prevent the operations of heat pumps during the peak hours by replacing the heating system with TW through DSM. The number of houses required to reduce 17.5-MW from the peak is 6842. It would be adequate to reduce the peak by 12-MW targeting 4688 houses; therefore, the extra number of houses considered in the present work would make the program safer in achieving success in clipping the peak. The number of houses purchasing electricity from KIB-TEK was 133,961 in 2017 (KIB-

TEK, 2019b). Therefore, it is possible to find the required number of eligible houses to implement the DSM program. It should not be forgotten that TW is a passive solar heating system and its performance depends heavily on the availability of solar energy and the outdoor temperature. It is clear from the simulations (see Figures 25 and 26) that on some days the room temperature can be as low as 14 °C. Therefore, precautions should be taken to prevent participants using their electrical heating devices at those times. It is proposed that the DSM program should include those consumers who accept installing an astronomic relay preventing the operation of the heat pumps during the peak hours in winter. A portable gas heater can also be offered to the consumers free of charge for the coldest days that they might require to do extra heating. The costs assumed for the astronomic relay and the portable gas heater are 100 and 70 EUR per house respectively. The cost of building a 15 m^2 TW is estimated from Table 9 to be 1418.25 EUR. The total cost of the rebate (including astronomic relay) is estimated to be 1588.25 and 1518.25 EUR with and without the gas heater deal, respectively.

Table 9: Costs taken into account for construction of 15 m^2 TW in NC (Ozdenefe et al., 2018)

Item	Cost (EUR)
Reinforced concrete wall construction	461.25
Aluminum window installation (4.8 m $\times$ 3 m)	904.5
Demolition of a standard outer brick wall	52.5

Construction of TWs in 6842 houses is expected to be time consuming. Therefore, the rebate program is assumed to spread over a period of three years. For this reason, in the conducted analysis the total rebate amount is divided into three equal amounts to be spent annually in the first three years. Apart from the investments required for the rebate program, the utility will be encountering lost income due to disconnection of heat pumps during peak hours in winter. This can be added to the investments. On the other hand, the extra sales due to the increase in air-conditioning usage in summer should be deducted from the lost incomes. For life-cycle cost (LCC) analysis a discount rate of 2% is applied and the project lifetime is assumed to be 20 years.

Economic feasibility of the case of NC is determined from Eqs. (15) and (16) which are introduced in Chapter 3. The value of *SIR* for the specific case of NC can be obtained from Eq. (17).

There will be cash flows due to savings in fuel consumption, O&M, insurance payments, and decreased sales of electricity which should be discounted each year due to time value of money. Eq. (11) is utilized to achieved the cash flows of each aforementioned parameter.

In the present study the values presented in Table 10 are used for estimating the amount of fuel savings. By substituting these values in Eq. (18) the amount of fuel savings can be estimated.

Table 10: Values assumed for the estimation of fuel savings in NC

Density of fuel oil no.6, ρ_{Fuel}	1.1 ton/m^3
Efficiency of the representative power unit, η_{PP}	0.35 (35%)
Grid loss ratio, L_{Grid}	0.06 (6%)
Heating value, H_v	11,778 kWh/m^3

The fuel cost savings can be estimated from Eq. (19), where the efficiency of the power plant considered as 35%, and the grid loss-ratio is 6%.

In winter, due to the requirements of the DSM program, the auxiliary heating system (i.e., the split unit heat pump) which is located in the room where TW is, will be disconnected during peak hours. Therefore, there will be fuel savings as well as lost income. In summer however, due to increased requirement of cooling caused by the TW, there will be more fuel usage and more sales of electricity. Depending on many factors (such as political developments, market conditions, roughness of the sea etc.) the cost of the fuel fluctuates. In the present study, in consultation to KIB-TEK (2019) the cost of fuel (including transportation cost) is assumed to be 425.5 EUR/ton. All the other unit costs associated with power production are obtained from KIB-TEK (2019) as shown in Table 11.

Table 11: Expenditures associated with power production (KIB-TEK, 2019)

C_{PP}	617.6	Eur/kW
C_{Fuel}	0.088	Eur/kWh
$C_{O\&M,PP}$	0.02	Eur/kWh
C_{Filter}	235.35	Eur/kW
$C_{O\&M, Filter}$	0.004	Eur/kWh
C_{Ins}	5.5	Eur/kW

The utilized assumptions in DSM analysis are provided in Table 12. Those houses transporting electricity to the grid with renewable energy sources cannot enter the multi-tariff system with the present rules of KIB-TEK. It would not be appropriate to select them for the present DSM program.

Table 12: Assumptions utilized in DSM analysis in NC

Discount Rate (%)	2
Analysis period (years)	20
DSM program completion period (years)	3
Winter peak hours (weekdays and weekend)	17:00-22:00
Summer peak hours (weekdays and weekend)	09:00-18:00
Power reduction anticipated (MW)	17.5
Occupied zone floor area (m^2)	35
Installed air conditioner heating capacity for the occupied zone (BTU/h / kW)	24,000 / 7.034

Tables 13 and 14 demonstrate the economic analysis of proposed DSM program for single and two storey buildings. Although there are several options of determining the rebate amount as can be seen from Tables 13 and 14 for NC it would be more appropriate to consider installing a timer and purchasing a portable gas heater as part of the rebate. Therefore, Option 3 is preferred for the success of the program. In all three options, the total cost of TW is included in the proposed rebate. It is essential to check if this option pays off before applying the DSM program. Under the conditions described in the present work for option 3, *SIR* is estimated to be 1.36 and 1.35 for single and two storey buildings, respectively.

Table 13: Results of the DSM program analysis for single storey building case of NC

	Option 1	Option 2	Option 3
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay	Rebate program covers construction of a TW, installation of an astronomic relay and providing a portable gas heater
Rebate/house (EUR)	1,418.25	1,518.25	1,588.25
NPV (EUR)	5,964,534	5,293,684	4,824,090
SIR	1.49	1.41	1.36
Shortcomings on very cold days	Can be uncomfortable due to low room temperature / Risky since participants can turn on the heat pump	Can be uncomfortable due to low room temperature / Risky since participants can use another electric heater	Less risky / Less uncomfortable

Table 14: Results of the DSM program analysis for two storey building case of NC

	Option 1	Option 2	Option 3
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay	Rebate program covers construction of a TW, installation of an astronomic relay and providing a portable gas heater
Rebate/house (EUR)	1,418.25	1,518.25	1,588.25
NPV (EUR)	6,006,969	5,336,120	4,866,525
SIR	1.48	1.4	1.35
Shortcomings on very cold days	Can be uncomfortable due to low room temperature / Risky since participants can turn on the heat pump	Can be uncomfortable due to low room temperature / Risky since participants can use another electric heater	Less risky / Less uncomfortable

5.1.2 Case of Erbil

Iraq is one of the OPEC members that affected by decreases in oil prices after 2012. In one hand, Erbil (capital city of Kurdistan region of Iraq) faced with a big economic recession after this loss in oil prices which caused deficit in all section of power sector such as generation, transmission, and distribution. On the other hand, the demand for power was increasing significantly. It was found that the utility would be able to provide power just for an average of one third of a day in 2017. Based on official statistics, with a power capacity shortage of 1450 MW, utility needed to found a solution to meet the demand and peak demand during heating season (Azeez, 2019).

In Kurdistan region of Iraq (where Erbil is placed), the total installed capacity is 6717 MW and mostly they are thermal power plants which involve gas turbine cycles or reciprocating engines. It is noticeable to mentioned that, 88% of the produced power is supplied by private companies utilizing thermal power plants (Baban & Askari, 2019). The required natural gas for these private companies is provided by the Ministry of Natural Resources without charge. The power produced by them is bought by the government and finally subsidized to the consumers. These subsidies generate overloading in transmission and distribution electricity grids. Thereby the expansion of transmission and distribution is essential. The yearly cost of transmission and distribution expansion obtained by the electricity utility of Erbil is US$140/kW (Azeez & Atikol, 2019). It is noticeable to mention that; government is responsible for all the expenses of the expansion. Clearly, on one hand government is subsidizing the electricity to the customers and on the other hand investing hugely on the expansion of transmission and distribution network.

The thermal power capacity utilized in economic analysis is 17.5 MW diesel generator. Due to different strategy of power generation in Erbil, the economic calculation employed for Erbil is slightly different from the case of NC. In case study of Erbil, since government is subsidizing the electricity, the economic analysis is from government point of view, not private utility. As a matter of fact, the economic feasibility analysis is about promoting TW-implementation in residence, in order to prevent customers to power AC during peak hours in winter. This help government to pay less for electricity subsidizing and the expansion of transmission and distribution network. The employed building for simulation is described in simulation chapter. For a room of the size considered in the present study, heat pumps with a heating capacity of 24,000 Btu/h (7.032 kW) is commonly installed. The power requirement for such a heat pump would be approximately 2.56 kW assuming a *COP* of 2.75. The aim is to prevent the operations of heat pumps during the peak hours by replacing the heating system with TW through DSM. The number of houses required to reduce 17.5-MW from the peak is 6842. Those houses should be participating in this program which are agree to shut down their AC during peak hours and accept installing the astronomic rely by government. A portable gas heater can also be offered to the customers free of charge for the coldest days that there might be extra heating demand. The cost of building a 15 m^2 TW is estimated from Table 15 to be 888.75 EUR. The total cost of the rebate is estimated to be 988.75 with astronomic rely, and 1058.75 EUR with astronomic relay and gas heater deal, respectively. The costs assumed for the astronomic relay and the portable gas heater are 100 and 70 EUR, respectively.

Table 15: Costs taken into account for construction of 15 m^2 TW in Erbil (Erbil governor's office, 2020)

Item	Cost (EUR)
Reinforced concrete wall construction	112.5
Aluminum window installation	675
Demolition of a standard outer brick wall	101.25

The DSM program considered for Erbil is a three years' program, and the cost of DSM program is distributed equally in the first three years. Apart from the investments required for the rebate program, the government will be subsidizing more electricity for extra sales due to the increase in air-conditioning usage in summer. This can be added to the investments. For life-cycle cost analysis a discount rate of 2% is applied and the project lifetime is assumed to be 20 years. Eqs. (15) and (16) can be used to evaluate the *NPV* and *SIR* to determine the economic feasibility of the DSM program. The *SIR* can be estimated as follows:

$$SIR = \frac{C_{Subsidizing} + C_{T\&D}}{C_{DSM} + C_{summer\ extra\ subsidizing}} \qquad (20)$$

where $C_{Subsidizing}$ and $C_{T\&D}$ are the cost of electricity subsidizing and transmission and distribution network expansion. There will be cash flows due to savings in subsidizing, *T&D*, and increased sales of electricity in summer which should be discounted each year due to time value of money from Eq. (11).

The utilized assumptions in DSM analysis are provided in Table 16. Those houses transporting electricity to the grid with renewable energy sources can also selected for the present DSM program.

Table 16: Assumptions utilized in DSM analysis in Erbil

Discount Rate (%)	2
Analysis period (years)	20
DSM program completion period (years)	3
Winter peak hours (weekdays and weekend)	17:00-21:00
Summer peak hours (weekdays and weekend)	13:00-16:00
Power reduction anticipated (MW)	17.5
Occupied zone floor area (m^2)	35
Installed air conditioner heating capacity for the occupied zone (BTU/h / kW)	24,000 / 7.034

The result of three different options after applying DSM program for the case of Erbil are illustrated in Tables 17 and 18, for single and two storey buildings, respectively.

In all three options, the total cost of TW is included in the proposed rebate. It is essential to check if this option pays off before applying the DSM program. Under the conditions described in the present work for Option 3, *SIR* are estimated to be 5 and 4.98 for single and two storey buildings, respectively.

Table 17: Results of the DSM program analysis for single storey building located in Erbil

	Option 1	Option 2	Option 3
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay	Rebate program covers construction of a TW, installation of an astronomic relay and providing a portable gas heater
Rebate/house (EUR)	888.75	988.75	1058.75
NPV (EUR)	30,738,028	30,067,179	29,597,585
SIR	5.91	5.34	5
Shortcomings on very cold days	Can be uncomfortable due to low room temperature / Risky since participants can turn on the heat pump	Can be uncomfortable due to low room temperature / Risky since participants can use another electric heater	Less risky / Less uncomfortable

Table 18: Results of the DSM program analysis for two storey building located in Erbil

	Option 1	Option 2	Option 3
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay	Rebate program covers construction of a TW, installation of an astronomic relay and providing a portable gas heater
Rebate/house (EUR)	888.75	988.75	1058.75
NPV (EUR)	30,643,130	29,972,281	29,502,686
SIR	5.88	5.31	4.98
Shortcomings on very cold days	Can be uncomfortable due to low room temperature / Risky since participants can turn on the heat pump	Can be uncomfortable due to low room temperature / Risky since participants can use another electric heater	Less risky / Less uncomfortable

5.1.3 Case of San Diego

The approached economic analysis for San Diego is from utility point of view. Similar to the other case studies, the target is to prevent the operations of AC during peak hours by switching the ACs with TW through DSM program. For a room of the size considered in the present study, heat pumps with a heating capacity of 24,000 Btu/h (7.032 kW) is commonly installed. The power requirement for such a heat pump would be approximately 2.56 kW assuming a *COP* of 2.75. As it is mentioned, the aim is to prevent the operations of heat pumps during the peak hours by replacing the heating system with TW through DSM. The number of houses required to reduce 17.5-MW from the peak is 6842. Table 19 demonstrates the costs of TW construction considered in DSM program. The cost of building a 7.8 m^2 TW with a 1.5 m overhang is estimated from Table 19 to be 2443.9 EUR.

Table 19: Costs taken into account for construction of 7.8 m^2 TW in San Diego (Primary structure company, 2021)

Item	Cost (EUR)
Reinforced concrete wall construction	600
Aluminum window installation (2.6 m × 3 m)	1360
1.5 m louvre overhang	198.9
Demolition	285

It is noticeable to mention that, those houses should be participating in this program which are agree to shut down their AC during peak hours and accept installing the astronomic rely by utility. The costs assumed for the astronomic relay is 100 EUR per house. Despite of other case studies, portable gas heater is not considered in the DSM program for the case of San Diego. The reason is the indoor temperature of the room integrated with 7.8 m^2 area never dropped below 18^o C (see Figure 31) and auxiliary heating device is not required. Another reason is this type of gas heater is not popular in San Diego.

Since the construction of TW is assumed to be finish in three years, the total investment of construction is also spread over a period of three years. The lost income due to disconnection of ACs during winter and extra sales due to increase in ACs usage in summer is calculated as case of NC.

Eqs. (15) and (16) can be used to evaluate the *NPV* and *SIR* to determine the economic feasibility of the DSM program. In the case of San Diego, the *SIR* can be estimated as follows:

$$SIR = \frac{C_{Fuel}+C_{PP}+C_{O\&M,PP}}{C_{DSM}+C_{DS}} \quad (21)$$

The fuel used in the power plant is natural gas. Thereby, cost of filter is not included in the *SIR* calculation. It is noticeable to mention that $C_{O\&M}$ involves two different cost of variable and fixed which are presented in Table 20. There will be cash flows due to savings in fuel consumption, O&M, and decreased sales of electricity which should be discounted each year due to time value of money and can be calculated from Eq. (11).

Fuel cost savings for one house due to energy savings can be estimated as follows:

$$C_{Fuel,sav} = \frac{E_{Site,sav}}{\eta_{PP} \times (1 - L_{Grid})} \times C_{Fuel} \quad (22)$$

where $E_{Site,sav}$ is the electric energy saving at the site (i.e., houses), η_{PP} is the efficiency of the power plant considered as 35%, L_{Grid} is the grid loss-ratio which is assumed to be 6% and C_{Fuel} is the cost of fuel used in the power plant. In the present study, the average cost of natural gas delivered to electric power plant is assumed to be 0.0099195 EUR/kWh (publicpower, 2020). All the other unit costs associated with power production are shown in Table 20 (eia.gov, 2020).

Table 20: Expenditures associated with power production (eia.gov, 2020)

C_{PP}	1140.7	Eur/kW
$C_{O\&M,PP(variable)}$	0.0049725	Eur/kWh
$C_{O\&M,PP(fixed)}$	5.865	Eur/kW-yr

where the C_{pp} is the cost of 17.5 MW capacity power plant, $C_{O\&M,PP(variable)}$ include production-related cost which depends on electrical generation and $C_{O\&M,PP(fixed)}$ incurred at a power plant which is not related to generation.

The utilized assumptions in DSM analysis are provided in Table 21. There is no restriction for those houses transporting electricity to the grid with renewable energy sources, which means they can be participant in the present DSM program.

Table 21: Assumptions utilized in DSM analysis in San Diego

Discount Rate (%)	2
Analysis period (years)	20
DSM program completion period (years)	3
Winter peak hours (weekdays and weekend)	16:00-21:00
Summer peak hours (weekdays and weekend)	16:00-21:00
Power reduction anticipated (MW)	17.5
Occupied zone floor area (m^2)	35
Installed air conditioner heating capacity for the occupied zone (BTU/h / kW)	24,000 / 7.034

Tables 22 and 23 demonstrate the economic analysis of proposed DSM program for single and two storey buildings. For the case of San Diego, despite of the other case studies, only the cost of TW and astronomic relay are included in the DSM program. The gas heater is not involved in the proposed DSM program. The reasons are first by building a 7.8 m^2 area TW, it is observed that the room temperature never dropped below 18 ^oC and this type of gas heater is not very common there. As it can be seen from Tables 22 and 23, the proposed DSM program is feasible for single and two storey buildings under San Diego conditions. In option 1 where the rebate covers only the TW construction cost, the value of *SIR* for single and two storey buildings are estimated as 1.11, and 1.25, respectively. In case if the rebate covers both the cost of TW construction and astronomic relay (option 2), the value of *SIR* decreased to 1.08, and 1.2 for single, and two storey building, respectively.

Table 22: Results of the DSM program analysis for single storey building located in San Diego

	Option 1	Option 2
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay
Rebate/house (EUR)	2443.9	2543.9
NPV (EUR)	2,246,750	1,575,901
SIR	1.11	1.08
Shortcomings on very cold days	Risky since participants can turn on the heat pump	Less risky

Table 23: Results of the DSM program analysis for two storey building located in San Diego.

	Option 1	Option 2
Description of rebate program	Rebate program covers construction of a TW	Rebate program covers construction of a TW and installation of an astronomic relay
Rebate/house (EUR)	2443.9	2543.9
NPV (EUR)	4,279,309	3,608,460
SIR	1.25	1.2
Shortcomings on very cold days	Risky since participants can turn on the heat pump	Less risky

5.2 Sensitivity Analysis

5.2.1 Effect of Orientation Offsets

It is generally accepted that, from energy point of view the best orientation for constructing a TW is south. As it is mentioned in chapter 3, there are other important parameters which need to be taken into account in the selection stage of houses. Considering these parameters plus orientation of buildings, lead to more difficulties in the selection of 6842 houses. Thereby, in order to make the selection of houses stage more practical, the effect of slight offset from south on the room temperature and *SIR* can be investigated. The effect of orientation offsets from south (between 45° East to 45° West) under NC climate condition has been investigated by Rezaei et al. (2020). It is found that the electricity consumption increases slightly in all cases except during the heating season when the orientation is 15° offset to East. On the other hand, the value of *SIR* will be increased gradually by any orientation changes from South. As a matter of fact, by increasing the electricity usage in summer and selling more electricity relative to that of lost sales in winter, the utility lost income during winter is compensated. The effect of TW orientation offsets from south on room temperature for the coldest days of winter is gathered in Figure 38. The maximum temperature difference during the peak hours on the coldest day (2nd of February) is estimated to be 0.22 °C. On the 4th February, when the orientation is offset to 45^{o} East, the maximum temperature during peak hours is 18.1 °C (at 19:00) and when it is offset to 15^{o} East it is 19.87 °C (at 18:00). This is a difference of 1.77 °C which does not cause a major discomfort to the occupants relative to what is experienced with the TW facing to south. Moreover, in the proposed DSM program a free gas heater is considered to be given to the participants to be used in cold days. It is clear that not only the zone temperatures do not undergo a significant change but also the *SIR* increases slightly when there is a need to select houses with their living rooms offset from the south direction up to 45° to East or West (see Table 24).

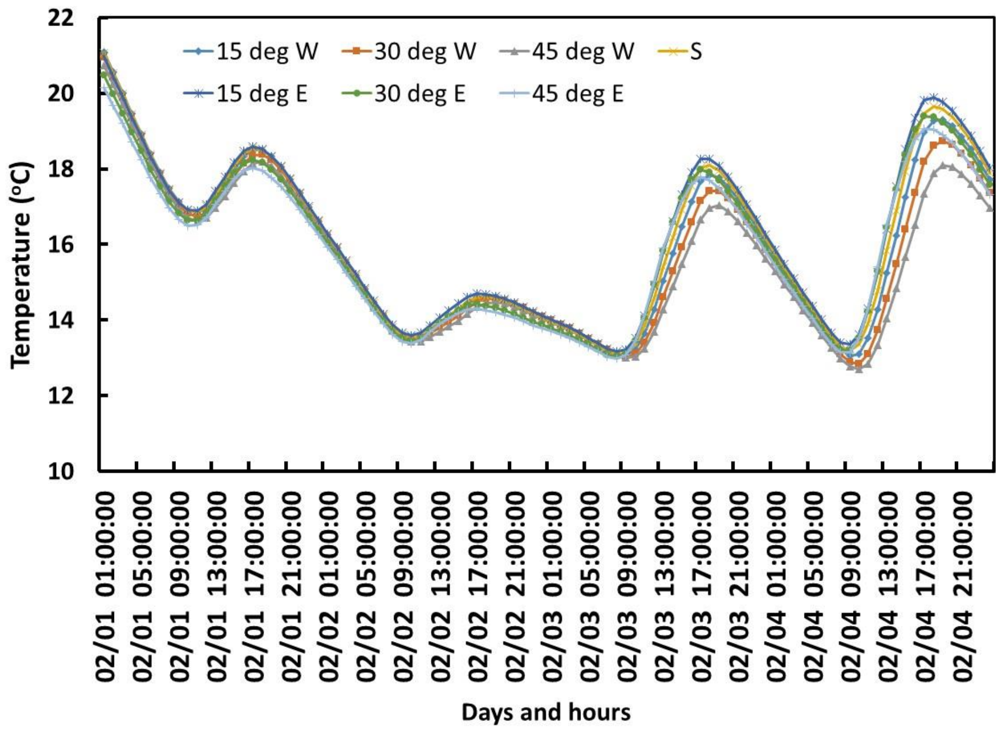
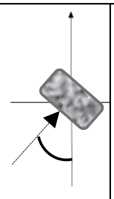
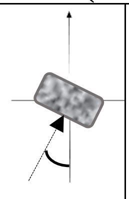
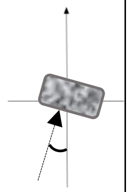
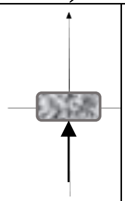
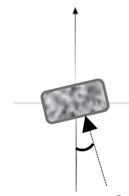
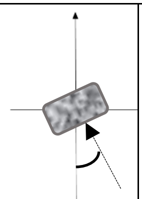
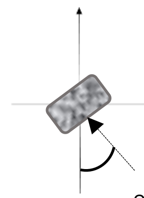


Figure 38: Zone temperatures for different orientation offsets from south between 1st and 4th February under NC conditions (Rezaei et al., 2020)

Table 24: Variation of electricity usage and *SIR* value due to different orientation of TW under NC conditions (Rezaei et al., 2020)

Orientation offset from South	 45° S	 30° S	 15° S	 S	 15 ° S	 30° S	 45 ° S
Increase in electricity use for heating (%)	+27	+13	+3	0	-3	+12	+24
Increase in electricity use for cooling (%)	+9	+7	+2	0	+3	+5	+7
SIR	1.51	1.49	1.46	1.45	1.49	1.50	1.53

It can be claimed that the effect of orientation on the room temperature and *SIR* value is not significant and can be negligible. Due to this, the effect of orientation on the *SIR* value for the case of Erbil and San Diego is not investigated.

5.2.2 Unforeseen Excess Rebates

In construction of the TW and installation of the glass cover on it may have hidden costs depending on the special cases at different sites. Due to this fact it should not be surprising to encounter increases in the rebate paid to the participants, especially when the full cost is to be paid. The change in *SIR* is monitored by increasing the rebate up to 35% for single and two storey buildings for NC, Erbil, and San Diego as can be seen in Figures 39 and 40. As it can be seen in case of NC the value of *SIR* is decreasing as rebate is increasing. In case of single storey the value of *SIR* reached its lowest point of 1.08 while the rebate is increased by 32%. On the other hand, in case of two storey building, the value of *SIR* decreases from 1.35 to 1.08 due to 32% unforeseen excess rebate. In general, owing to 32% rebate increases the value of *SIR* may drop 20.2% and 19.6%, for single and two storey buildings, respectively. It is clear that the DSM program is still feasible since *SIR* is greater than 1 up to an unforeseen increase in rebate of 32%. However, it would be advisable not to have an increase of rebate above 32% to avoid any risks.

For the case of Erbil, although the value of *SIR* will decrease due to unforeseen increase in rebate, because of high *SIR*-value there is no danger of ending up having an economically infeasible DSM program in both single storey and two storey buildings. It is clear that, the effect of unforeseen excess rebate on the *SIR* value for one and two storey building is almost same. In spite of reduction in *SIR* value while the rebate is increased to 32%, it is feasible for government to apply the proposed DSM program since the value of *SIR* is above 3.

In the case of San Diego, the *SIR*-value is very close to 1, and any increase in rebate will put the economic feasibility into danger. Similar to the NC and Erbil case studies, the value of *SIR* is decreasing while the unforeseen percentage in rebate is increased to 32 in case of San Diego. In case of single and two storey buildings the value of *SIR* is decreased to 0.92, and 1.01, respectively. It is clear that if the unforeseen increase in rebate is increased by 32% the proposed DSM program is not feasible in case of single storey, and it is very risky in case of two storey building. If the unforeseen increase in rebate is increased by 12%, the *SIR* value drops to 1.01 and 1.12, respectively. An increase of more than 12% in rebate cost, is not advisable and might put the DSM program under risk.

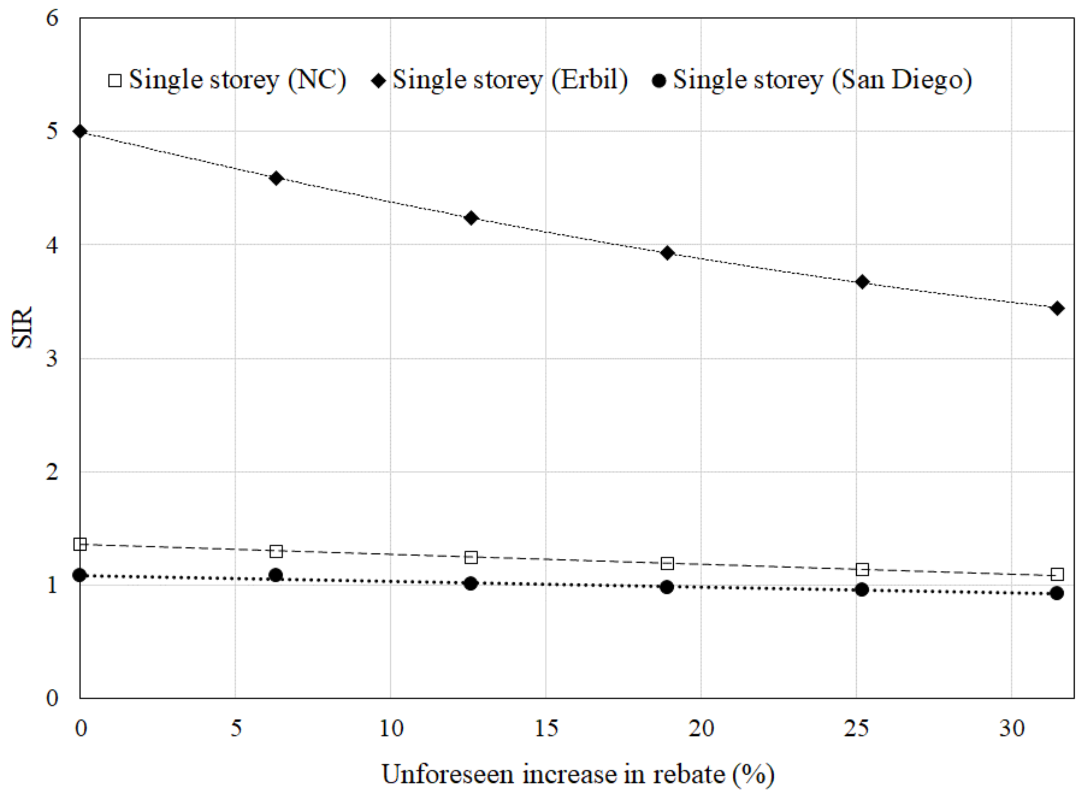


Figure 39: The change in *SIR* as the rebate is increased for single storey building located in NC, Erbil, and San Diego

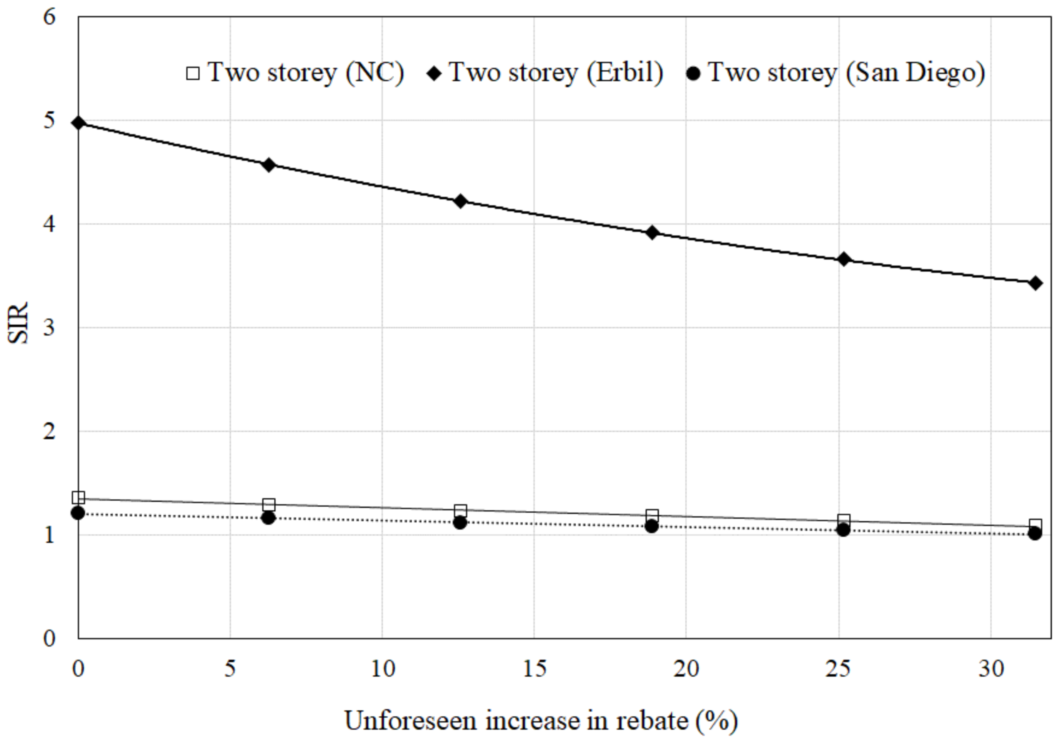


Figure 40: The change in *SIR* as the rebate is increased for two storey building located in NC, Erbil, and San Diego

5.2.3 Increase in Electricity Prices

Due to increasing fuel prices, utilities increase the electricity prices at times. In the LCC analysis the electricity prices were increased annually from 2% to 5% to observe its possible effects on the *SIR*. Figures 41 and 42 demonstrate the effect of annually increase in electricity prices in all case studies for single and two storey buildings, respectively. It is clear that, the value of *SIR* is decreasing slightly as the electricity prices are increased. For instance, under conditions of NC, in the case of 5% annual price increase, the *SIR* will be reduced by 12.5% from 1.36 to 1.19 for single storey and reduced by 14.1% from 1.35 to 1.16 for two storey building. Normally the lost income in winter is higher than the gained income in summer. This is due to the fact that in houses where TW is built, there will be no sales of electricity for heating during peak hours as a requirement of the DSM program. However, in summer, electricity sales will continue whether there is a TW or not, meaning less increase in income gains compared to lost incomes. The difference between lost income and gained income will be increasing as the prices are increased causing a drop in *SIR*.

For the case of Erbil, as it is mentioned previously, the electricity is subsidizing by government to the customers. Therefore, if utility decides to increase the price of electricity sells to the government, in case if government will not be able to increase the price of electricity relevantly, the amount of electricity subsidizing provided by government to customers will increase. Similar to the case of NC, in the LCC analysis the electricity prices were increased yearly from 2% to 5% to discover its possible effects on the *SIR*. As it can be seen from figures, the value of *SIR* is decreasing for both single and two storey buildings while the electricity price is increasing. This is due to the fact that the government should invest more on subsidizing the electricity for the customers. For instance, if the electricity subsidizing increases annually by 5%, the value of *SIR* will drop by 2.5% (from 5 to 4.88) and 2.51% (from 4.98 to 4.85) for single and two storey buildings, respectively.

In case of San Diego, similar as the other two case studies, when the price of electricity is increased by 5%, the value of *SIR*, for single and two storey buildings decreases. For instance, under conditions of San Diego, in the case of 5% annual price increase, the *SIR* will be reduced by 10.28% from 1.08 to 0.96 for single storey and reduced by 5% from 1.2 to 1.14 for two storey building.

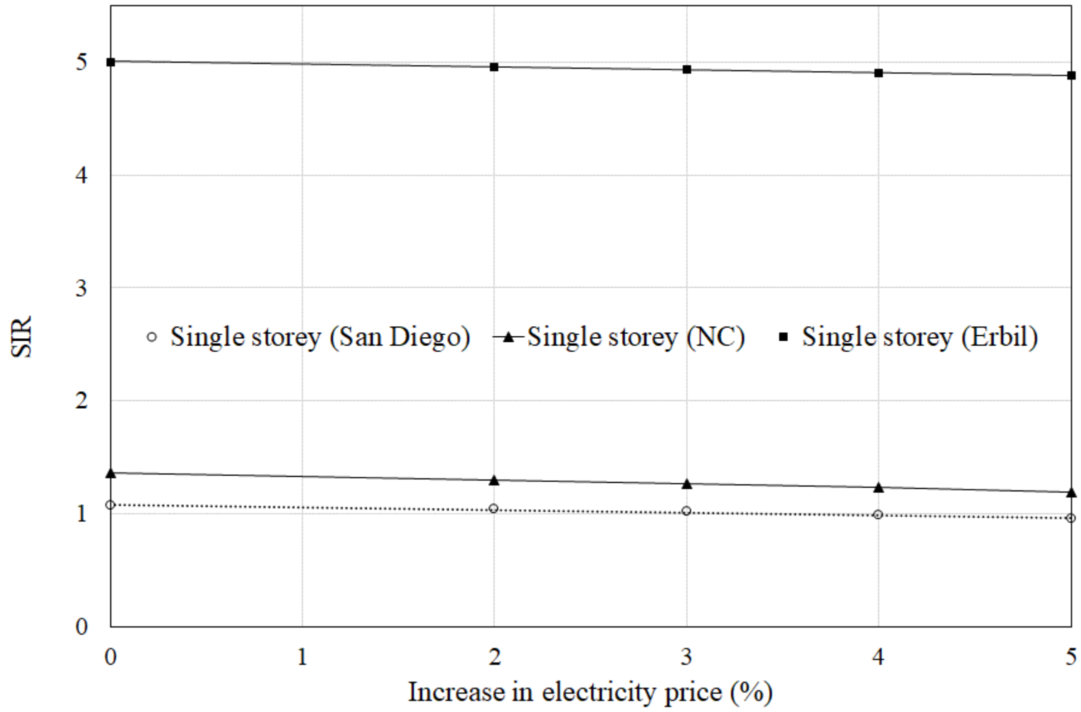


Figure 41: *SIR* as a function of percent annual increase in electricity prices for single storey building located in NC, Erbil, and San Diego

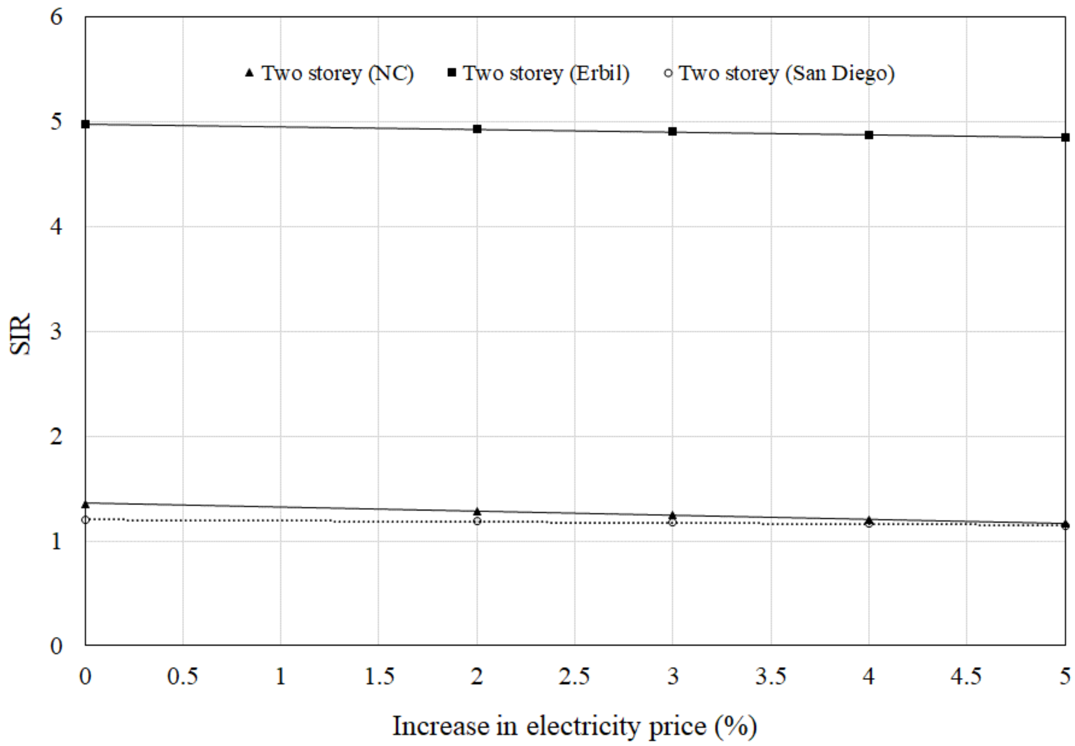


Figure 42: *SIR* as a function of percent annual increase in electricity prices for two storey building located in NC, Erbil, and San Diego

5.2.4 *SIR* as a Function of Rebate as a Percentage of TW Construction Cost

While the DSM program is feasible with the full cost of TW paid, in the case of devising a program, where a portion of the TW construction cost is paid to the participants, the value of *SIR* increases as can be seen in Figures 43 and 44 for single and two storey buildings, respectively.

Under NC conditions, in case of single storey building the value of *SIR* is increased from 1.36 to 1.91 if 60% of the TW construction is paid to the participant, while in case of two storey building under similar condition, *SIR* is increased from 1.35 to 1.87. It should not be forgotten that, the reduction in rebate is limited and should not make the TW construction from customer point of view infeasible.

In case of Erbil, if government pays the total cost of TW, the value of *SIR* for single and two storey buildings become 5 and 4.98, respectively. Despite the viability of the DSM program in full rebate payment, the feasibility of proposed program when a portion of the TW construction cost is paid to the participants has been investigated for single and two storey buildings (see Figures 43 and 44). It is clear that, if government pays less for TW construction and leaves a portion of it to the customers, the viability of the DSM program increases. However, it should not be forgotten that, in Erbil when the government is subsidizing the electricity for customers, it is unlikely to convince consumers to enter to the DSM program while they have to pay a portion of the TW construction cost as well.

Under San Diego conditions the value of *SIR* is increased while the cost of DSM rebate is decreased. It is found that, if 60% of total cost of TW is paid by the utility, the value of *SIR* is increased to 1.53, and 1.8 for single and two storey buildings, respectively.

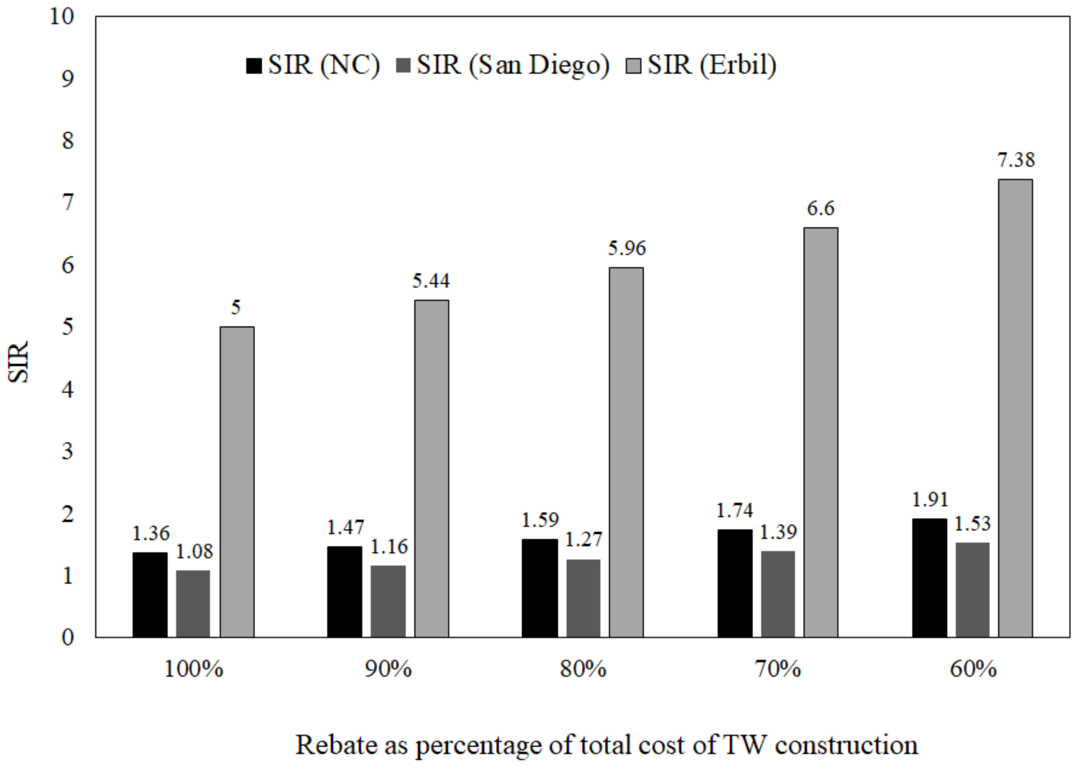


Figure 43: *SIR* as a function of rebate as a percentage of full TW construction for single storey building located in NC, Erbil, and San Diego

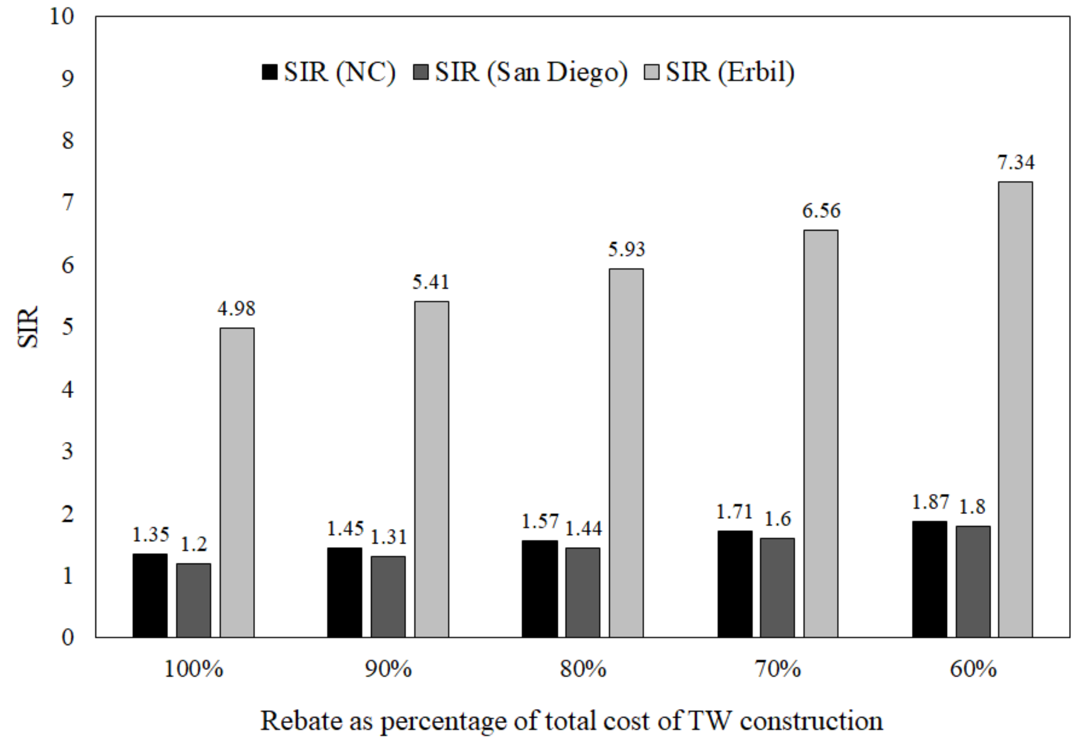


Figure 44: *SIR* as a function of rebate as a percentage of full TW construction for two storey building located in NC, Erbil, and San Diego

Chapter 6

CONCLUSION

6.1 Summary of the results

A DSM strategy is proposed in the current work to facilitate the purpose of matching the delayed solar energy usage provided by the TW system with the evening peak hours while both the electric utility and the consumers enjoy economic benefits. TW construction would be implemented by renovating one of the south-facing rooms in existing buildings. Due to the fact that the process requires a physical change on the building envelope the implementation of the program is difficult and the consumers may have reservations in accepting to take part in the program. For this reason, the benefits of having a TW should be well explained to them and the financial burden of the construction should be taken from their shoulders. This can be done by utility funding in terms of a rebate program with the anticipation of saving from future power capacity expansion.

The simulation results for the all case studies reveal that the TW provides satisfactory heating for a great portion of winter. However, it is found that in some cold days of winter, the indoor temperature of the room integrated with TW dropped and heating is required in case of NC, and Erbil. Therefore, it is clear that preventive measures need to be taken for ensuring electric heaters are not turned on during peak hours on such days. For this reason, it is advised that the utility should install astronomic relays in participating houses ensuring that the air conditioners are kept off during the peak hours. On the other hand, to safeguard the comfort temperature of the occupants, it is further advised to supply a portable gas heater to each participant. The total cost of the rebate program amounts to 1588.25, 1058.75, and 2543.9 EUR per house, for NC, Erbil, and San Diego, respectively. It is assumed that in each house a 24,000 BTU/h (7.034 kW) air conditioner is employed in the occupied room. If the air conditioners are not turned on during the winter peak hours, 17.5-MW reduction from the maximum peak can be achieved with the participation of 6842 houses in the program.

Under subtropical climate - Mediterranean and semi-arid type when the winter is very mild and summer is warm to hot (similar to NC), by building a 15 m^2 TW area, the ratio of total electrical energy required to floor area for the split unit air conditioner during heating season reduced by 5.65 and 5.1 kWh_e/m^2 for single and two storey non insulated buildings.

Under same climate condition, if the electricity prices are 0.203 and 0.154 Eur/kwh during on peak and standard time, building of the TW is a feasible DSM program.

In the case of funding only full cost of the TW construction, the *SIR* is evaluated to be 1.49, and 1.48 for single and two storey buildings. The addition of an astronomic relay, costing approximately 100 EUR would reduce the *SIR* to 1.41, and 1.40 for single and two storey buildings. If the DSM program covers the cost of TW, astronomic relay, and portable gas heater, the LCC analysis indicates that the rebate program would be feasible for the utility with *NPV* of 4,824,090, and 4,866,525 EUR and *SIR* value of 1.36, and 1.35 for single and two storey buildings, assuming a discount rate of 2% over a life time of 20 years. It is expected that for any developing country with similar climate condition and energy policy as NC, applying proposed DSM program is feasible for the utility.

This will also save each participating consumer 11.2 and 9.22 kWh_e/m^2 per year during the expensive peak hours in winter, in case of single and two storey buildings.

The sensitivity of changes in the orientation of occupied zones, unforeseen increases in rebate and unexpected increases in electricity prices were investigated and it was found that *SIR* is always greater than 1.

It is found that under Erbil climate condition, where the winter is cold and mostly cloudy and rarely becomes less than 0 ^oC and buildings are not insulated in residential sectors, building 15 m^2 TW reduces the ratio of total electrical energy required to floor area for the split unit air conditioner by 3.88 and 4 kWh_e/m^2 for single and two storey buildings during heating season.

In some developing countries, such as Erbil, government is subsidizing electricity to the customers and on the other hand investing hugely on the expansion of transmission and distribution network. Under Erbil climate condition and energy policy, building free TW for customers by government rather than subsidizing the electricity is economically viable for the government. The *SIR* value are 5.91 and 5.88 for single and two storey buildings. However, if rebate program covers construction of a TW, installation of an astronomic relay and providing a portable gas heater the *SIR* value decreased to 5 and 4.98 for single and two storey buildings, respectively.

The LCC analysis indicates that the rebate program which covers the fully cost of TW construction, astronomic relay and portable gas heater, would be feasible for the government with *NPV* of 29,597,585, and 29,502,686 EUR, assuming a discount rate of 2% over a life time of 20 years.

In case of Erbil, since the proposed DSM program has a supreme *SIR* value of approximately 5, in order to encourage the costumers to participant in the DSM program, it is advisable that government pay all the cost of TW construction, timer, and the gas heater to the participants.

A sensitivity analysis is investigated for the unforeseen increases in rebate and unexpected increases in electricity prices and it is found that *SIR* is always greater than 3.

Based on San Diego weather conditions and building structures, the appropriate TW area is found to be 7.8 m^2. Bigger area size than this might create discomfort both for winter and summer seasons.

Under San Diego climate condition with semi-arid climate with hot and dry summers, and cold and wet winters a 7.8 m^2 TW, saves 3.97 and 2.8 kWh_e/m^2 electrical energy required to maintain the room as the desired temperature for single and two storey buildings during heating season. On the other hand, under multi-tariff electricity pricing when the electricity price is 0.383 EUR/kWh during peak hours and mentioned cost criteria (San Diego case study) for building new power plant, construction of a 7.8 m^2 TW as a rebate, is economically viable for the utility. The estimated *SIR* value for single and two storey buildings is 1.08 and 1.2, respectively. Since the value of

SIR, is very close to 1, unforeseen increase in rebate or electricity price can put the DSM program under risk. In this situation, it is advisable to the utility to do not pay the whole cost of TW construction and pay a carefully selected portion of TW construction cost to the customers.

The summary of the obtained results from different case study is presented in Table 25. For the case study of NC and Erbil the proposed DSM program is economically viable, however for the case study of San Diego the proposed DSM program is not feasible under some unforeseen conditions such as increase in electricity prices and rebates.

Table 25: Comparison of case studies

Case study	Electricity cost (EUR/kWh)		Weather	Building structure	Rate structure	*SIR*		Conclusion
	Std	Peak				Single storey	Two storey	
NC	0.154	0.203	Subtropical climate-Mediterranean and semi-arid	Brick and concrete structure, without insulation	Multi tariff electricity structure introduced by the utility	1.36	1.35	Proposed DSM program is economically viable
Erbil	0.029	0.029	Cold and partly cloudy winter. Hot, arid and clear summer	Brick and concrete structure, without insulation	Electricity is subsidized by the government	5	4.98	Proposed DSM program is economically viable
San Diego	0.213	0.383	Semi-arid climate with hot and dry summers, and cold and wet winters	Wood-framed structure with insulation	Multi tariff electricity structure introduced by the utility	1.08	1.2	Proposed DSM program is critically viable

6.2 Future Work and Recommendations

Based on the performed analyses and obtained results of the current study, future work suggestions and recommendations are as follows:

- Introducing shading devices or any other solution in order to reduce the solar absorption by TW during summer season to analyze its effect on the DSM program.
- Investigating different sizes and materials of TWs and their suitability to different weather conditions, life style and culture of people.
- Investigating the viability of PCM integrated TWs from consumer and utility perspective.
- Investigating DSM Exergy analysis of promotion of TW through DSM.

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