Design optimization of Dutch single-family houses taking into account energy flexibility

Master of Science Thesis

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Abstract

This thesis aims at analyzing the energy flexibility (EF) potential of building structural thermal energy storage (STES) by the implementation of active demand response (ADR) and providing a representative recommendation for building renovation and operation. The objective building type is existing Dutch single-family houses built between 1965 and 1974 which need to be renovated in the (near) future.

Firstly, ADR-event is used to activate the energy flexibility of STES by increasing the setpoint temperature of heat emission system. In order to quantitatively evaluate the energy flexibility potential, three indicators are defined: available storage capacity, storage efficiency and effective storage capacity, which are time-dependent and closely related to dynamic boundary condition including occupant behavior and weather condition. With the ADR-event of 4 hours and the temperature increase of 2C°, the maximum available storage capacity is around 25 kW which is equivalent to a storage tank with the volume of 1070L with the assumption that the temperature is increased by 20C° in a hot water storage tank.

Secondly, in building renovation phase, after replacing boilers to heat pumps and implementing PV system to create the interaction between heating system and electricity system for ADR-event, the impacts of different building design parameters on energy flexibility are assessed and energy flexibility potential of 15 building renovation options are quantified. The results demonstrate that with the improvement of building renovation level, for example, increasing insulation level or airtightness, the available storage capacity decreases significantly while the storage efficiency shows a better performance in the mild renovation level. Additionally, building with external insulation presents a high available storage capacity while a low storage efficiency. Furthermore, the renovation option with usual renovated external insulation level and 0.4ACH infiltration rate can be recommended to the users or house agencies considering the exploitation of building structural energy flexibility, offering the highest typical effective storage capacity and acceptable robustness to dynamic boundary condition.

Finally, from operation perspective, appropriate use of STES can increase the penetration of renewable and reduce CO_2 emission and operation cost. ADR-event is not beneficial under low PV production condition while 2 pm is regarded as the most profitable and environmentally-friendly ADR-event starting time for all building renovation options with high PV production. As for the future-oriented operation scenario which is with real-time electricity price and without net metering, energy flexibility plays a more crucial role in saving operation cost. Therefore, when starting ADR-event at 2 pm in the building with usual renovated external insulation level and 0.4ACH infiltration rate, the average reduction of CO_2 emission and operation cost can both reach 9%.

Keywords: Energy flexibility, Structural thermal energy storage, Active demand response, Building renovation

Contents

Nomenclature

Symbols

C_{ADR}	Available storage capacity [kWh]
C_{EFF}	Effective storage capacity [kWh]
η_{ADR}	Storage efficiency [-]
dT_{comf}	Comfort range available for ADR [°C]
hor	Prediction horizon [h]
l_{ADR}	Duration of the ADR-event $[s]$
n_{50}	Air change rate [ACH]
Q_{ADR}	Relevant ADR heating power of the building $[W]$
Q_{Ref}	Reference heating power of the building $[W]$
Q_{Rel}	Relative heat demand $[W]$
T_{hc}	Heating curve temperature [°C]
$T_{Ambient}$	Ambient temperature [°C]
T_{Design}	Minimum ambient temperature designed for the heating system [°C]
$T_{R,N}$	Return water temperature [°C]
T_R	Nominal room temperature [°C]
$T_{S,N}$	Supply water temperature [°C]
T_{bottom}	Bottom tank temperature [°C]
T_{top}	Top tank temperature [°C]

Acronyms

ACH	Air Changes per Hour
ADR	Active Demand Response
DHW	Domestic Hot Water

DSM	Demand Side Management
EBC	Energy in Buildings and Communities Program
EF	Energy Flexibility
EPBD	Energy Performance of Buildings Directive
IEA	International Energy Agency
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
nZEB	Nearly Zero Energy Buildings
PV	Photovoltaics
RES	Renewable energy sources
STES	Structural Thermal Energy Storage

1

Introduction

1.1. Background and problem statement

Renewable energy sources (RES) play a significant role in solving the problem of fuel poverty and climate change [1]. The penetration of RES is increasing rapidly worldwide, for example, the global installed capacities for photovoltaics (PV) and wind are around 302GW and 487GW by the end of 2016, with at least 50 times and 6 times increase respectively, compared to 2006 [2][3]. Besides, from the electricity production point of view, RES (excluding hydro) contribute to 8% in 2016, with an increase of 14% compared to the previous year, and accounts for almost 40% of the growth in global electricity generation [4]. The continuous increase can be expected since many countries have already set their ambitious targets, for instance, Denmark wants to realize 100% share of electricity generation by 2050 [5]. However, The intrinsic variability of RES, due to the dependence of external environmental factors, can result in the low reliability of supply and the grid instability problem with a high percentage of electricity generation by RES [6]. Additionally, the mismatch between renewable electricity generation and local electricity demand may occur.

RES are not only involved in large scale electricity production, with the development of Smart Grid, but also in the distributed energy system, as shown in Figure 1.1, where buildings as the carriers of distributed energy resources (DERs) play an important role. The buildings sector including people's activities in buildings is responsible for approximately 31% of global final energy use, more than 40% of Europe [8][8]. According to the Energy Performance of Buildings Directive (EPBD), in order to reduce the building energy consumption, all new buildings in the EU must be nearly zero energy buildings (nZEB) by 2020, of which the electricity will be generated from RES to a very large extent [8]. The increase penetration of distributed RES will further lead to the mismatch between local energy production and demand, and strongly affecting the power quality as well as grid stability, especially if net metering is allowed [9].

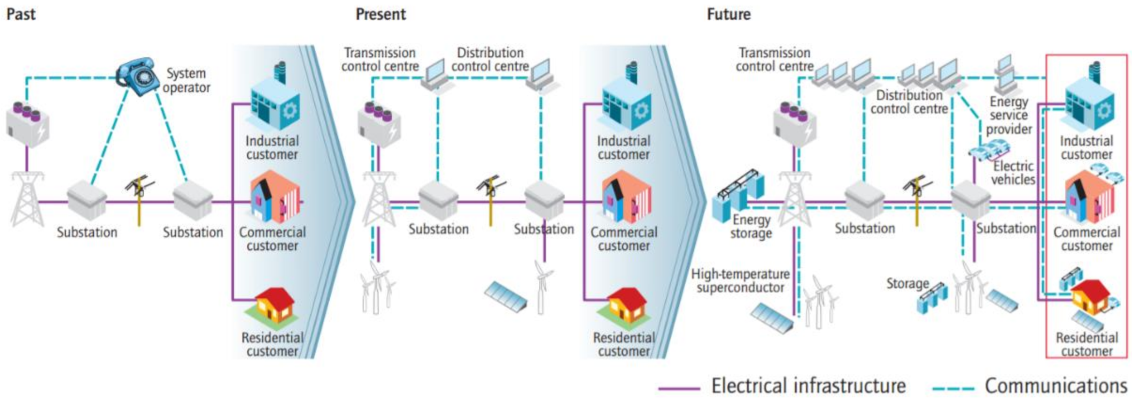

Figure 1.1: *Smarter electricity system* [10]

Therefore, it is necessary to control the energy consumption to meet the instantaneous energy generation in order to reduce even eliminate the mismatch and stabilize the grid. Buildings as the "micro energy-hubs" in the distributed energy system which actively interact with on-site renewable systems, storage systems and users, have the ability to deliver demand responses by the utility of built-in energy flexibility [11]. As defined by ANNEX 67 from the Energy in Buildings and Communities Program (EBC) of International Energy Agency (IEA) [6], the Energy flexibility of a building is "the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements", which allows for demand side management by load shifting in time, particularly, the thermal load, such as heating/cooling, domestic hot water (DHW), even hot water for washing machines and dish washers. The utilization of electrical heating systems, which shows an increased potential considering the transition from centralized power plants to RES, is necessary to realize the interaction between on-site electricity generation system and heating/cooling system.

Many kinds of storage contained in buildings can increase the buildings' energy flexibility, such as structural thermal storage and hot water storage tank. It is worthwhile to note that thermal mass, with the ability to store a certain amount of heat, is embedded in all buildings and shows to be a cost-effective energy storage technology, especially compared to conventional energy storage like batteries [1][6]. The structural thermal energy storage can be activated to pre-heat or pre-cool the building to reduce the mismatch on a daily level, with high incentives of demand response, for instance, low electricity price or high electricity production by RES. Since load shifting with the use of thermal mass is realized by increasing or decreasing the setpoint temperature of heat emission system, indoor comfort, as an important constraint, should not be jeopardized. However, some drawbacks still limit the use of buildings' energy flexibility potential [1]. Generally, high energy production by PV panels is always corresponding to low heat demand in the same time periods, because of the use of high passive solar gains and lower temperature difference respectively. Therefore, the availability of loading shifting by heating system is restricted [12]. Furthermore, the activation of structural thermal energy storage by rising set-point temperature increases buildings' annual heat demand [13]. Moreover, available energy flexibility of buildings is affected by climate, building characteristics, heating system, heat emission system and control strategy, all of which should be taken into account, in order to optimize the usability of energy flexibility [1].

Energy flexibility can be introduced both for new constructions and renovation of existing buildings. The latter is of significant importance because, on the one hand, around 75% of existing buildings will still be there by 2050. In the Netherlands, the number of renovated dwellings are twice as much as that of newly built as estimated [14]. On the other hand, buildings built from the 1960s to 1970s, need to be renovated in the near future [6]. From the building types perspectives, as shown in Figure 1.2, in Dutch building stock by 2011, single-family houses account for 27%, of which around 13% are built between 1965 and 1974 [15].

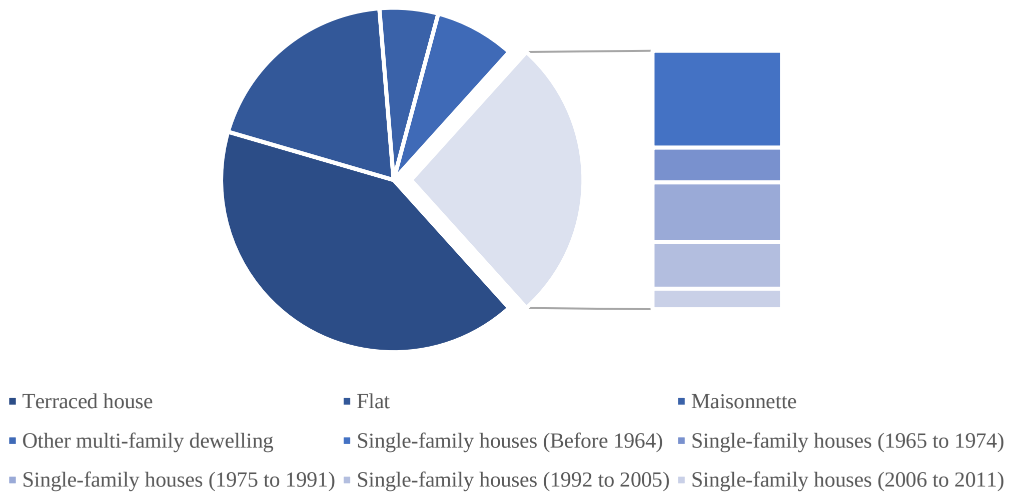

Figure 1.2: *Building types and ages of Dutch building stock* [16]

According to the Dutch Central Bureau of Statistics (CBS), at the end of 2015, residential PV capacity accounts for 69% of total accumulated PV market volume which is still increasing continuously with the aim "2.5 million Dutch households on solar power by 2023" , set by National Action Plan on Solar Power (NAZ) [17]. As the major driving force, net metering scheme, which is currently guaranteed until 2020, facilitates the significant growth. Together with the policy and financial support like SDR, from the building renovation point of view, consumers are encouraged to install PV systems for local electricity production. Additionally, with the help of energy flexibility of energy storage system, especially, the cost-effective embedded structural thermal storage, it is potential to reduce energy consumption and energy cost without causing the overloading of the grid [18].

Therefore, it is of great importance to investigate which kind of building renovation options has the best performance in matching with the local PV production through exploiting energy flexibility potential of structural thermal energy storage. Besides, in the operation phase, when is the most beneficial and environmentally-friendly time of the day to use energy flexibility potential of structural thermal energy storage.

1.2. Research objective and questions

The concept of energy flexibility in buildings was put forward in 2014 in IEA EBC ANNEX 67, of which the goals include analysis of energy flexibility potential in buildings and how to control energy flexibility without jeopardizing indoor comfort [6][17]. However, in this thesis, the main objective is implementing and quantifying Energy Flexibility on Dutch existing single-family house built and taking it into account during building retrofit from a CO_2 emission reduction and cost saving point of view. Therefore, two main research questions can be formulated as:

1. What renovation options can improve the usability and exploitation of the energy flexibility potential of structural energy storage for the existing Dutch single-family houses (1965-1974)?
2. When is the best time to start active demand response event in order to get the maximum CO_2 emission reduction and operation cost savings with the use of energy flexibility of structural thermal energy storage for the existing Dutch single-family houses (1965-1974)?

In order to give a clear insight into the research questions, three groups of sub-questions are drawn up as follows:

The first group of sub-questions aims at implementation and quantification of energy flexibility of structural thermal energy storage on the existing Dutch single-family houses (1965-1974):

- How can the energy flexibility of structural thermal energy storage be activated?
- How to quantify energy flexibility of structural thermal energy storage in Dutch climate?

The second group of sub-questions is focused on the building renovation aspects, considering the usability of energy flexibility of structure thermal energy storage, and giving the renovation suggestion taking into account the uncertainties of occupant behaviors and weather conditions:

- Which building renovation options can be implemented in existing Dutch single-family houses?
- How do building design parameters influence the energy flexibility potential of structural thermal energy storage for the existing Dutch single-family houses (1965-1974)?
- How is the energy flexibility robustness of each building renovation design with dynamic boundary condition?

The third group of sub-questions purposes to find the best time to use the energy flexibility potential of structure thermal energy storage, in order to receive the maximum CO_2 emission reduction and operation cost saving considering the impact of occupant behavior and operation scenarios:

- How are the CO_2 emission and operation cost influenced by the use of energy flexibility of structural thermal energy storage?
- How are the CO_2 emission and operation cost saving influenced by occupant behavior and operation scenarios?

1.3. Thesis outline

The thesis is structured as follows:

Chapter 2 introduces the theoretical basis of this thesis based on the literature review, including the definition and activation method of energy flexibility of buildings' structure thermal energy storage, followed by the indicators to quantify the energy flexibility and the impact of design parameters with a constant boundary condition.

Chapter 3 describes the methodology of this thesis. Firstly, computational building performance simulations are developed based on the base case building with TRNSYS, furthermore, involving system renovation and building renovation options for the existing Dutch shingle-family houses. Additionally, occupant behavior and weather condition scenarios are presented. Finally, energy flexibility indicators with detailed parameters are adapted to this thesis.

Chapter 4 compares the performance of various building renovation options in exploiting energy flexibility of structure thermal energy storage and investigates the operation guidelines of using energy flexibility based on the obtained result;

Chapter 5 summarizes and concludes this thesis, furthermore, identifies the future research directions and opportunities.

2

Literature Study

2.1 Energy flexibility in buildings

2.1.1 Definition of energy flexibility in buildings

The energy flexibility of a building is defined as the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements [6]. In detailed, energy flexibility can be described by three attributes: direction *a* (up or down), electrical capacity (or power) *b* and availability defined by a starting time *c* and duration *d* [20], as shown in Figure 2.1. In order to balance the supply and demand, the power, which can be shifted, increased or decreased, is adjusted by the external signal (price or RES production) and sustained for a given duration. This indicates two electrical consumption profiles in reference and flexible scenario respectively.

"The amount of power" and "the duration" are integrated to describe energy flexibility in a quantitative phase [21]. For instance, a storage system that can shift a certain amount of energy for a long period of time is considered to be more flexible than another system which can only shift the same amount of demand for a short period of time. And accordingly, a system shifting a high amount of energy has more flexibility compared to a system shifting a low amount of energy during the same period.

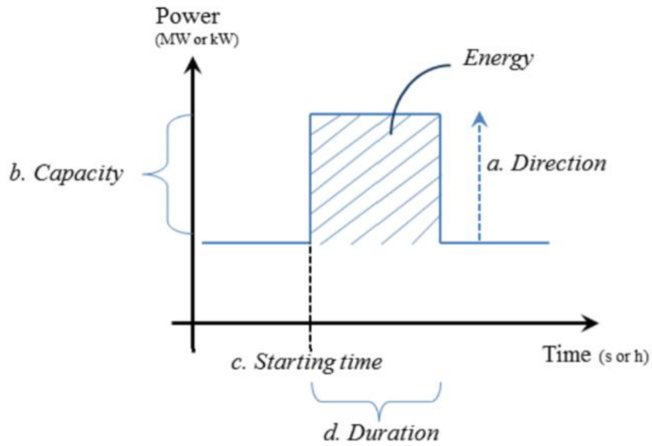

Figure 2.1: *Characterization of Energy Flexibility* [20]

Generally, the potential energy flexibility is used to minimize energy cost or procurement cost of purchasing electricity and heat from the power grids, increase RES share in distributed networks, or develop the ability of real-time matching of consumption and generation to keep the stability of the grid. Those objectives can be accomplished by optimal control strategy, however, under several constraints: the indoor thermal comfort level, the acceptance of users and the available capacity of RES and storage systems within a specific time span [22]. Sometimes, the annual energy consumption or carbon emissions may increase because of the frequent importing or exporting of electricity to the grid. Therefore, another more detailed definition of flexibility is "flexibility is the ability of demand side installations to respond to power systems requirements for ramping up or down using on-site storage capabilities, increasing or decreasing electricity consumption patterns whilst maintaining acceptable indoor comfort bandwidth during a specific time period [21]".

A building can be regarded as a "prosumer", taking the role of "producer" and "consumer" at the same time. The main energy flexibility suppliers include thermal energy storage in building's structures, generation from RES, storage systems (e.g. hot-water storage tank, battery), shiftable and curtailable electrical loads, and thermal conversion in building's heating and cooling systems coupled with thermal storage [23]. As the most cost-effective one, structural thermal energy storage will be discussed in this thesis. Research shows that energy cost saving, peak electrical use reduction and RES penetration increase can be realized through optimal control strategy with the use of intrinsic thermal storage within the building structure [24]. Furthermore, it is indicated by both the simulation-based and experimental results that 26% up to 40% energy cost can be saved by considering both the structural and non-structural thermal storage of the building with the use of model predictive control (MPC) strategies, while maintaining or even improving thermal comfort [25][26][27].

2.1.2 Active demand response

In order to produce a load shape change matching with the electricity generation profile, demand side management (DSM) is implemented to influence the electricity uses of customers [28]. Among different DSM strategies, active demand response is defined as ‘changes in electric usage implemented directly or indirectly by end use customers/prosumers from their current/normal consumption/injection patterns in response to certain signals’ [29]. As contrast, passive demand response concerns activities aiming at modifying the normal electricity consumption/injection patterns without interacting with the consumers (e.g. rolling black-outs) [30].

In this thesis, ADR is implemented to utilize energy flexibility potential of buildings’ structural thermal energy storage which has the ability to cope with the intermittent character of RES and facilitate the load profile of electric heating system to match with the variable on-site RES production [31]. The demand side energy flexibility is exploited in three ADR modes: peaking clipping (instant demand reduction), valley filling (instant demand increase) and load shifting (demand shifting in a time period), which is shown in Figure 2.2.

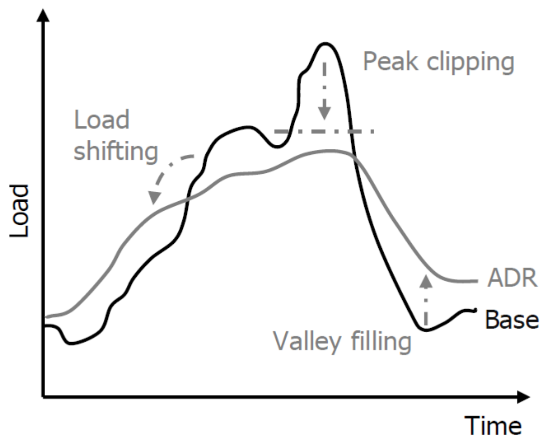

***Figure 2.2**: Conceptual daily load profile with (black) and without (grey) active demand response*

ADR is activated when the incentives of demand reduction are high, such as high RES production and low real-time electricity price. With the use of electric heating systems, the energy flexibility of building structural thermal energy storage pre-heats or pre-cools the building by increasing or decreasing indoor temperature, without jeopardizing indoor thermal comfort and occupant satisfaction, as the constraint.

2.2 Energy flexibility indicators for structure thermal energy storage

Many studies used a bottom-up approach to demonstrate the impact of using energy flexibility of building structure thermal energy storage. This approach is based on case studies with simplified and generalized models of buildings and optimal control strategies which are developed to ensure an optimal operation of the entire system [32]. Load shifting, energy cost saving and local RES penetration increase were realized by the use of structural energy storage, which, therefore, are applied as performance indicators to describe the energy flexibility potential [27][33][34][35]. However, these indicators are more focused on the result of implementing optimal control strategies to minimize energy cost and consumption rather than the actual energy flexibility of building structural thermal energy storage. That implies, except the building design, control strategies and electricity market are regarded as two impact factors involved in quantifying energy flexibility of structural thermal energy storage [1]. Therefore, a rule-based control strategy is used in this thesis to simplify the system when analyzing the impact of building design on energy flexibility with the use of active demand response in both design phase and operation phase. Based on the literature review, available storage capacity and storage efficiency, two performance indicators of energy flexibility potential for structural thermal energy storage with ADR, are defined and quantified [1]. It has to be emphasized that these indicators are influenced by climatic conditions, occupant behavior and thermal comfort.

2.2.1 Available storage capacity

Available storage capacity (C_{ADR}[kWh]) quantifies the maximum amount of heat that can be added in the structural thermal energy storage of a dwelling during the duration of an ADR-event, without jeopardizing thermal comfort, in a given dynamic boundary condition [1]. ADR-event is realized by increasing indoor setpoint temperature of the electric heating system on the basis of original temperature for pre-heating, illustrated in Figure 2.3, therefore the available storage capacity is limited by the temperature increase and corresponding thermal comfort level. Besides, the multiple impacts of climate, occupancy and thermal properties of buildings determines that available storage capacity is a time-dependent indicator. In addition, this methodology can be extended to the cooling system as well, which is not considered in this thesis.

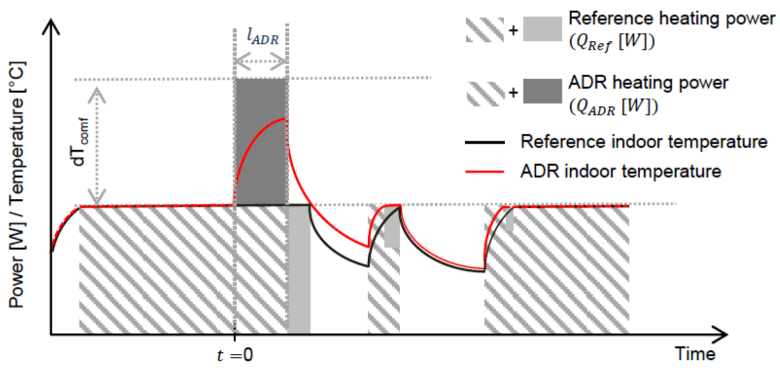

Figure 2.3: *Scheme of ADR-event used to quantify the available storage capacity and the storage efficiency*

Two scenarios are defined for the ADR-event. The reference scenario is represented by the black line of which the heating system is controlled to maintain the reference set-point temperature, corresponding to the reference heating power of the building ($Q_{Ref}[W]$). The ADR scenario representing by the red line shows a setpoint temperature increase by $dT_{comf}[°C]$ from $t = 0$ for the duration $l_{ADR}[s]$, with the relevant ADR heating power of the building ($Q_{ADR}[W]$). Hence, the available storage capacity is formulated by the integral of the difference between the heat input during the ADR-event (Q_{ADR}) and in reference operation (Q_{Ref}), illustrated by the dark gray area in Figure 2.3:

$$C_{ADR}\left(t, l_{ADR}, U_t, dT_{comf}(t), \theta\right) = \int_0^{l_{ADR}} \left(Q_{ADR} - Q_{Ref}\right) dt \tag{2.1}$$

$$Q_{ADR} = f\left(t, l_{ADR}, U_t, dT_{comf}(t), \theta\right) \tag{2.2}$$

$$Q_{Ref} = f(t, U_t, \theta) \tag{2.3}$$

with l_{ADR} the duration of the ADR-event, U_t the dynamic boundary condition such as climate and occupant behavior, $dT_{comf}(t)$ the comfort range available for ADR which may vary in time, and θ the building and system design parameters [1].

2.2.2 Storage efficiency

The storage efficiency (η_{ADR}[-]) is defined as the fraction of the heat that is stored during the ADR-event that can be used subsequently to reduce the heating power needed to maintain thermal comfort [1], which can be calculated, with the same scheme shown in Figure 2.3, as

$$\eta_{ADR}\left(t, l_{ADR}, U_t, dT_{comf}(t), \theta\right) = 1 - \frac{\int_0^{\infty} (Q_{ADR} - Q_{Ref}) dt}{\int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref}) dt} \tag{2.4}$$

The denominator is the available storage capacity while the numerator signifies the storage losses, which is the fraction of heat stored during the ADR-event that is not recovered after a long period. Additionally, the higher the temperature increase during ADR-event, the higher the losses. The heat supplied by the emission system to the building rather than energy use by heating system is taken into account when calculating storage efficiency since the focus is on the overall performance of the building instead of the heating system [1].

2.3 Impact of building parameters on energy flexibility

A study has been done to assess the impact of building design parameters, for instance, insulation level and ventilation rate, on energy flexibility with a constant boundary condition. It is concluded that, firstly, the available storage capacity is higher for the uninsulated buildings due to the higher thermal power of heating system available for ADR-event. On the contrary, higher insulation level results in a higher storage efficiency. And the author pointed out that from the grid point of view, as reflecting by the effective storage capacity, it is expected a balance whereby a high available storage capacity and an acceptable storage efficiency can be obtained at the same time. Secondly, the results show that by reducing the infiltration and ventilation losses, a significant positive impact can be found on storage efficiency [1].

2.4 Building renovation

The building sector contributes approximately 41% of the total national final energy consumption in the Netherlands [36]. Based on the Dutch energy use shown in Figure 2.4, it is indicated that heating/cooling accounts for the majority of the total energy use including gas and electricity for households.

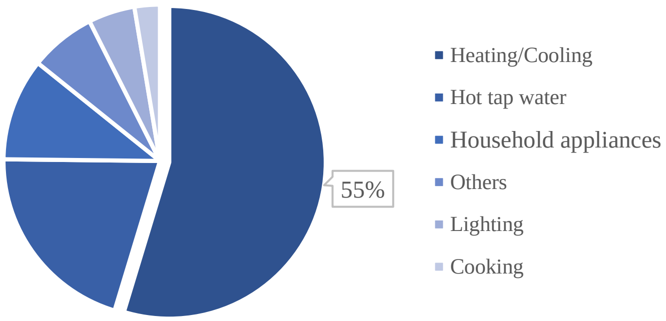

Figure 2.4: *Distribution of Dutch residential energy consumption*

From the sustainability point of view, together with the growing limitations on land use, building renovation is regarded as a cost-effective and environmentally-friendly method to reduce the energy consumption, especially heating/cooling demand [37]. Five key phases, demonstrated in Figure 2.5, are included in a sustainable building retrofit process, of which from a research perspective, only phase 3 is introduced in this thesis.

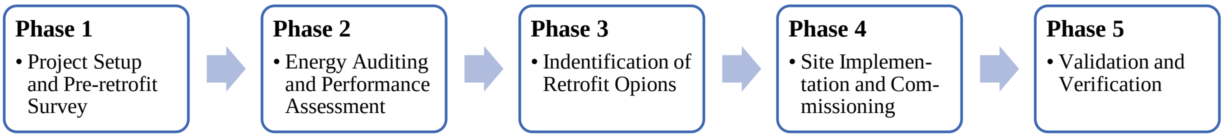

Figure 2.5: *Key phases in a sustainable building retrofit process* [38]

Building retrofit options are summarized up and divided into two groups, supply side management and demand side management, as illustrated in Figure 2.6. The retrofit options for the former focus on the renovation of building electrical system and implementation of RES as alternative electricity production system with the incentives like net metering and SDR financial supporting. The retrofit options for the latter chiefly comprises the strategies aiming at reducing building heating and cooling demand as well as energy efficient equipment. Based on the literature study, improving the insulation of building's components such as roof, wall and floor; replacing windows and implementing RES are the most common retrofit technologies for residential buildings. Additionally, increasing the wall/window ratio and air sealing are used for building renovation as well [39][40][41][42].

For the existing Dutch single-family houses built between 1965 and 1974, the previous retrofits emphasize on improving single glazing to double glazing (69% of the glass surface) and HR glass (14%). For the dense parts, 20% of the façade, 15% of the floor and 20% of the sloping roof are insulated [15]. Based on the literature study, three design renovation options are considered in the case study: insulation level improvement, changing the insulation location and airtightness improvement.

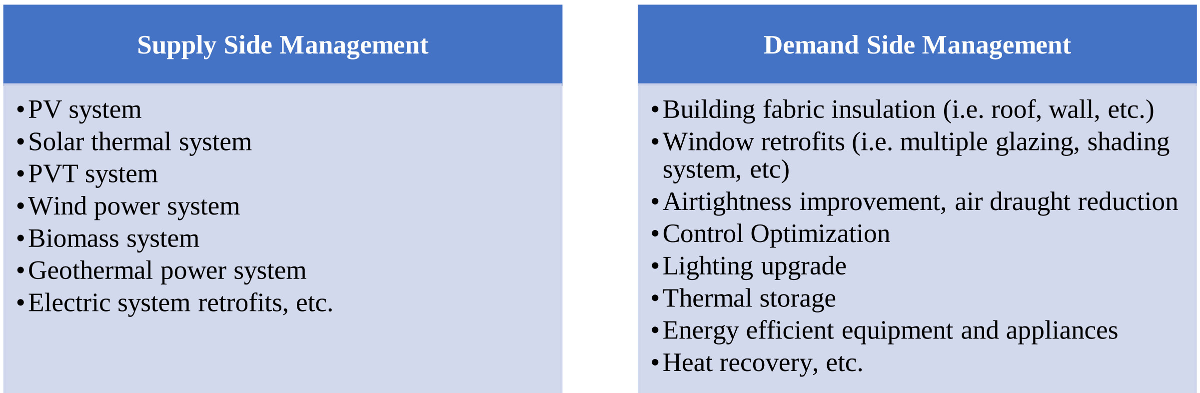

Figure 2.6: *Overview of building retrofit options* [38][43]

3

Methodology

3.1 Overview of methodology

Literature study is ongoing throughout the project, firstly, which is performed to give an overview of the buildings' energy flexibility definition and sources. From the quantification of view, the energy flexibility indicators of structural thermal energy storage which is one of the main suppliers of energy flexibility are following described. Besides, a typical building design of existing Dutch single-family houses and available renovation options are introduced. Moreover, as one of the most significant factors causing uncertainty and influencing buildings' energy performance [18], representative Dutch occupant behaviors are considered.

A case study is set up to investigate the energy flexibility on existing Dutch single-family houses (1965-1974). The detailed building performance simulation (BPS) model of the base case building is implemented in TRNSYS. Simulations are run under typical building design (base case) and renovated design with different occupancy scenarios and weather conditions. Results are analyzed in two phases: on the one hand, in design phase, the impact of building design parameters on energy flexibility is assessed and the building renovation option with the highest robustness is identified; on the other hand, in operation phase, the aim is to find the optimized ADR-event starting time with maximum CO_2 emission reduction and operation cost saving for every building renovation options. Both phases take into account the impact of occupant behaviors. Based on the analysis in two phases, building renovation and operation suggestion are put forward for existing Dutch single-family houses (1965-1974). The overview of the methodology is demonstrated in Figure 3.1.

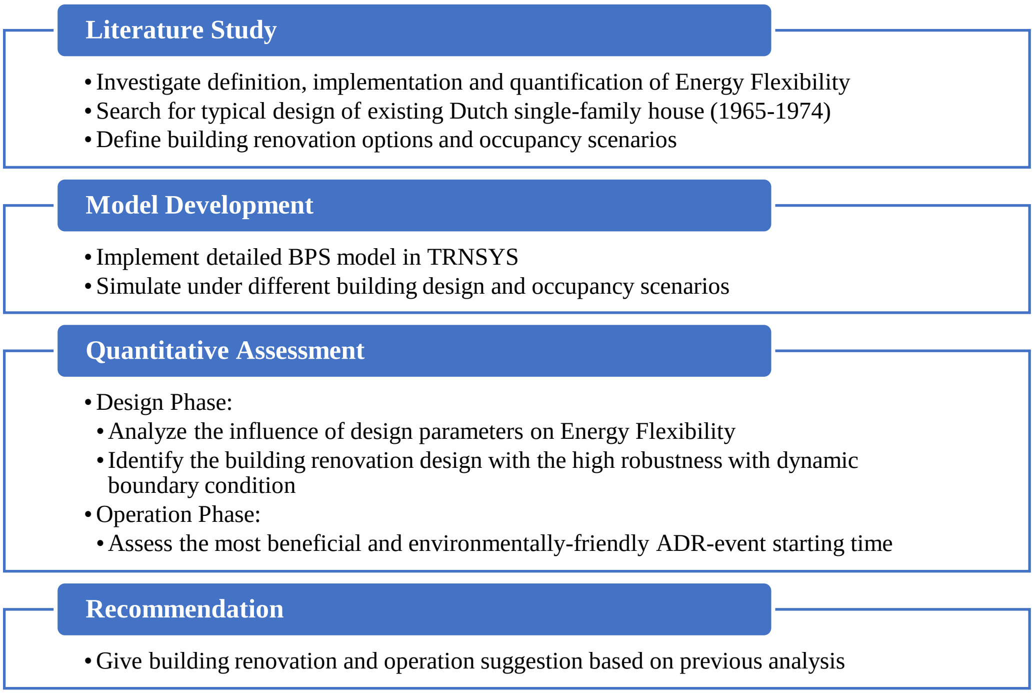

Figure 3.1: *Overview of the methodology*

3.2 Building performance simulation model development

Building performance simulations are implemented to quantify the energy flexibility of building structural thermal energy storage with the use of TRNSYS. The simulation process is shown in Figure 3.2. Weather condition and occupant behavior are input to the simulation model which consists of building model, HAVC, control and PV system. The output data is used to calculate energy flexibility and operation indicators.

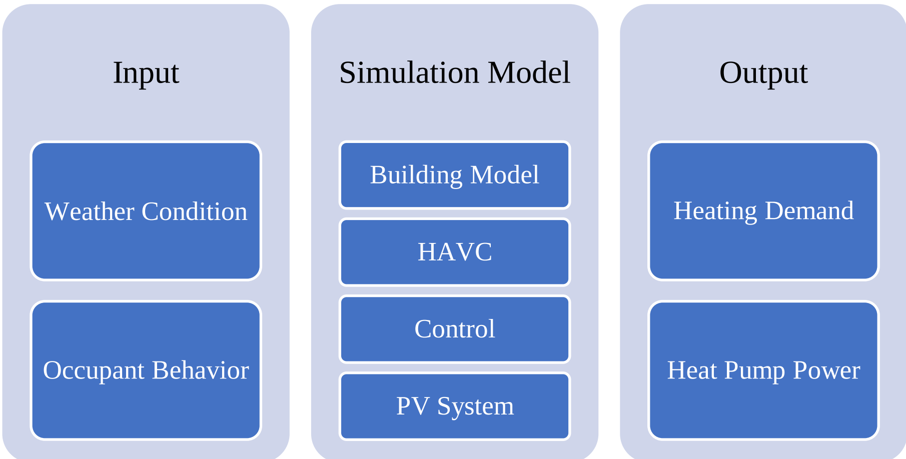

Figure 3.2: *Simulation process scheme*

3.2.1 Base case building model

The case study building is a typical existing Dutch single-family house built between 1965-1974 and all the design is based on the data available in the European TABULA-project [16][45].

The building is modeled and simulated with Type 56 in TRNBuild and the other building sub-systems are designed by the computational building performance simulation tool TRNSYS. Two thermal zones, performed by two thermal nodes individually, are created for the relevant two layers. The model is simulated under Dutch climate with the weather data in Amsterdam-Schiphol in the format generated by Meteonorm, which is identical to the Typical Meteorological Year (version 2) standard form. No external blinds are designed in this case study. The detailed TRNSYS model is shown in Appendix A.

3.2.1.1 Building construction

The building is simplified to consists of two floors: ground floor and first floor as day-zone and night-zone respectively. External dimensions of the case study building are shown in Table 3.1. The detailed surface properties are demonstrated in Table B.1 in Appendix B. Besides, the thermal properties of building construction are represented by thermal transmittance (U-value) in Table 3.2. Internal walls and floors are designed as massive structures that significantly contribute to the thermal mass with concrete floors and masonry walls. The front façade is assumed to be oriented North.

Table 3.1: *Summary of building external dimensions*

Property	Value	Unit
Length front wall	15.2	m
Length side wall	8.7	m
Height	7.6	m
Usable floor surface area	264.0	m^2
Total window area	192.4	m^2
Total roof area	44.1	m^2
Total envelope area	186.0	m^2
Total volume	805.2	m^3

Table 3.2: *Overview of the thermal properties of building construction*

	Façade	Floor	Roof	Window	Door
U-value [W/m^2·K]	1.45	2.33	0.89	5.2	3.5

3.2.1.2 Heating system

For existing Dutch single-family houses built between 1965-1974, nearly all have central heating. Individual condensing boilers (high temperature) are most commonly used, accounting for 70% (HR107 38% and HR100 32%). In addition to condensing boilers, electric boilers (3%), gas boilers (4%) and kitchen boilers (4%) are also used for the production of hot water [15]. According to the TABULA project as well, high temperature individual condensing boiler is equipped for space heating as well as domestic hot water (DHW).

For heating emission system, it is appraised that three-quarters of the total 120 million heating system installed in Europe works at high temperature with the inlet temperature between 50°C and 80°C [46]. Therefore, a hydronic system with high-temperature radiators (55/45/20) is used as the heat emission system controlled by a central room thermostat with thermostatic values on the radiators [47], also known as setpoint/setback temperature, which is related to occupant behavior and will be discussed later. The radiators deliver heat to the surroundings and heat the room mainly by convection and a small part of radiation [47]. Accordingly, for the computational model in TRNSYS, the convective and radiative heat fraction are set to 0.7 and 0.3 respectively [1].

However, in this thesis, in order to exploit the energy flexibility potential of structural thermal energy storage, the boiler will be renovated to an electric heating system (heat pump) since the interaction between electricity system and heating system is required. Besides, heat pump in the renovated heating system is designed for both space heating and DHW, which means their consumption are coupled to the heat pump output. When activating the ADR-event by increasing the set-point temperature of radiators, the working profile of heat pump is changed compared to the reference without ADR. If the DHW is produced at the same time, it will lead to a problem in distinguishing the impact caused by these two factors. Hence, the condensing boiler is not modeled in TRNSYS. Additionally, DHW is not considered in this thesis so as to improve the interpretability of the results. The scheme of the theoretical reference heating system is shown in Figure 3.3.

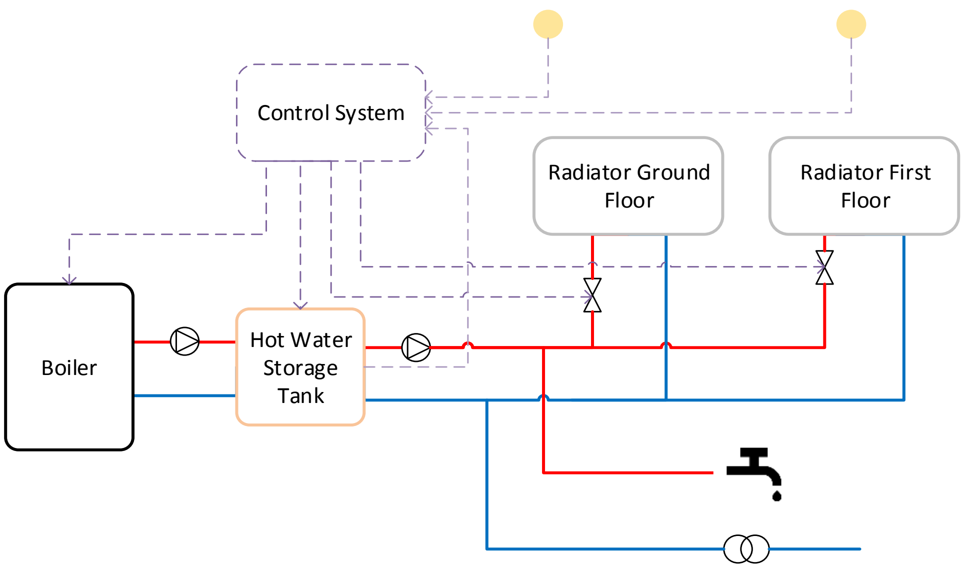

Figure 3.3: *Scheme of reference heating system*

3.2.1.3 Ventilation and infiltration

Most of the existing single-family houses built between 1965 to 1974 are equipped with natural ventilation (91%). The remaining part has the mechanical extraction. A major part of the houses is provided with a seal (52%) [15]. The minimum ventilation rate is clarified as 0.9 dm^3/s per m^2 by Dutch building decree [48].

Air permeability $(m^3/(h \cdot m^2))$ is used to quantify the airtightness in most studies, which is defined as the capability of a surface to let air pass through. The higher the air permeability, the lower the airtightness of the building. Besides, air change rate, normally representing as the n_{50} value with the unit as air changes per hour (ACH), is another metric to express airtightness as a regarded convenient expression. Both two indicators are used under a pressure difference of 50Pa. However, Dutch regulations request to express airtightness with the specific leakage (dm^3/s) for a 10 Pa pressure difference as a reference [49]. The relationship between specific leakage @10 Pa and air change rate @50 Pa depends on the flow coefficient n. The latter is obtained when the former is divided by 25 to 30 [49]. In the TRNBuild model, airtightness is requested to express with infiltration rate in ACH, which can be approximately calculated as [50]:

$$n_{inf} = \frac{n_{50}}{x} \tag{3.1}$$

where x is a constant parameter, which is assumed as 20 [51].

Hence, together with the information provided by TABULA project, the natural ventilation rate of 0.4 ACH is implemented in the case study and the infiltration rate is set to 0.4 ACH as well.

3.2.1.4 Internal gains

Internal gains are of great importance for the building performance simulation, which impact the heating demand and thermal comfort [52]. Three main sources are taken into account in most cases: Occupant, lighting and equipment such as computers and cooker [53]. Thus, internal gains are closely related to occupancy profile since when the room is occupied, high internal gains occur, especially with cooking activities, yet during the unoccupied time, small internal gains are created by the appliances in stand-by mode. In total, a medium level of the daily average internal gains as 4 W/m^2 is implemented in this case study [54].

Occupant

As to the occupant aspect, two kinds of activities are defined as slightly work in day-zone and sleeping in the night-zone, with the heat gains as 130 W and 90 W per person respectively [53][55][56].

Lighting

The overview of minimum lighting levels for residential spaces is listed in Table 3.3.

***Table 3.3**: General minimum room lighting levels* [18]

Residential spaces	Lighting level [Lux]
Kitchen	300
Bedroom	300
Bathroom	300
Living room	300
Laundry	200
Dining room	200

The lighting levels for the case study are assumed as 300 lux, equivalent to 2.37 W/m^2, for both day-zone (a living room and a kitchen) and night-zone (bedrooms).

Equipment

In this thesis, the heat gains of typical equipment are shown in Table 3.4.

***Table 3.4:** Heat gains of typical equipment in residential buildings*[53][55]

Equipment	Heat gains (W)
Cooker	100
Refrigerator	30
PC	50
Equipment in stand-by mode	10

3.2.2 System renovation

For system renovation, boilers are replaced by heat pumps and PV panels are installed in order to exploit the energy flexibility potential of structural thermal energy storage.

As discussed in 3.2.1.2, boilers which are normally used for heating system in most existing Dutch single-family houses built between 1965 and 1974, will be renovated to heat pump as an electric heating system, in order to create the interaction between electricity system and heating system and exploit the energy flexibility potential of structural thermal energy storage. This shift contributes significantly to the peak electricity demand [11]. The renovated system scheme is shown in Figure 3.4, where PV system is also implemented as the local electricity supplier.

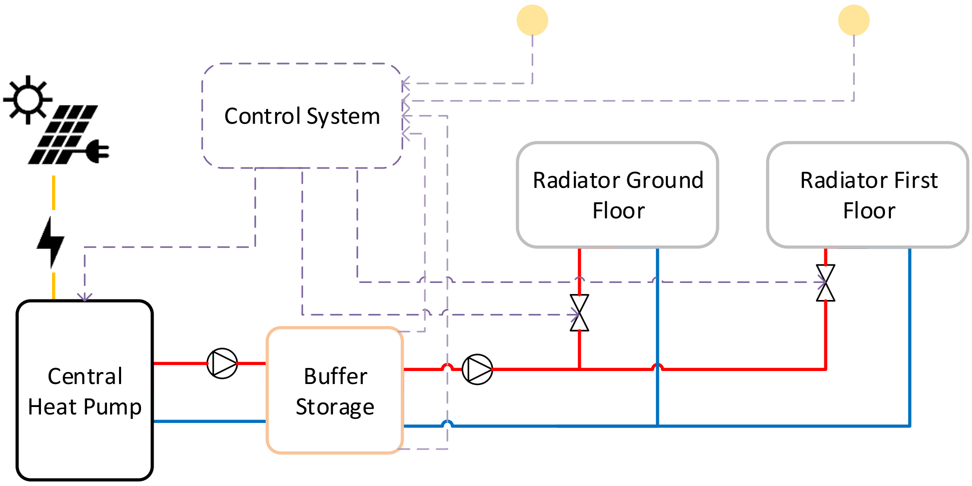

Figure 3.4: *Scheme of renovated heating system with PV panels as the local electricity supplier*

3.2.2.1 Heat generation system replacement

Heat pump has been widespread used in European countries [57] and based on the assumption of 500,000 installed heat pumps in 2020 in the Netherlands, for the period from 2013 to 2020, around 40% of the newly implemented heat pumps are expected to be placed in single-family houses [58]. There are various types of heat pump available in the market, such as water/water or ground source heat pump, air/air heat pump and air/water heat pump, etc. An air/water heat pump is implemented in the base case building, combined with an auxiliary heater, due to the good performance in heating dominated climate, for space heating without the consideration of DHW.

It is demonstrated in Figure 3.4 that a buffer storage tank is equipped with the heat pump to reduce the number of operation cycles of an on/off controlled heat pump [59], which is a cost-effective way to improve overall system operating efficiency [60]. According to the recommendation of BS EN 14511, a heat pump should be controlled not to start more than three times in an hour, which means the operation time should be limited no less than 20 minutes, since the high starting current of the compressor-drove motor may have an impact on the local electricity infrastructure. The size of buffer storage is formulated by various rules, for example, 20 L/kW of the heat pump capacity is recommended to optimize the operating time and 20-30 L/kW is advocated for a geothermal heat pump [59]. Besides, BS EN 14511 also suggests that the size of the buffer storage tank should be kept as approximately 25 liters per kW output of the heat pump, which is used in the TENSYS model, in order to defrost [61].

The heat pump works with a heating curve control strategy, which is normally used in fast reacting systems, for instance, high-temperature radiators [13]. The heating curve is defined by the heating curve temperature (T_{hc}), which is the function of ambient temperature [62]:

$$T_{hc} = T_R + \left(\frac{T_{S,N}+T_{R,N}}{2} - T_R\right) \cdot {Q_{Rel}}^{m^{-1}} + \left(\frac{T_{S,N}+T_{R,N}}{2} - T_R\right) \cdot Q_{Rel} \tag{3.2}$$

$$Q_{Rel} = \frac{T_R - T_{Ambient}}{T_R - T_{Design}} \quad (3.3)$$

where T_R is the nominal room temperature, $T_{S,N}$ is the supply water temperature, $T_{R,N}$ is the return water temperature, Q_{Rel} is the relative heat demand, T_{Design} is the minimum ambient temperature designed for the heating system. In TRNSYS, $T_{R,N}$, $T_{S,N}$ and T_R are assigned as 55/45/20℃ respectively. T_{Design} is set to -8℃ according to the Dutch climate. m is the heat transfer exponent of radiators, of which the common value is 1.33 in the market.

The control strategy for heat pump and the auxiliary heater is shown as follows, with the principle of comparing the top tank temperature (T_{top}) and bottom tank temperature (T_{bottom}) with the setpoint temperature of the heating water. Besides, a time delay of 6 minutes is modeled in TRNSYS to reduce operation cycles.

$$\text{Heat pump ON, when } T_{top} < T_{hc} + 3K \quad (3.4)$$

$$\text{Heat pump OFF, when } T_{bottom} > T_{hc} + 4K \quad (3.5)$$

$$\text{Auxiliary heater ON, when heat pump ON AND } T_{Ambient} < 2℃ \quad (3.6)$$

3.2.2.2 PV system implementation

PV system is implemented as the local electricity supplier. Panasonic Photovoltaic module HIT® VBHN330SJ47 with a peak power of 330W is selected due to its high efficiency of 19.7%, of which the datasheet is shown in Figure C.1 in Appendix C. 45 PV modules, of which the total area is are 74 m^2, are installed on the Southern roof with the slope of 36°. In full load, the peak power of the PV system can reach 14.85 kW. In TRNSYS, the PV system is modeled with Tpye94a and the modules are assumed always operating at the maximum power point tracking (MPPT). The annual PV electricity generation profile is demonstrated in Figure 3.5.

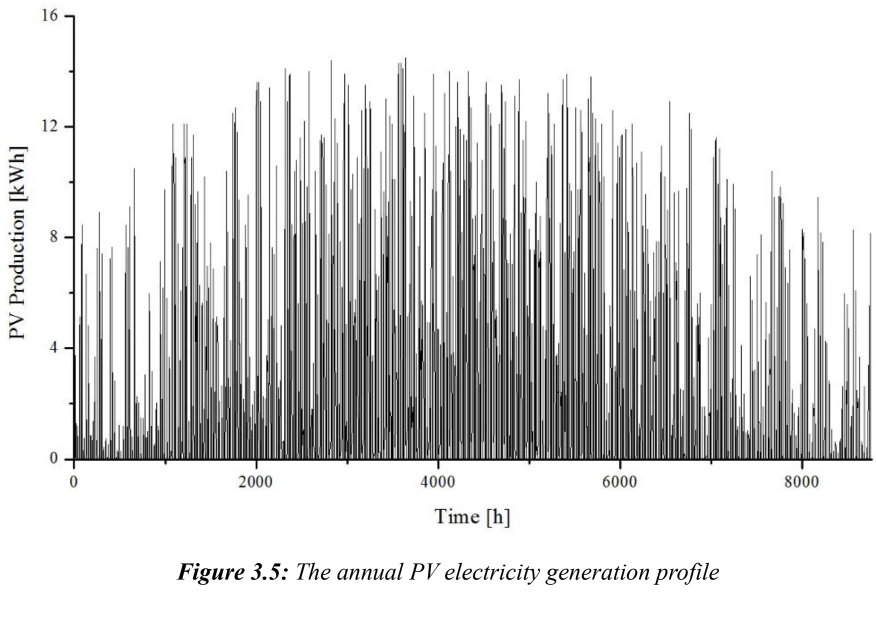

Figure 3.5: *The annual PV electricity generation profile*

3.2.3 Building renovation

Based on the literature study, three design renovation options are considered in the case study: insulation level improvement, changing the insulation location and airtightness improvement.

3.2.3.1 Insulation level improvement

According to the TABULA project, for existing Dutch single-family houses built between 1965 and 1974, two renovation levels for building insulation are defined. Firstly, usual renovation is to insulate the entire building, including façade, roof, floor, windows and doors, to the current standard. Followed by advanced renovation, the insulation level of the entire building is improved to nZEB level. The improvement of insulation level is realized by adding insulation layers, which does not influence the thermal mass [63]. The detailed U-value for each building component in each level are compared in Table 3.5.

Table 3.5: *Insulation level for reference existing state, usual renovation and advanced renovation*

U-value	Existing state	Usual renovation	Advanced renovation
Façade	1.45	0.24	0.18
Floor	2.33	0.25	0.18
Roof	0.89	0.22	0.14
Window	5.2	1.8	1.0
Door	3.5	3.5	1.4

3.2.3.2 Changing insulation location

From the renovation perspective, both internal and external insulation are the alternatives due to the ability to improve the energy efficiency and save energy cost [64]. Internal wall insulation is regarded as an easier and cost-effective option while it results in the loss of the internal space and has to remove all items from the interior face of the external walls [64]. External insulation is applied by adding an insulating layer as well as a decorative waterproof, which improves the weather protection and noise insulation [65]. Additionally, it offers an opportunity to change the look of the building [66]. However, in some cases, it is not suitable to use external insulation, such as insulation improvement for flats. Generally, where to add the insulation layer does not influence the total U-value of the wall and roof, however, it may impact the use of energy flexibility of structural thermal energy storage. For internal insulation, the interior insulation layer reduces the heat storage value, which leads to a quick leave of heat with the air [65]. On the contrary, for external insulation cases, the walls are continuously getting warm by the heating system since the massive part is connected to the indoor environment and shielded by the exterior insulation layer. When the heating is turned off, the heat stored will be released gradually into the room [67]. Therefore, it is crucial to analysis the performance of energy flexibility exploitation for both internal and external insulation in a quantitative way.

3.2.3.3 Airtightness improvement

Based on the TABULA project, low and high airtightness levels are defined by infiltration rate as 0.4ACH and 0.1ACH respectively. For the newly built buildings in the Netherlands, the specific leakage rate is 0.52 dm^3/s per m^2 [49], which is converted as 0.18ACH to 0.35ACH based on the method in 3.1.3. Thus, the infiltration rate of medium airtightness level is assumed as 0.25ACH. The infiltration rates for various airtightness levels are shown in Table 3.6. The higher the airtightness level, the lower the infiltration rate.

Table 3.6: *Infiltration rate for various airtightness levels*

Airtightness	Low level	Medium level	High level
Infiltration rate	0.4	0.25	0.1

3.2.3.4 Combination of the design renovation parameters

Table 3.7 shows an overview of base case and renovated cases. The base case is modeled with low airtightness and existing state insulation level which means no insulation implemented. Therefore, another 14 renovated cases can be designed with the combination of these design renovation parameters. Besides, all 15 cases are equipped with heat pumps as the heat generation system.

Table 3.7: *Overview of base case and renovated cases*

Case type and number		Insulation level	Insulation location	Infiltration rate
Base case	1	Existing state	-	0.4ACH
Renovated case	2	Existing state	-	0.25ACH
	3	Existing state	-	0.1ACH
	4	Usual renovation	Internal	0.4ACH
	5	Usual renovation	Internal	0.25ACH
	6	Usual renovation	Internal	0.1ACH
	7	Usual renovation	External	0.4ACH
	8	Usual renovation	External	0.25ACH
	9	Usual renovation	External	0.1ACH
	10	Advanced renovation	Internal	0.4ACH
	11	Advanced renovation	Internal	0.25ACH
	12	Advanced renovation	Internal	0.1ACH
	13	Advanced renovation	External	0.4ACH
	14	Advanced renovation	External	0.25ACH
	15	Advanced renovation	External	0.1ACH

3.2.4 Scenarios

Scenarios are used to evaluate the performance robustness of renovated design cases during building design optimization [48]. In this thesis, three categories of scenarios are defined: occupant behavior scenarios, weather condition scenarios and operation scenarios which are considering the combination of various electricity price mode and net metering scheme. All scenarios are implemented with the aim of assessing the robustness of energy flexibility for building renovation options.

3.2.4.1 Occupant behavior scenarios

As a result of the improving requirement of building thermal quality, the energy consumption of building sector is decreasing. Therefore, occupant behavior plays an even more important role than ever [36]. Normally, three factors are taken into account when defining occupant behavior: occupancy, internal gains and ventilation [48]. However, in this thesis, only the first two factors are considered since natural ventilation is implemented in the case study building. Furthermore, occupancy consists of three aspects: occupancy pattern, household type and setpoint/setback temperature.

Occupancy pattern

Figure 3.6 and 3.7 show two typical occupancy patterns, defined as 'day & evening' pattern and 'evening' pattern. The former pattern accounts for 48% of the Dutch household and rooms are always occupied in the day time, thus normally for retired occupant. The latter takes up 19% of the Dutch household while it is for working occupant since rooms are unoccupied from 9 am to 6 pm [68].

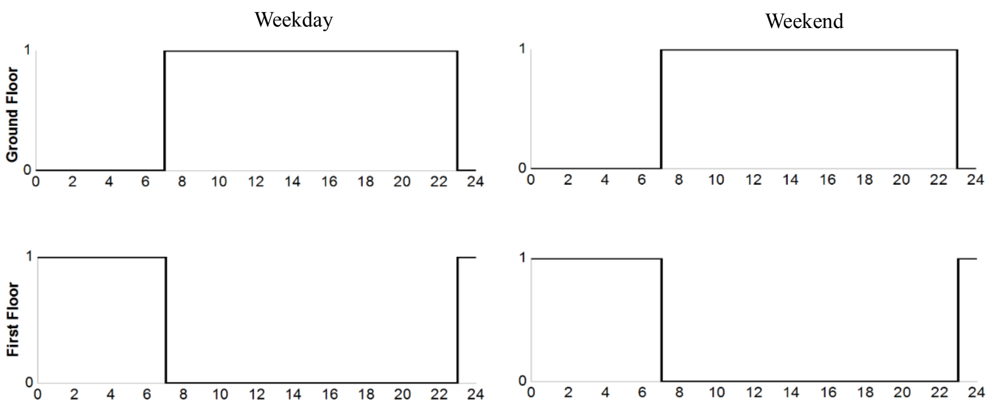

Figure 3.6: *Daily occupancy patterns for retired occupant, occupied (1) and unoccupied (0)*

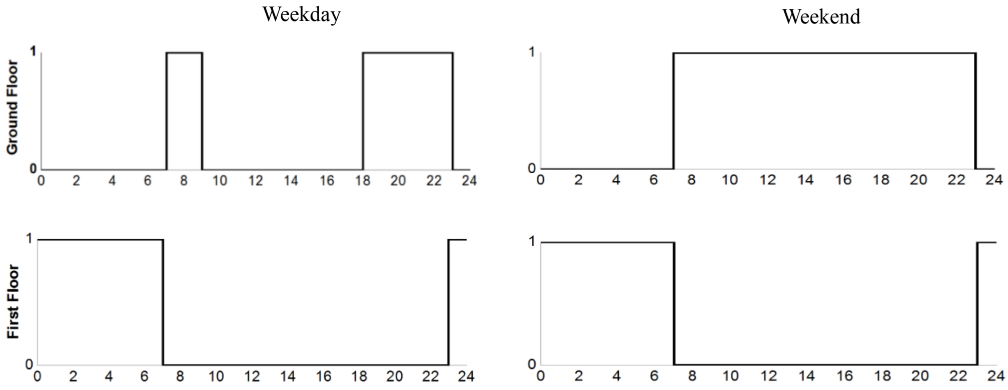

Figure 3.7: *Daily occupancy patterns for retired occupant, occupied (1) and unoccupied (0)*

Household types

The result of Woononderzoek Nederland (WoON) dataset survey about household types for all building types is demonstrated in Figure 3.8. Regarding the type of detached single-family house, which often has 4 to 6 rooms, it is inhabited by 35+ers (98%), of which 43% are over 65 years old and by double households, with children (38%) or without children (45%) [15]. Therefore, the household type '1 adult or senior' is not considered in this thesis. The other four typical household types: 2 adults, 2 adults with 1-3 children, 3-4 adults and 2 adults (at least 1 senior), in total accounting for over 65% of Dutch households, are taken into account.

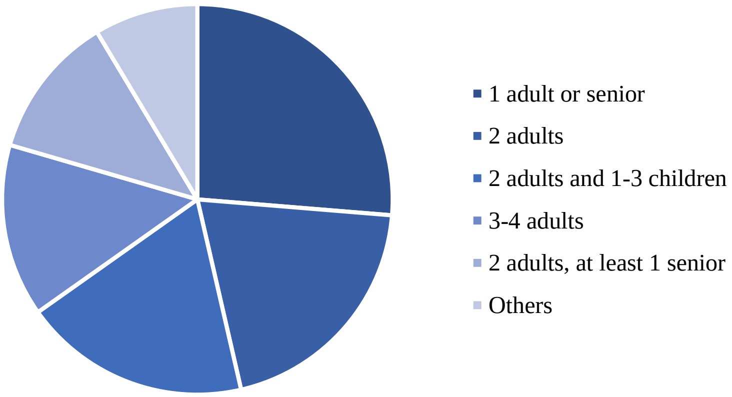

***Figure 3.8**: Typical household types in the Netherlands*

Occupant behavior scenarios

Four typical household types are defined with corresponding occupancy pattern and setpoint/setback temperature, which is shown in Table 3.8. The setpoint temperature is used during occupied hours while setback temperature for unoccupied hours. Besides, both temperature for day-zone and night-zone are assumed as the same.

Table 3.8: *Overview of occupant behavior scenarios for existing Dutch single-family houses*

Occupant behavior scenarios	Occupancy pattern	Occupant	Setpoint/setback temperature
1	Evening	Parents with 2 children	20℃
2	Evening	2 seniors (65+)	21℃/19℃
3	Day & Evening	2 adults (35-64 years old)	20℃/16℃
4	Day & Evening	4 adults (18-34 years old)	20℃/16℃

Internal gains

Internal gains are highly related to occupancy and calculated based on the description in 3.2.1.4. The daily average internal gains are around 4 W/m^2. The detailed data of internal gains for each occupant behavior scenario are shown from Table D.1 to D.4 in Appendix D.

3.2.4.2 Weather condition scenarios

In order to assess the influence of different weather condition on energy flexibility performance for each building renovation options, two typical days are selected. January 22 represents for the typical heating season, with the average ambient temperature of 6.3℃ and a low PV production. May 12 is on behalf of the transition season, when the average ambient temperature is 9℃ and the peak of PV generation is around 13 kW, over 90% of full load. The relevant daily profiles of these two typical days are illustrated in Figure 3.9.

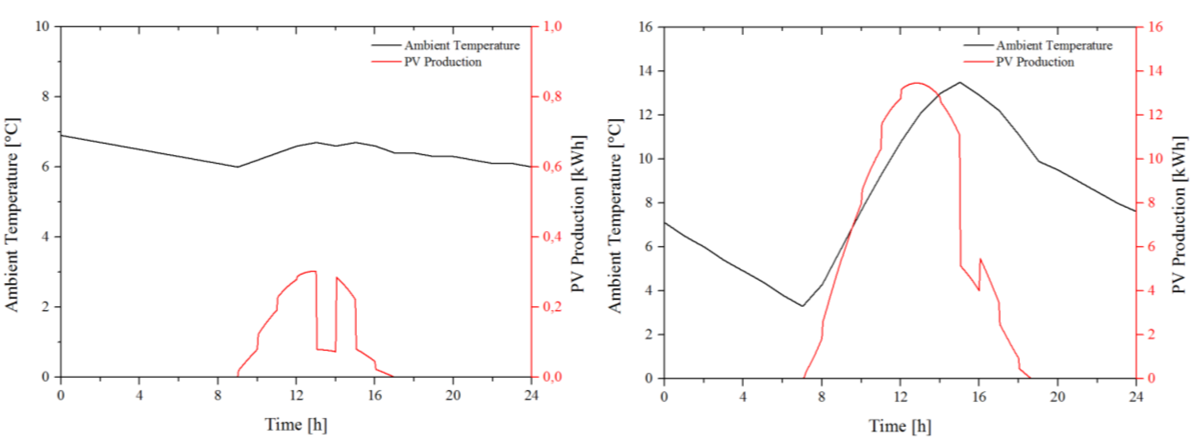

Figure 3.9: *Daily ambient temperature and PV production of January 22 (left) and March 12 (right)*

3.2.4.3 Operation scenarios

Electricity price

Energy flexibility is normally activated with high ADR incentives such as high RES production and low electricity price in the operation phase. PV generation is determined by the weather condition scenarios, as for electricity price, two modes are provided by present Dutch electricity market to the individual consumers: the fixed and dynamic electricity price schemes [69] which are regarded with the ability to realize the demand shifting and reduction [70][71][72]. Generally, the electricity price is based on the time-of-use (ToU) and critical-peak pricing (CCP) programs. Additionally, real-time pricing (RTP) is considered as a (near) future scheme [73]. Time-of-use electricity price is set in advance of the period while not related to the real situation of the electricity market. It varies over the day with the aim of demand shifting between different periods, for example, encouraging consumers to use less energy when overall energy consumption is higher [73]. As for critical-peak pricing, considerably higher tariffs are charged during critical peak hours while lower year-round tariffs during off-peak hours [73]. Furthermore, real-time pricing is closely related to the electricity price of the whole electricity market, which reflects the real conditions compared to the first two electricity price schemes [74]. In this thesis, since a future-oriented recommendation is discussed, RTP is considered as the base of dynamic electricity price. In the present stage, RTP is implemented as a day-ahead RTP predicted by the electricity price on the APX [73][75].

The fixed electricity price is assumed as 0.159 EUR/kWh, which is the average value of second half 2016 for household consumers in the Netherlands [76]. The total price consists of three parts which are shown in table 3.9.

Table 3.9: *Total fixed electricity price and its components* [76]

Total price (EUR/kWh)	Energy and supply (EUR/kWh)	Network costs (EUR/kWh)	Taxes and levies (EUR/kWh)
0.159	0.065	0.054	0.040

When predicting the RTP profile, of which the detailed methodology is described in Appendix E, network costs and taxes/levies are kept as constant as the values shown above. The hourly electricity price posted on the APX is used to calculate the fluctuation of the price curve which is illustrated in Figure 3.10, with the highest variation between the top and bottom as 2.5 cents/kWh.

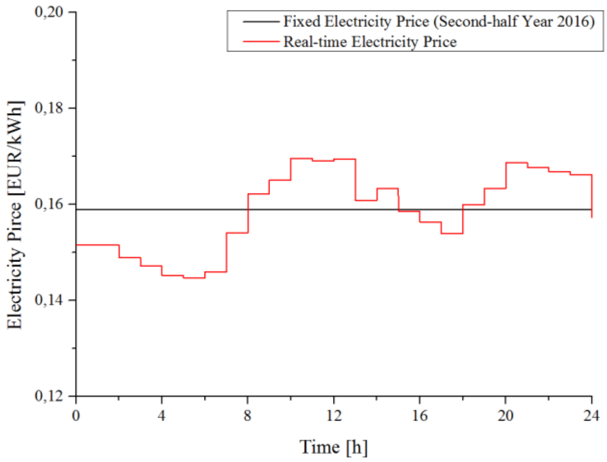

Figure 3.10: *The fixed electricity price and daily real-time electricity price*

Net metering scheme

The net metering scheme, which is likely to be extended from 2020 to 2023, is one of the main driving force for the increasing market volume of PV [77] and has led to an approximately 1.5 GW installed residential PV capacity in the Netherlands [78]. The SDR+ premium feed-in scheme is the main support instrument to apply for an operating subsidy for the RES production [79][80]. When the production of RES is not profitable compared to that of fossil fuel, SDE+ compensates for the non-profitable portion, which is the difference between the cost of RES and the market value of the energy supplied [80]. According to SDE+ 2017, only PV panels with a capacity higher than 15 kWp and a large-scale energy connection to the grid are qualified for the subsidy. In this thesis, although the capacity of 14.85 kWp is slightly lower, from the future perspective, if the PV panels are connected together within a district, it is allowed to apply the subsidy from SDE+. Therefore, the net metering scheme is also considered in this thesis. Different phases are defined based on time period with various subsidy in SDE+, however, it is simplified to have a fixed subsidy in the simulation period as 0.057 EUR/kWh [80].

Overview of operation scenarios

Considering three aspects: PV production, electricity price and net metering, the overview of operation scenarios which only impact operation cost, is shown in Table 3.10.

Table 3.10: *Overview of operation scenarios*

Operation scenarios	PV production	Electricity price	Net metering
1	Low	Fixed	Yes
2	Low	Real-time	Yes
3	Low	Real-time	No
4	High	Fixed	Yes
5	High	Real-time	Yes
6	High	Real-time	No

Overview of building cases and scenarios

Table 3.7 gives a summary of the 15 building cases, together with scenarios discussed in this chapter, the overview of building cases and scenarios are listed in Table 3.11. Therefore, 120 and 720 combinations are considered in design phase and operation phases respectively.

Table 3.11: *Overview of building cases and scenarios*

Building cases and scenarios	Distribution	Remarks
Building cases	U [1:15]	Base case and 14 renovated cases
Occupant behavior scenarios	U [1:4]	Combination of occupancy pattern; occupant, setpoint/setback temperature and internal gains
Weather condition scenarios	U [1:2]	Typical heating season (22nd January); Transition season (12th May)
Operation scenarios	U [1:6]	Combination of PV production, electricity price and net metering scheme

3.3 Quantitative assessment

In order to assess the output of simulations, two groups of performance indicators are selected for design and operation phases respectively. Energy flexibility indicators are defined for quantifying and investigating the performance of energy flexibility of structural thermal energy storage for 15 building cases combined with occupant behavior and weather condition scenarios. Additionally, operation indicators, operation cost and CO_2 emission, are selected to search for the most beneficial and environmentally-friendly ADR starting time and operation scheme of using energy flexibility considering all building cases and scenarios.

3.3.1 Energy flexibility indicators

As described in Chapter 2, two indicators: available storage capacity (C_{ADR}) and storage efficiency (η_{ADR}) are defined to quantify energy flexibility of structural thermal energy storage. For a better understanding of the principle, two working conditions of the heat pump are shown in Figure 3.11. The upper one demonstrates ADR-event starts at t=0 when the heat pump is not working, which means high heating potential is available for ADR-event and the heat pump turns to work in its full load in order to increase the setpoint temperature. The lower graph illustrates ADR-event starts at t=0 when the heat pump is working in its full load, thus, no extra heat can be input to the heating system for the ADR-event and the temperature cannot be increased at that time. However, when heat pump turns off, since ADR-event is still being implemented to the system, the indoor temperature rises while cannot be ensured up to the new thermal comfort level, which results in a lower available storage capacity.

Additionally, it is emphasized that the temperature fluctuates around 20℃ with the dead band of ± 1℃ in periods without ADR-event, however, it is not shown in Figure 3.10, in order to give a simplified conceptual scheme.

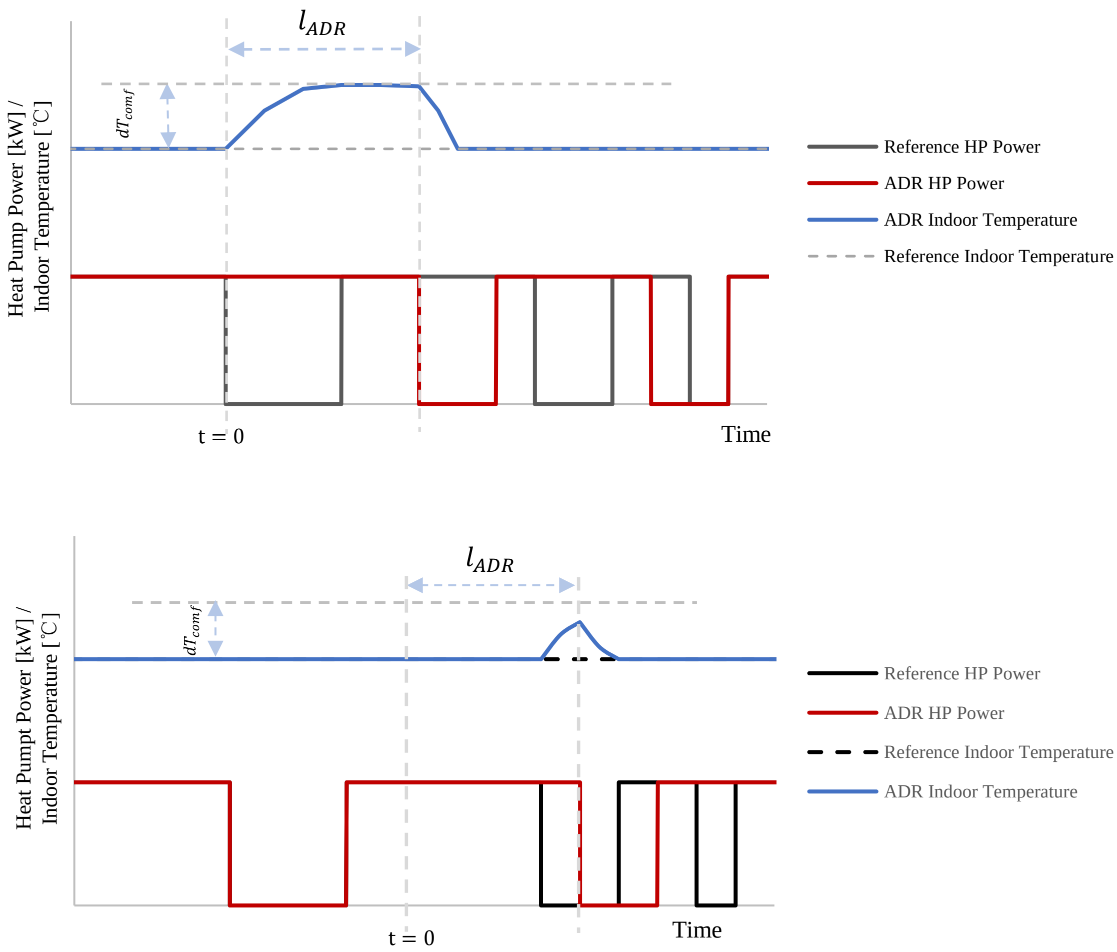

Figure 3.11: *Scheme of ADR-event used to quantify the available storage capacity and the storage efficiency*

The equations (2.1 and 2.4) to quantify these three indicators are simplified as follows with the dynamic boundary condition:

$$C_{ADR} = \int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref}) dt \tag{3.7}$$

$$\eta_{ADR} = 1 - \frac{\int_0^{hor} (Q_{ADR} - Q_{Ref}) dt}{\int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref}) dt} \tag{3.8}$$

with l_{ADR} is the ADR-event duration, hor is the prediction horizon, Q_{ADR} and Q_{Ref} are the heat input during the ADR-event and in reference operation.

The detailed parameters involved in the indicators are assigned to adapt to the case study. A univariate parameter analysis has been done to investigate the impact of the ADR-event duration (30mins, 90mins, 240mins, 480mins) and the temperature increase (1℃, 4℃) during ADR-event on available storage capacity and storage efficiency [1], with a constant outdoor temperature. The result concluded that with the increase of the ADR-event duration, available storage capacity increases while storage efficiency decreases. Therefore, considering the trade-off between two energy flexibility indicators, l_{ADR} will be 4 hours in this thesis. As for the temperature increase, cases with $\Delta T = 4°C$ result in a substantially higher available storage capacity than cases with the $\Delta T = 1°C$, without influencing the storage efficiency. However, it has to be emphasized that a higher temperature increase means a higher nominal heating demand with the request of a larger heating system capacity. Hence, the temperature increase during ADR-event is set as 2°C. Besides, since energy flexibility is used to reduce the mismatch between energy consumption and local PV generation with a daily profile, prediction horizon is assigned as 24h, which means the energy flexibility will be quantified in the following 24 hours after the ADR-event starting.

All cases combined with various scenarios are simulated from the beginning of the year in order to ensure the model is working in a stable condition when ADR-event starts, although the ADR-events starts at 0 am in the two typical days selected in 3.2.4.2.

Furthermore, according to the definition and quantification of available storage capacity and storage efficiency in Chapter 2, it is indicated that only a part of heat added into the structural storage can be used effectively due to the transmission and ventilation losses. Especially, taking into account the dynamic boundary condition, it is possible that a high available storage capacity corresponds to a low storage efficiency. Therefore, effective storage capacity (C_{EFF}[kWh]) is defined as an additional indicator to consider the trade-off, which is the product of available storage capacity and storage efficiency:

$$C_{EFF} = C_{ADR} \times \eta_{ADR} \tag{3.9}$$

3.3.2 Operation indicators

In operation phase, both the CO_2 emission and operation cost are the important aspects that should be considered to assess which building case and ADR-event starting time have the best performance in greenhouse gas emission reduction and operation cost saving.

3.3.2.1 CO_2 emission

In the building sector, CO_2 emission mainly comes from the use of gas and electricity in the Netherlands [81]. In this thesis, gas use is not considered since heat generation system is renovated to a heat pump. Moreover, two sources of electricity consumption are the grid and PV, however, only the former contributes to the total CO_2 emission in the following 24 hours after the starting of ADR-event with a standard emission factor of 0.413

kgCO_2/kWh [82]. As only operation phase is taken into account, the CO_2 emission factor is regarded as zero for PV [83]. The CO_2 emission can be formulated as:

$$CO_2 \text{ emission} = \int_{t_{ADRStarting}}^{t_{ADRStarting}+24} (CO_2 \text{ emission factor of electricity} \times electricity\ from\ grid)\text{dt} \quad (3.10)$$

3.3.2.2 Operation cost

In this thesis, operation cost means the accumulated energy price in the following 24 hours after the starting of ADR-event. When calculating this indicator, the electricity consumption by heat pump, auxiliary heater, plug load and lighting are taken into account. Energy use by ventilation is not considered since natural ventilation is implemented in the TRNSYS model. Electricity is firstly supplied by local PV generation with no operation cost and grid acts as a backup to compensate the extra part. Therefore, the operation cost is calculated as:

$$\text{Operation cost} = \int_{t_{ADRStarting}}^{t_{ADRStarting}+24} (Instantaneous\ electricity\ price \times Electricity\ from\ grid)\ \text{dt} \quad (3.11)$$

$$\text{Electricity from grid} = \text{Total electricity consumption} - \text{Consumed electricity from PV} \quad (3.12)$$

When net metering is considered, equation 3.11 is revised as:

$$\text{Operation cost}_{Netmetering} = \int_{t_{ADRStarting}}^{t_{ADRStarting}+24} (instantaneous\ electricity\ price \times electricity\ from\ grid - net\ metering\ subsidy \times electricity\ feed-in\ from\ PV)\ dt \quad (3.13)$$

$$\text{Electricity feed-in from PV} = \text{Total PV production} - \text{Consumed electricity from PV} \quad (3.14)$$

The instantaneous electricity price corresponds to the fixed/real-time electricity price profiles and the net metering subsidy is assumed as 0.057 EUR/kWh, both described in 3.2.4.3.

4

Results and Discussion

4.1 Base case analysis

The base case refers to building model with no insulation and high infiltration rate as described in 3.1, additionally equipped with a heat pump as the heat generation system. In this section, the energy flexibility indicators and operation indicators are calculated with dynamic boundary condition reflecting by various ADR-event starting time. The occupant behavior is assigned as scenarios 1 in table 3.8, which is the combination of evening pattern, 4 occupants (parents and 2 children) and the setpoint temperature of 20℃. The result is obtained under the weather condition of January 22 representing the typical heating season.

4.1.1 Energy flexibility with dynamic boundary condition

Based on equation 3.7 and 3.8, available storage capacity and storage efficiency are calculated as 18.29 kWh and 0.514 when ADR-event starts at $T = 0h$ with the corresponding weather condition. In order to assess the energy flexibility with dynamic boundary condition, available storage capacity and storage efficiency are quantified as a function of ADR-event starting time. That means ADR-event starts every 2 hours at $T = 0h, 2h, \cdots, 24h$ in total 13 separate simulations. Together with the reference operation case without ADR-event, 14 simulations are run to obtain the curves demonstrated in Figure 4.1.

It is indicated that for the base case, available storage capacity varies from 10 kWh to 18 kWh. It is equivalent to a storage tank with the volume of 430L to 770L to store the same amount of heat as structural thermal energy storage with the assumption that the temperature is increased as 20C° in a hot water storage tank. Therefore, the potential of place saving is one significant advantage of structural thermal energy storage.

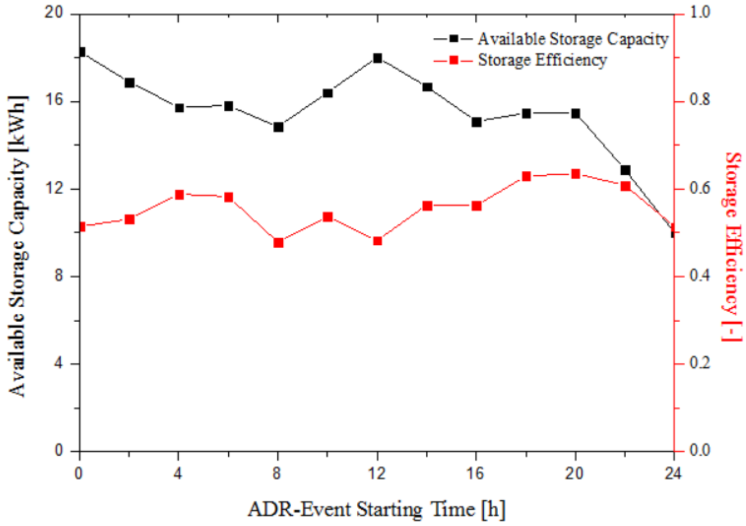

Figure 4.1*: Available storage capacity and storage efficiency varying with ADR-event staring time for January 22 with occupant scenario 1.*

For the purpose of investigating the robustness of energy flexibility for dynamic boundary condition, median and quartile deviation of available storage capacity and storage efficiency for different ADR-event starting time are illustrated respectively in Figure 4.2.

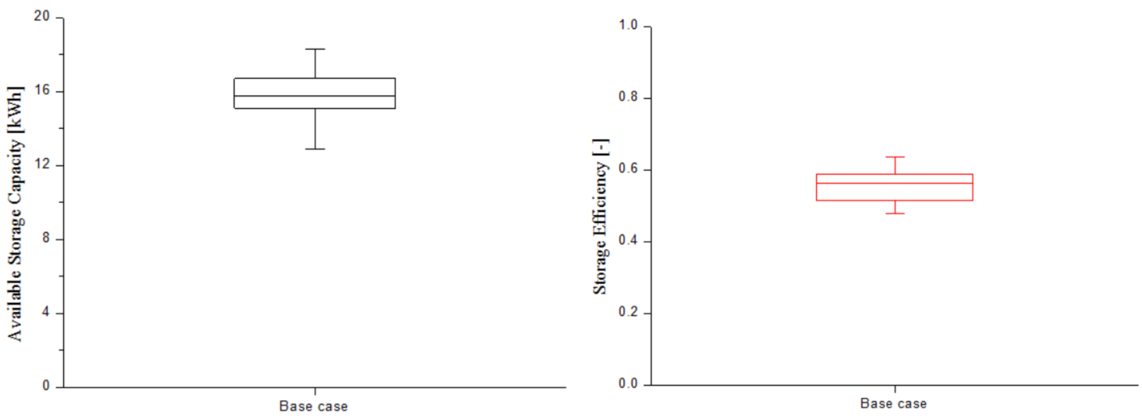

Figure 4.2: *Median and quartile deviation of energy flexibility indicators for different ADR-event starting time for January 22 with occupant scenario 1.*

Median and quartile deviation are taken into account when comparing the performance of exploiting energy flexibility of structural thermal energy storage for each building renovation option. Compared to mean, median, which represented by the middle line in the boxplot, is better to represent a 'typical' value as it is not skewed too much by extremely large or small values [84]. Quartile deviation which is the range of the boxplots relative to the median is selected as a robustness indicator to assess the variation causing by ADR-event starting time, occupant behavior and weather condition. As for the base case, the median of available storage capacity and storage efficiency are 15.74 kWh and 0.563 respectively. Besides, the quartile deviation of two energy flexibility indicators are 1.820 kWh and 0.047 separately.

As defined, effective storage capacity considers the trade-off between available storage capacity and storage efficiency. Therefore, in Figure 4.3, the median of effective storage capacity is around half of that of available storage capacity and the range relative to the median is smaller.

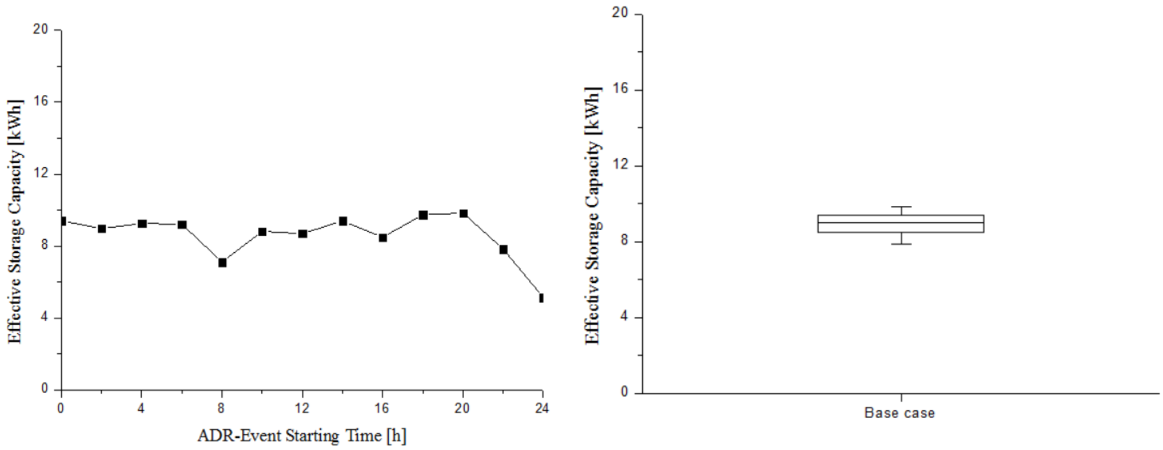

Figure 4.3*: Effective storage capacity varying with ADR-event staring time (left) and corresponding boxplot (right) for January 22 with occupant scenario 1.*

4.1.2 CO_2 emission

The CO_2 emission is calculated for the following 24 h after the ADR-event starts. The results in Figure 4.4 demonstrate the CO_2 emission as the function of ADR-event starting time for base cases with and without implementing ADR-event. However, with low PV production or in cloudy days, ADR-event does not contribute to reducing CO_2 emission since the electricity generated by PV panels is not enough to cover the extra heat inputted for ADR-event.

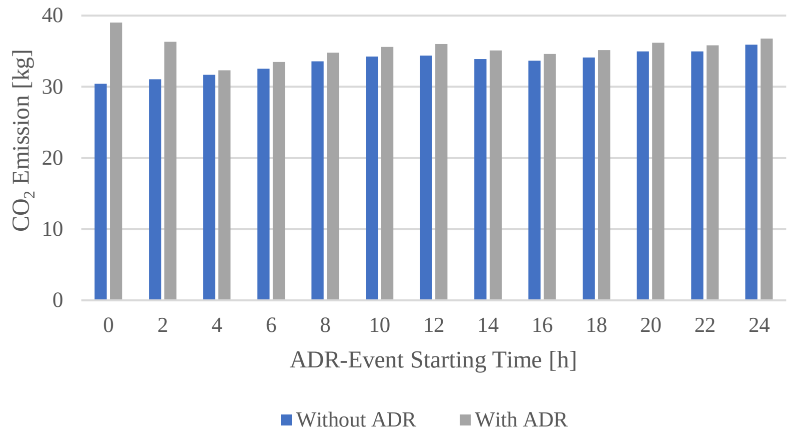

Figure 4.4: *CO2 emission as the function of ADR-event starting time for cases with and without ADR-event for January 22 with occupant scenario 1.*

4.1.3 Operation cost

The operation cost is calculated for the following 24 h after the ADR-event starting as well. The results are presented as the function of ADR-event starting time for base cases with and without implementing ADR-event considering three operation scenarios: (1) Fixed electricity price with net metering scheme; (2) Real-time electricity price with net metering scheme, and (3) Real-time electricity price without net metering scheme, according to chronological order of (predicted) implementation in the market, of which the results are shown in Figure 4.5-4.7 respectively. Like the results of CO2 emission, with low PV production or in cloudy days, ADR-event is not profitable for all three scenarios.

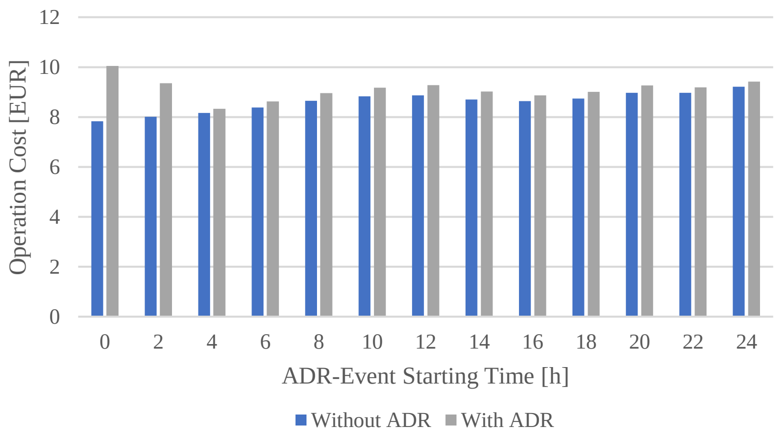

Figure 4.5: *Operation cost as the function of ADR-event starting time for cases with and without ADR-event with fixed electricity price and net metering scheme for January 22 with occupant scenario 1.*

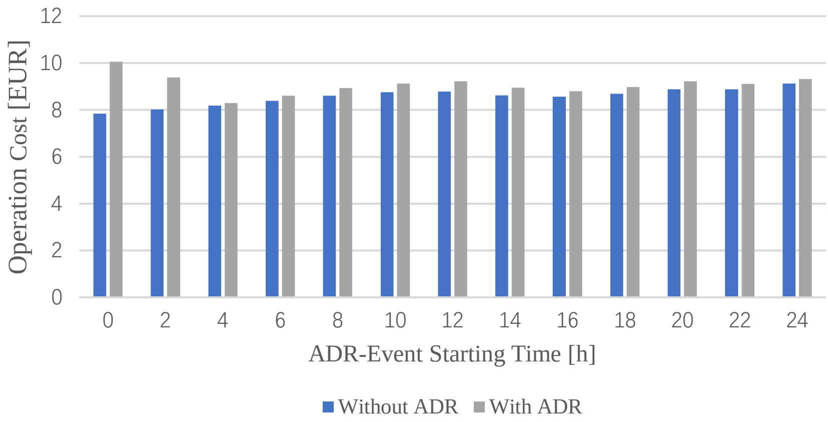

Figure 4.6: *Operation cost as the function of ADR-event starting time for cases with and without ADR-event with real-time electricity price and net metering scheme for January 22 with occupant scenario 1.*

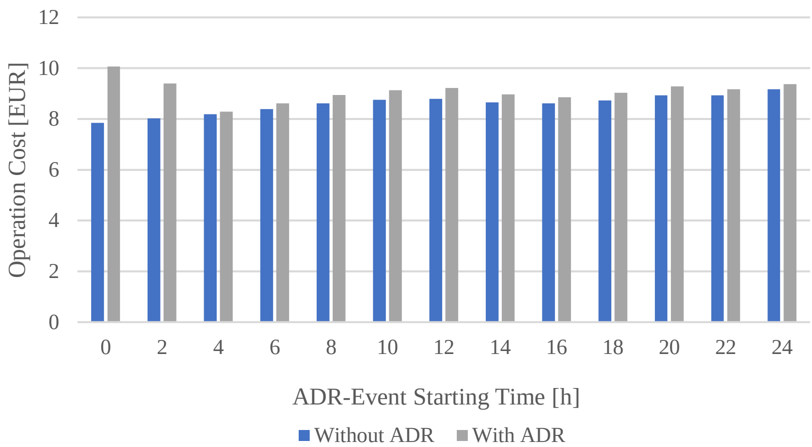

Figure 4.7: *Operation cost as the function of ADR-event starting time for cases with and without ADR-event with real-time electricity price and no net metering scheme for January 22 with occupant scenario 1.*

4.2 Impact of building renovation parameters on energy flexibility

In this thesis, three building renovation parameters, namely insulation level, insulation location and infiltration rate, are selected. In order to evaluate their impact on energy flexibility with a dynamic boundary condition, the time-dependent ADR characteristics are investigated for the total 15 building renovation options of the existing Dutch single-family houses [63]. In the following analysis, the results are based on the occupant behavior assigned as scenarios 1 in table 3.8, which is the combination of evening pattern, 4 occupants (parents and 2 children) and the setpoint temperature of 20C° and the weather condition of January 22. They are representative for the other 119 combinations described in 3.2.4.3. Median and quartile deviation are still the main indicators to assess the 'typical' storage capacity of building structural thermal energy storage and the robustness respectively.

4.2.1 Impact of insulation level

The resulting available storage capacity and storage efficiency are illustrated in Figure 4.8 and 4.9 respectively as a function of the insulation level. As expected, existing state insulation level leads to the highest typical available storage capacity of 15.74 kWh. Besides, the typical available storage capacity decreases by 45.6% and 33.7% with the improvement of insulation level from existing state to advanced renovation for internal and external cases separately, of which the reason is the decreases of the available thermal energy for the ADR-event.

As for the typical storage efficiency, it is 17.3% higher for usual renovation internal insulation level than that of existing state while there is almost no difference between two renovated internal insulation levels. Additionally, the same trend has found in external insulation cases. It can be concluded that without high levels of insulation, the stored heat dissipated quickly, which follows the expectation obtained by the conclusion with a constant boundary condition.

In Figure 4.10, effective storage capacity shows the same trend with available storage capacity. The typical values of the former are around half of the latter, with the consideration of storage efficiency, and the differences between each insulation level are narrowed. Furthermore, the range of the boxplots relative to the median decreases with the increase of insulation level, which means a higher the insulation level leads to a higher robustness.

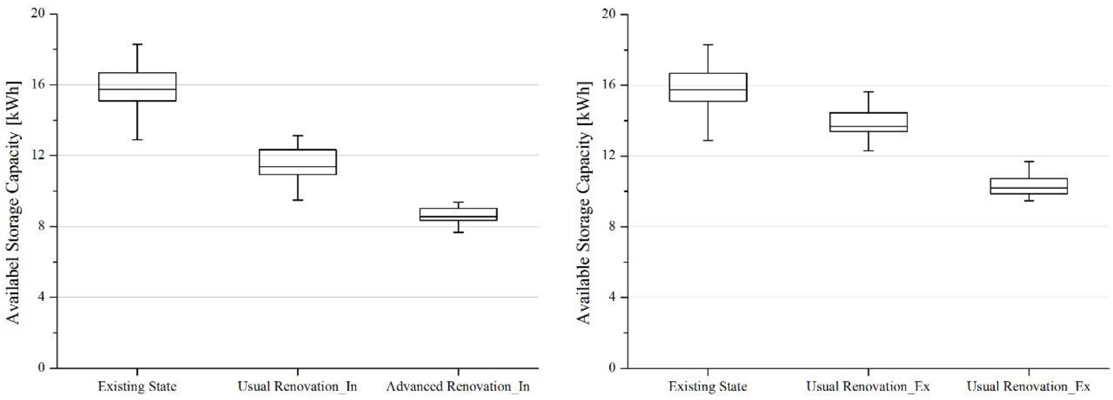

Figure 4.8: *Available storage capacity as a function of the insulation level for internal insulation (left) and external insulation (right). The results are shown for infiltration rate of 0.4 ACH, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

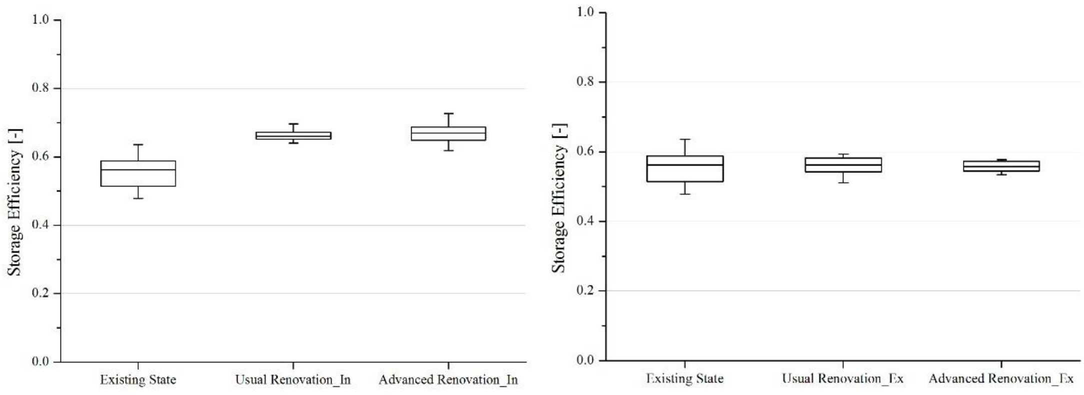

Figure 4.9: *Storage efficiency as a function of the insulation level for internal insulation (left) and external insulation (right). The results are shown for infiltration rate of 0.4 ACH, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

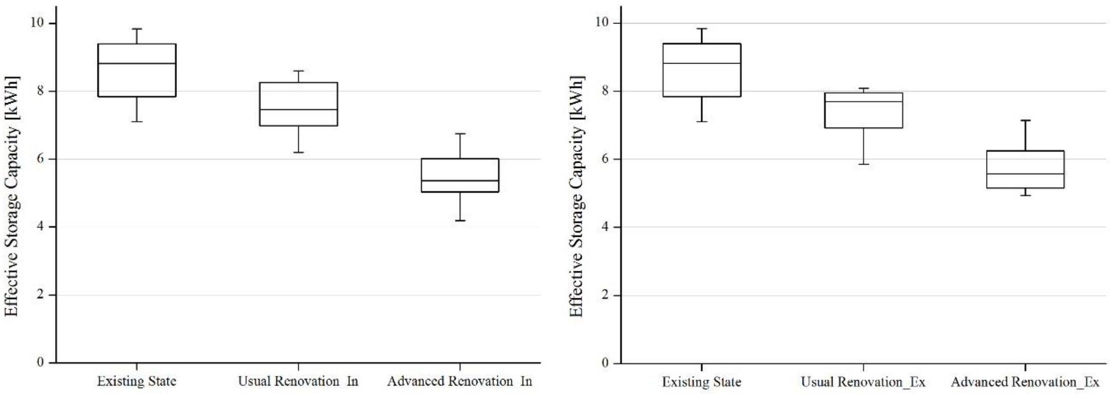

Figure 4.10: *Effective storage capacity as a function of the insulation level for internal insulation (left) and external insulation (right). The results are shown for infiltration rate of 0.4 ACH, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

4.2.2 Impact of insulation location

The results of available storage capacity and storage efficiency are demonstrated in Figure 4.11 as a function of the insulation location in two insulation levels. It is indicated clearly that external insulation corresponds to a higher typical available storage capacity and lower typical storage efficiency in both insulation levels. As explained in 2.4, for external insulation, the massive parts of external walls, roof and floor are directly connected to the indoor environment, thus, the heat generated by increasing the setpoint temperature in ADR-event can easily be stored without barriers, which results in a higher temperature of external construction than that of internal insulation. Therefore, heat losses more in cases with external insulation than internal insulation due to the higher temperature difference between ambient temperature and external construction. However, storage efficiency is determined by the ratio of heat losses to the amount of heat stored in the thermal mass. Although both heat losses and available storage capacity are higher in external insulation cases, the growth of heat losses is less than that of available storage capacity, leading to a lower overall storage efficiency.

As shown in Figure 4.12, for external insulation cases, although the lower storage efficiency offsets part of the extra available storage capacity compared to internal insulation cases, the typical effective storage capacity is still a little bit higher. Therefore, it can be concluded that external insulation has a better performance in exploiting energy flexibility than internal insulation.

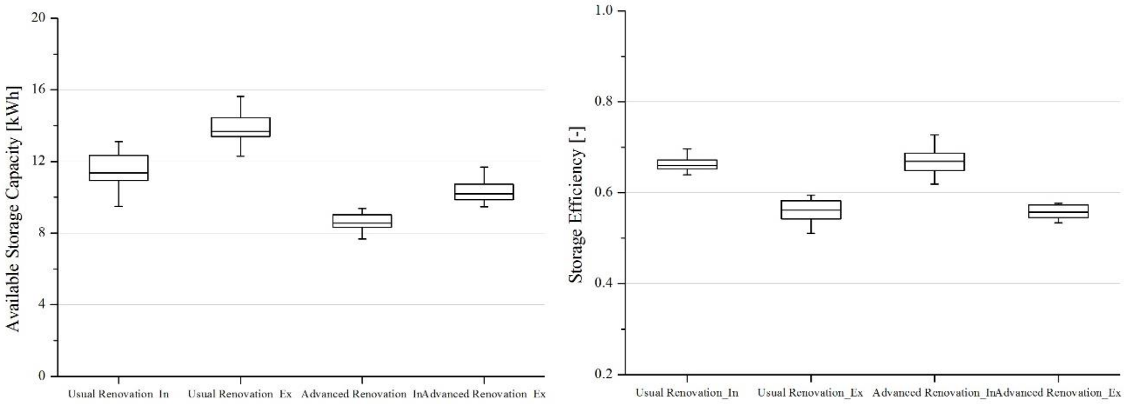

Figure 4.11: Available storage capacity (left) and storage efficiency (right) as a function of the insulation location for two insulation levels. The results are shown for infiltration rate of 0.4 ACH, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.

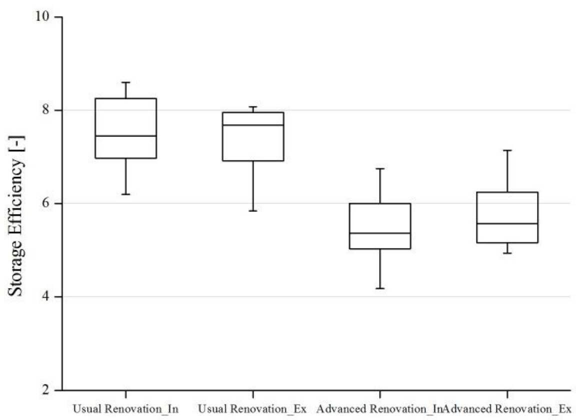

***Figure 4.12**: Effective storage capacity as a function of the insulation location for two insulation levels. The results are shown for infiltration rate of 0.4 ACH, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

4.2.3 Impact of infiltration rate

As demonstrated in Figure 4.13, when decreasing the infiltration rate from 0.4ACH to 0.1ACH, typical available storage capacity reduces by 20.3% due to the reduction of available heat for ADR-event. The typical storage efficiency reaches the maximum with the medium level of infiltration rate, however, theoretically, it should increase with the improvement of airtightness. The reason is that when decreasing infiltration rate from 0.25ACH to 0.1ACH, the reduction of heat losses is less than that of available storage capacity, which results in the decrease of storage efficiency.

In Figure 4.14, the effective storage capacity shows the similar trend with available storage capacity considering the impact of storage efficiency. For the case with 0.1ACH infiltration rate, although the typical value is the lowest, the fluctuation with different ADR-event starting time is the most slightly.

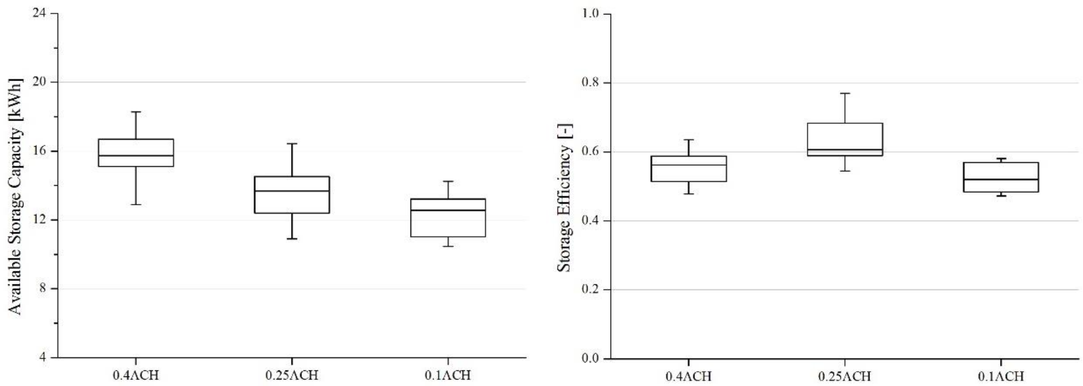

Figure 4.13*: Available storage capacity (left) and storage efficiency (right) as a function of infiltration rate. The results are shown for existing state insulation level, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

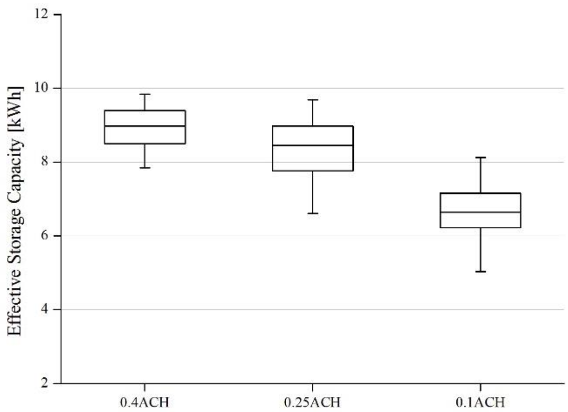

Figure 4.14*: Effective storage capacity as a function of infiltration rate. The results are shown for existing state insulation level, occupancy scenario 1 described in table 4.1 and weather condition of January 22 considering the variation of ADR-event starting time.*

4.3 Impact of occupant behavior and weather condition on energy flexibility

In this section, the first main research question is answered. A multivariate parameter analysis is carried out in this section for the impact of occupant behavior and weather condition on energy flexibility and finding a building renovation solution with a high energy flexibility and high robustness, indicated by a high absolute value (median) and a small relative performance range of effective storage capacity (quartile deviation).

The results of effective storage capacity are illustrated in Figure 4.15 as a function of building renovation options considering 4 occupant behaviors described in table 3.8 for the typical heating season. As discussed in 4.2, with the improvement of insulation level and airtightness, the effective storage capacity shows a decreasing trend due to the reduction of available heat for ADR-event of the heating system. Therefore, although the first three renovation options present the competitive typical effective storage efficiency represented by the median, it implies a higher heating demand and leads to a higher operation cost and CO_2 emissions. Besides, cases with external insulation have a better performance in exploiting energy flexibility of building structure thermal energy storage except for one disadvantage as the relatively heavier fluctuation of effective storage capacity. Moreover, the highest airtightness level corresponding to the 0.1 ACH infiltration rate has a negative impact on effective storage capacity and cannot ensure a higher robustness to the occupant behavior. From the quantitative perspective, the median and quartile deviation of effective storage capacity for each building renovation option are calculated. The results indicate the renovation option 7 with usual renovated external insulation level and 0.4ACH infiltration rate has the highest typical effective storage efficiency as 6.14 kWh without considering the first three options. Renovation option 7 acquires a decent quartile deviation as 1.76 kWh compared to cases with advantage renovated insulation which shows a satisfying robustness to the occupant behavior with the values in the range of 0.94-1.63 kWh. Since a balance whereby a high available capacity and an acceptable storage efficiency can be obtained at the same time is expected, renovation option 7 is regarded as the best solution to exploiting energy flexibility in typical heating seasons.

The results demonstrated in Figure 4.16 describes the occupancy-concerned effective storage capacity as a function of building renovation options for transition seasons, in order to assess the impact of weather condition. It presents the decreasing typical values of effective storage capacity in transition seasons compared to the typical heating season, which results from the reduction in heating demand on account of the raising of outdoor temperature and solar gains. Besides, an obvious increasing variation is obtained due to the heavy fluctuation of daily ambient temperature in the typical day chosen for representing the transition season.

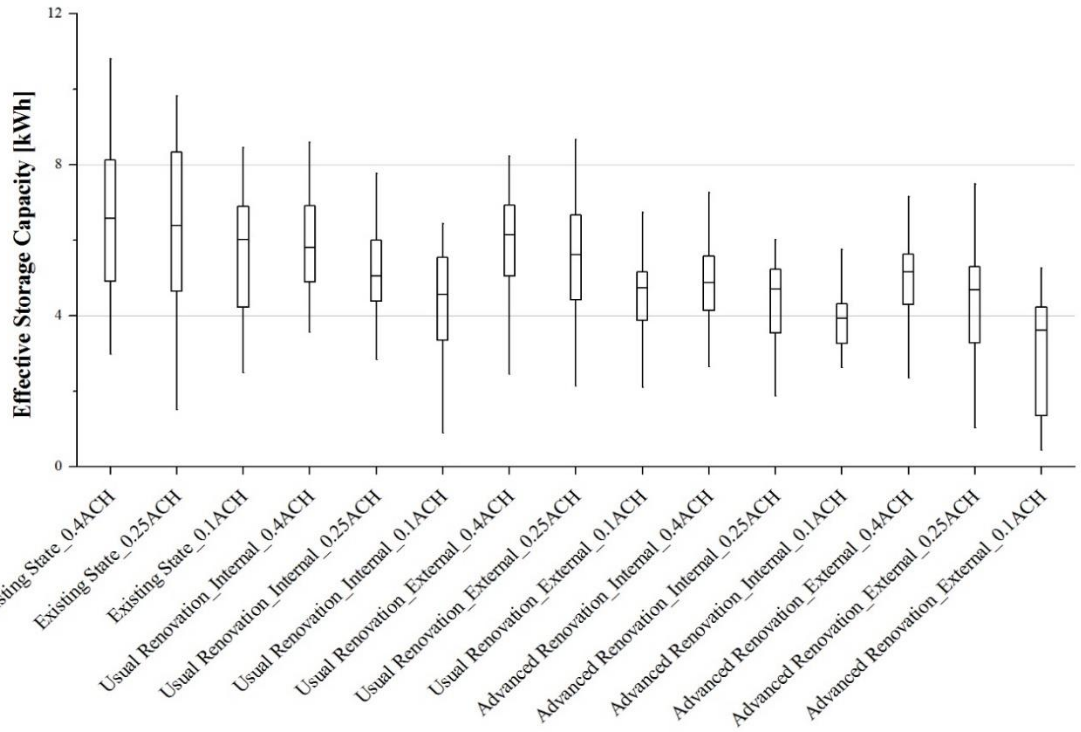

***Figure 4.15**: Effective storage capacity as a function of building renovation options. The results are shown for weather condition of January 22 considering 4 occupant behavior scenarios and the variation of ADR-event starting time.*

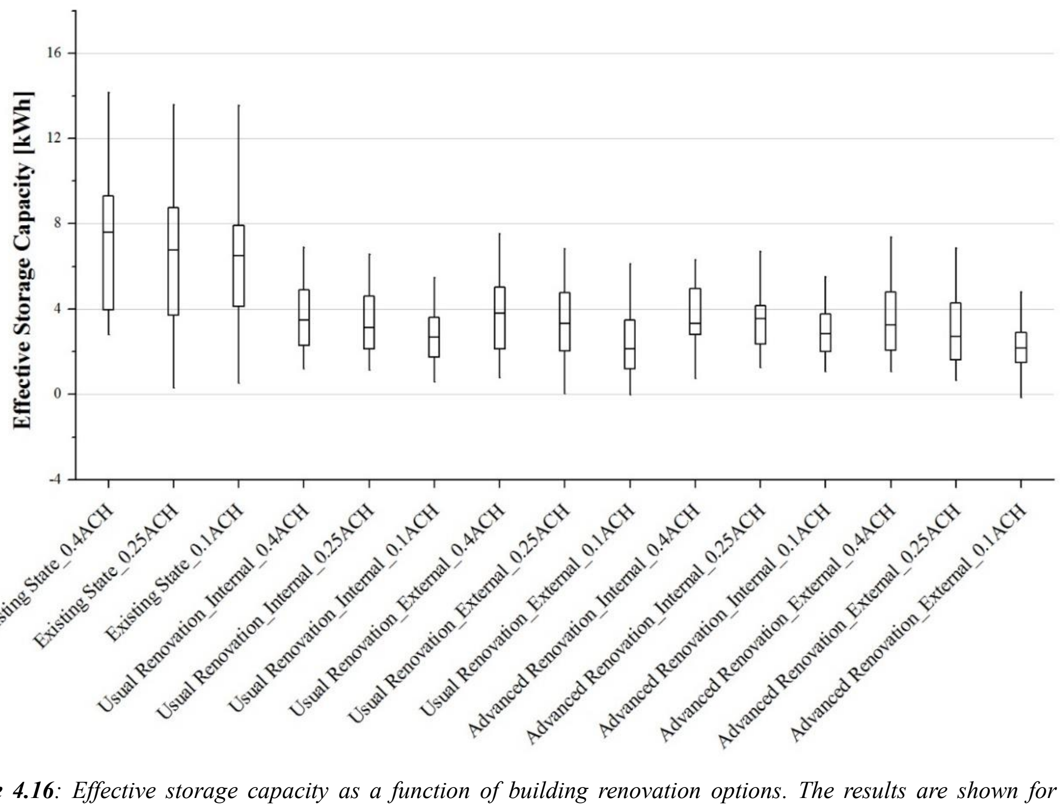

***Figure 4.16**: Effective storage capacity as a function of building renovation options. The results are shown for weather condition of March 12 considering 4 occupant behavior scenarios and the variation of ADR-event starting time.*

Combining the two groups of results together, Figure 4.17 shows the effective storage capacity as a function of building renovation options considering both the influences of occupant behavior and weather condition, according to which a representative building renovation recommendation could be given to users or house agencies during building renovation process to exploit energy flexibility. The renovation option with usual renovated external insulation level and 0.4ACH infiltration rate still obtains the highest typical effective storage capacity of 5.08 kWh while it is sensitive to dynamic boundary condition with a relative high quartile deviation compared to other options. However, it can be acceptable since the larger range of fluctuation is in the positive direction which is caused by higher effective storage capacity in some scenarios. Therefore, it can be concluded that renovation option with usual renovated external insulation level and 0.4ACH infiltration rate has the best performance in exploiting energy flexibility of structural thermal energy storage, offering the highest typical effective storage capacity and strong robustness to the dynamic boundary condition.

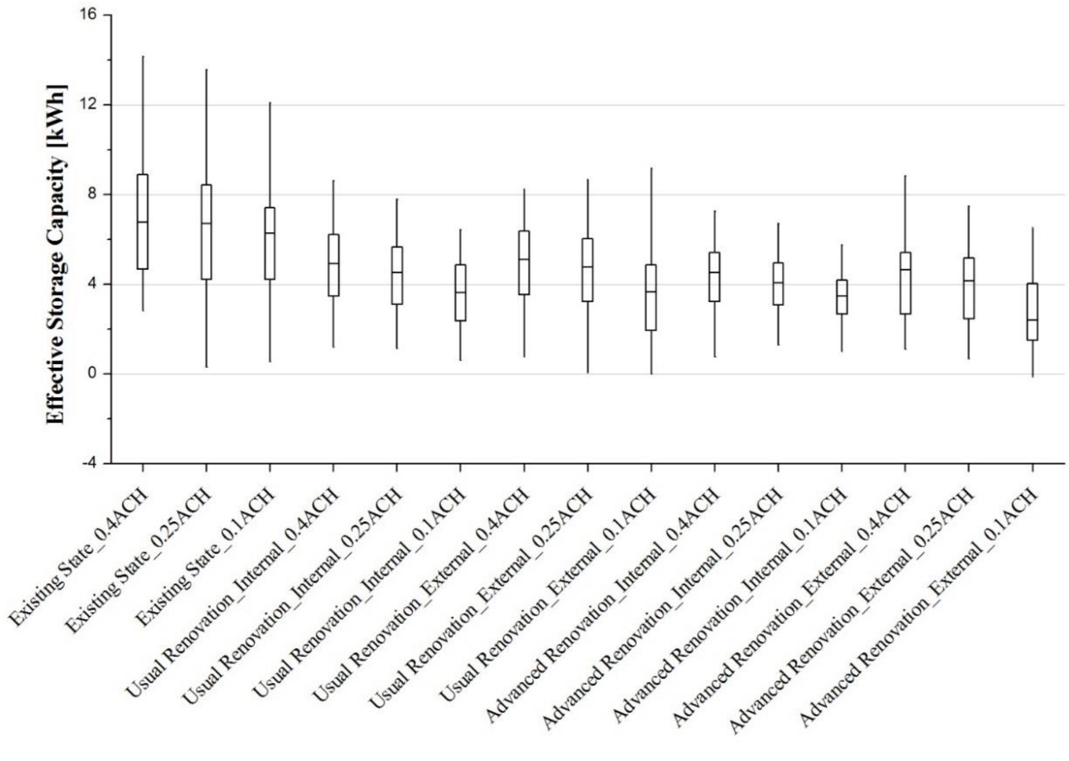

Figure 4.17*: Effective storage capacity as a function of building renovation options considering 4 occupant behavior scenarios, 2 weather condition scenarios and the variation of ADR-event starting time.*

4.4 Impact of ADR-event staring time on operation indicators

In this section, the second main research question is answered by analyzing the impact of ADR-event starting time on CO_2 emission and operation cost, taking into account six operation scenarios with the combination of PV production, electricity price and the net metering policy. As discussed in 4.1, with low PV production or in cloudy days, ADR-event is not profitable and does not contribute to reducing CO_2 emission since the electricity generated by PV panel is not enough to cover the extra heat inputted for ADR-event. Therefore, the results shown below are all based on the weather data of March 12, representing a sunny day, with a PV peak power of over 13 kWh. Both two indicators are calculated for the following 24 hours after the ADR-event starting.

4.4.1 CO_2 emission

As the base value of CO_2 emission is different for building renovation options without ADR-event, so the reduction because of the use of ADR-event is selected to reflecting the environment protection performance. Since the CO_2 emission is only related to the electricity consumption from grid and CO_2 emission factor, the results of three operation scenarios with high PV production are all the same. The results in Figure 4.18 demonstrate the CO_2 emission reduction as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios, obtained by 840 runs in total. In other words, there are 60 data for each ADR-event starting time. It is indicated that all data for ADR-event starting time 8h, 10h and 14h are above zero, which means the CO_2 emission can be ensured to be reduced for all building renovation cases if the ADR-event is started among these three time points. Besides, $T_{ADR-Starting} = 14\text{h}$ shows the best performance in reducing CO_2 emission with the average of around 8%. The relative performance range is wider than that of $T_{ADR-Starting} = 8\text{h}, 10\text{h}$ and 12h due to the appearance of the considerably high value of around 13%. Therefore, the most beneficial time to start ADR-event is 14h for all building renovation options.

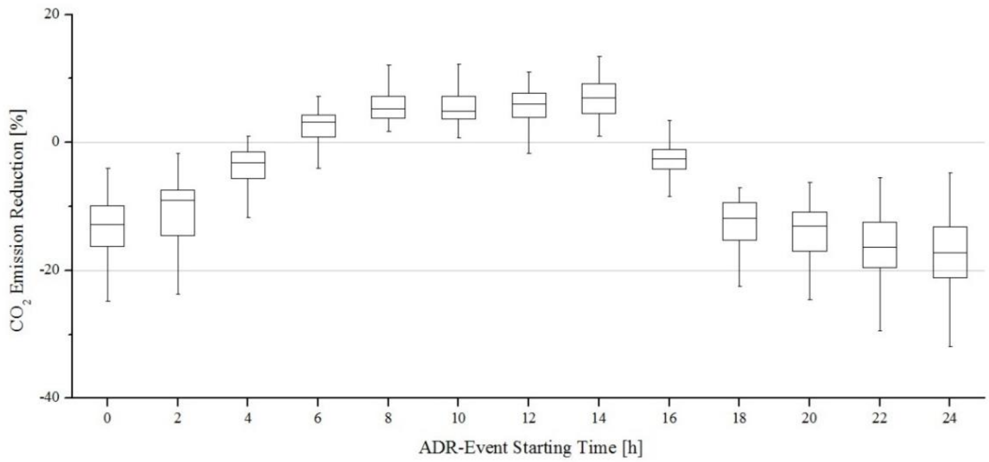

***Figure 4.18**: CO_2 emission reduction (%) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios for March 12 (with clear sky conditions).*

4.4.2 Operational cost

As described in 4.1, three operation scenarios are considered when assessing the impact of ADR-event on operation cost and the results are shown in Figure 4.19-4.21 respectively. The results illustrate the operation cost saving between cases with and without ADR-event as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios, with 60 data for each ADR-event starting time. As for the scenarios with the net metering scheme, the obtained operation costs are negative, therefore in the following analysis the cost saving is shown as the absolute value in EUR for the following 24 hours after the ADR-event starts.

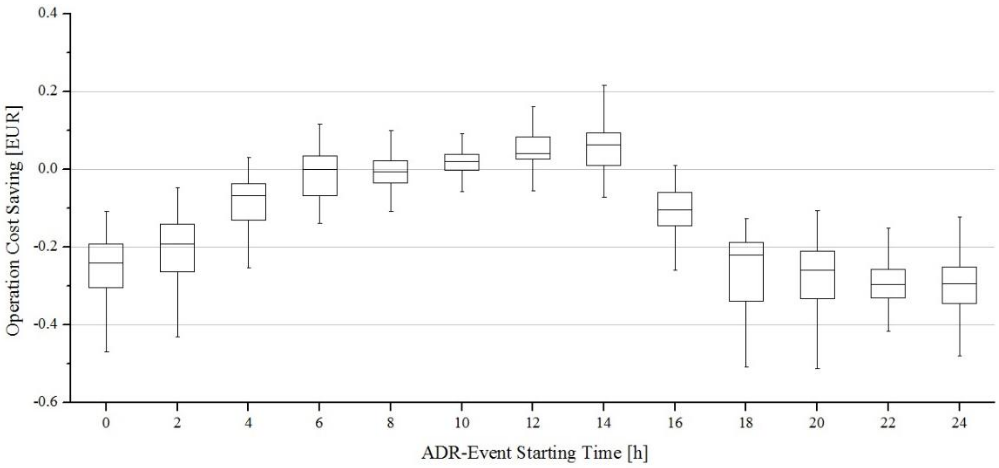

Figure 4.19: *Operation cost saving (EUR) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios* ***with fixed electricity price and net metering scheme*** *for March 12 (with clear sky conditions).*

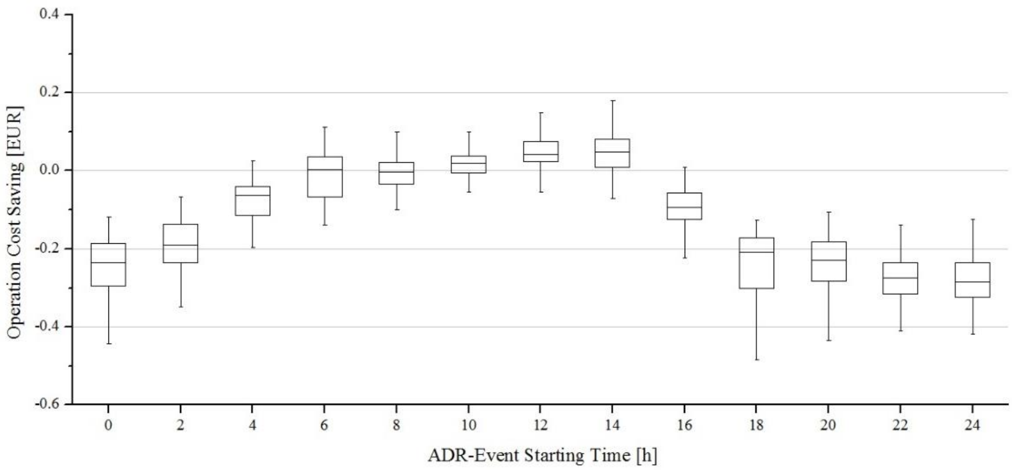

Figure 4.20: *Operation cost saving (EUR) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios* ***with real-time electricity price and net metering scheme*** *for March 12 (with clear sky conditions).*

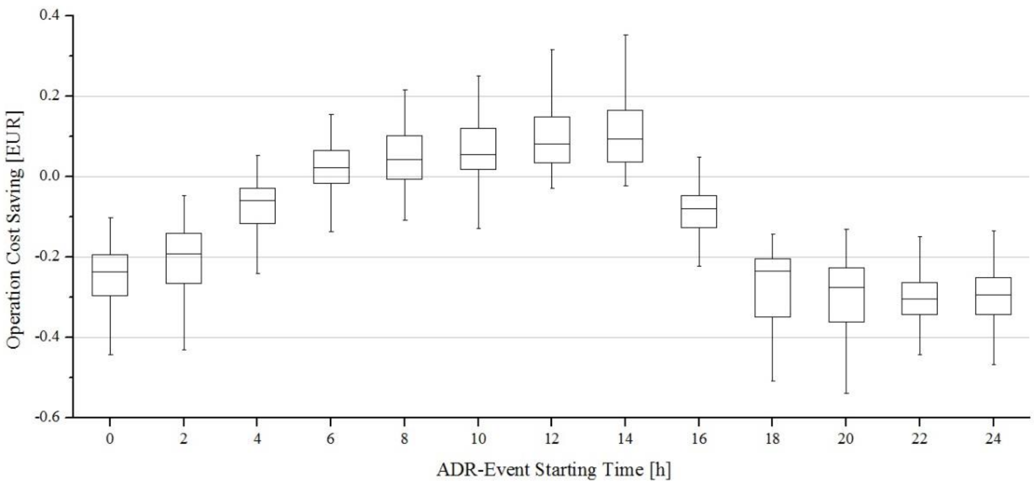

Figure 4.21: *Operation cost saving (EUR) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios* ***with real-time electricity price and no net metering scheme*** *for March 12 (with clear sky conditions).*

It is implied that operation cost saving can be realized in part of cases for two scenarios with net metering while in vast majority cases for the scenario without net metering with the ADR-event starting time from 8h to 14h. Furthermore, the maximum cost savings are all obtained when ADR-events are started at 14h for three scenarios and the corresponding robustness to the building design and occupant behavior is also acceptable. Additionally, in order to compare the performance in saving operation cost, the median for each ADR-event starting time are connected together into three lines respectively corresponding to three operation scenarios, as shown in Figure 4.22. It is indicated that there is almost no difference between the results of two scenarios with net metering, which is resulted in by two reasons. On the one hand, the range of variation is around 2.5 EUR cents/kWh of the real-time electricity price daily profile and the farthest point away from the average which is also the fixed electricity price is even less as 1.5 EUR cents/kWh. That means the dynamic electricity price scheme contributes little to the operation cost saving with the use of ADR-event. On the other hand, the availability of loading shifting by heating system is restricted, because high energy production by PV panels is always corresponding to low heat demand in the same time periods and the heat pump is the only shiftable load in this project. Especially, for the advanced renovated buildings which are highly insulated corresponding to a lower nominal power of the heating system, the available amount of shifted power is even lower. Therefore, the superiority of real-time electricity price scheme is possible to be highlighted if ADR-event is implemented combining with the other demand response strategy, for instance, shifting the load of the appliance, to increase the total shifted power capacity. Besides, the results of scenarios 3 present a better operation cost saving potential with the maximum of 0.14 EUR when $T_{ADR-Starting} =$ 14h, which means when the subsidy from net metering is stopped, ADR-event takes a more crucial role in saving operation cost. As net metering cannot be ensured after 2023, the combination of real-time electricity price scheme without net metering is regarded as a future-oriented scenario, therefore, of which the potential of reducing operation cost of ADR-event is expectable. For the purpose of investigating the most profitable ADR-event starting time in scenario 3, the absolute values in EUR are converted to percentage since the base operation costs are different for each ADR-event starting time, illustrated in Figure 4.23, with the maximum saving of around 13% and the median of 8% when $T_{ADR-Starting} = 14$h.

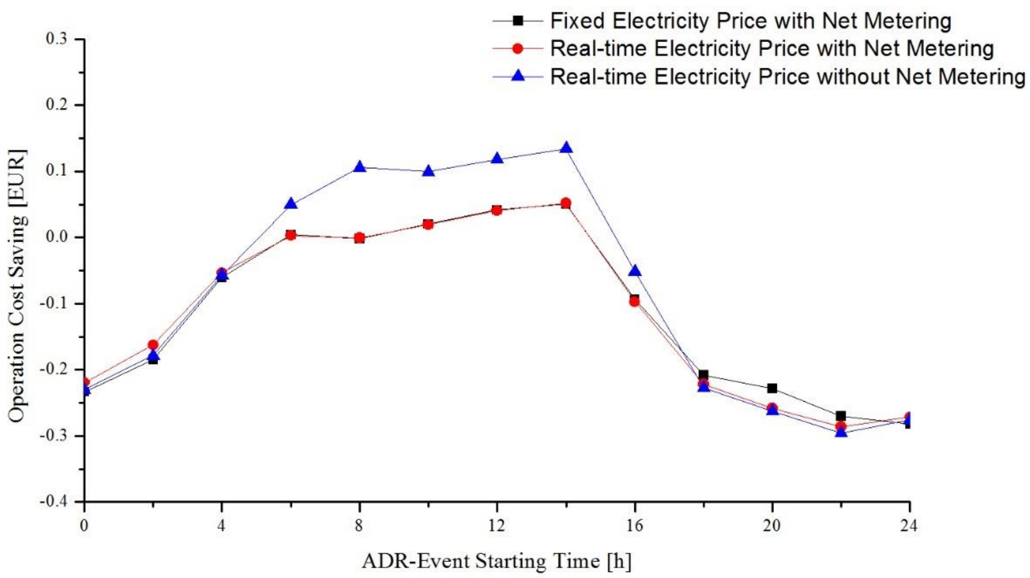

Figure 4.22 *Typical value (median) of operation cost saving (EUR) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios for March 12 (with clear sky conditions).*

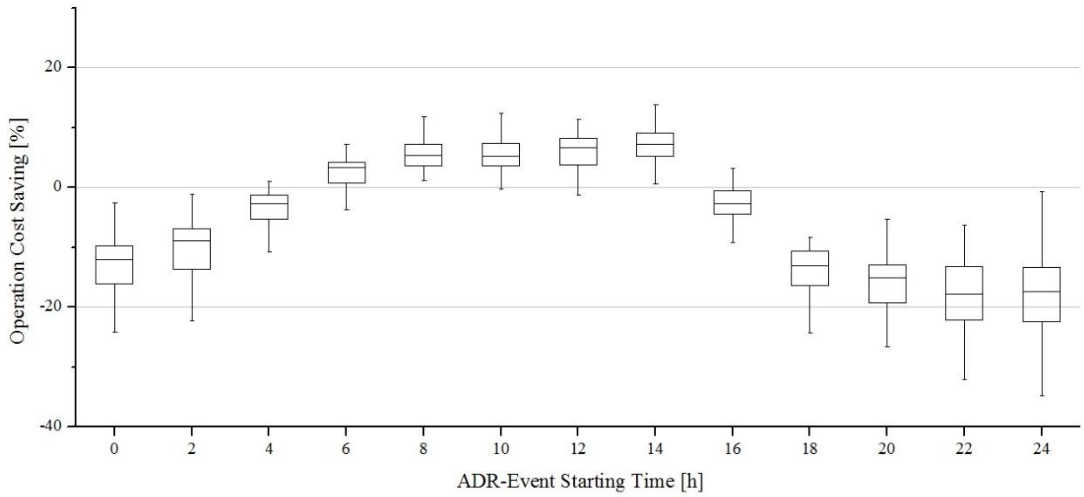

Figure 4.23*: Operation cost saving (%) as the function of ADR-event starting time considering 15 building renovation cases and 4 occupant behavior scenarios with real-time electricity price and no net metering scheme for March 12 (with clear sky conditions).*

Based on the discussion above, it is found that staring ADR-event from 8 am to 2 pm shows the CO_2 emission reduction and operation cost saving potential. According to the definition, energy flexibility indicators concern the usage of energy flexibility in the following 24 hours after the ADR-event starting time. From 8 am to 2 pm, the increasing PV production covers the extra load of heating system for rising setpoint temperature, which compensates the relevant electricity costs. Besides, the power shifted mainly comes from the closely following time period after the ADR-event lasting for 4 hours and the ability of power shifting turns to be smaller with time going on. For ADR-event starting at 2 pm, compared to starting ADR-event at 8 am to 12 am, it means more power can be shifted from 6 pm later when is no PV production to a period when extra electricity can be covered by PV production. Additionally, the operation cost saving is related to electricity price variation as well. As shown in Figure 4.7, the hourly electricity price is higher than the average after 6 pm, which leads to a high incentive to active the ADR-event at the corresponding starting time as 2 pm. Therefore, 2 pm is proofed as the profitable and environmentally-friendly ADR-event starting time. However, the typical value of CO_2 emission and operation cost saving are limited as both 8% due to the same reason mentioned above, which is the availability of loading shifting by heating system is restricted. Furthermore, for ADR-event starting time before 8 am and after 2 pm, the corresponding CO_2 emission reduction and operation cost saving are negative because ADR-event is activated by increasing the heat input to the heating system to raise the setpoint temperature. When PV production is not enough to cover the extra heat demand, the ADR-event is not beneficial.

From design perspectives, building with usual renovated external insulation and 0.4 ACH infiltration rate has the best performance in exploiting energy flexibility of building structural thermal energy storage. ADR-event staring at 14h, in this case, leads to a 9% reduction both in CO_2 emission and operation cost, which is higher than the average level of 8%.

5

Conclusion and Recommendation

5.1 Conclusion

This study analyzed the energy flexibility potential of building structural thermal energy storage for existing Dutch single-family houses built between 1965 and 1974 in both design and operation phase. Two main questions described in Chapter 1 were further divided into three groups of sub-questions.

The first group focused on the definition, implementation and quantification of energy flexibility under heating dominated Dutch climate. Energy flexibility was defined as the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements [6]. The main strategy to activate energy flexibility of building structural thermal energy storage was the active demand responds, which increased the setpoint temperature of heating emission system, namely the radiator in this thesis, to realize load shifting. Besides, available storage capacity and storage efficiency were selected as two basic indicators to quantify the intrinsic energy flexibility of building structural thermal storage. Additionally, effective storage capacity is defined as the product of these two indicators to consider the trade-off. It was emphasized that these all three performance indicators which relies on the building design and dynamic boundary condition including occupant behavior and weather condition were calculated for the following 24 hours after ADR-event starting, of which the duration is set as 4 hours in order to avoid the decrease of storage efficiency.

The second group aimed at assessing the impact of different building design parameters on energy flexibility and quantifying energy flexibility potential of 15 building renovation options with the use of ADR-event taking into account the typical occupant behavior in the Netherlands and weather condition. All results are obtained based on two typical days representing typical heating season and transition season respectively. Firstly, as for design phase, it was found by a univariable analysis that for typical Dutch single-family houses built between 1965 and 1974, with the improvement of building renovation level, for example, increasing insulation level or airtightness, the available storage capacity decreased significantly while the storage efficiency showed a better performance in the mild renovation level. Although available storage capacity of the uninsulated building which is the original state of the objective building is the highest, a higher nominal heating power is also requested. In addition, the results of building with external insulation demonstrated a high available storage capacity while a low storage efficiency. Assuming an ADR-event of 4 h and a temperature increase of 2C°, the highest available storage capacity obtained was 25 kWh, which was equivalent to a storage tank with the volume of 1070L to store the same amount of heat as structural thermal energy storage with the assumption that the temperature is increased as 20C° in a hot water storage tank, showing the potential of place saving. Secondly, the energy flexibility robustness of 15 building renovation cases to dynamic boundary condition was investigated by effective storage capacity. The results indicated that higher ambient temperature and solar gains correspond to a decreasing effective storage capacity because of the low heating demand. Therefore, the energy flexibility potential of building structural thermal storage in transition seasons are lower, even marginal, than that in the typical heating season. Besides, it can be concluded that renovation option with usual renovated external insulation level and 0.4ACH infiltration rate can be recommended to the users or house agency considering the exploitation of building structure energy flexibility, offering the highest typical effective storage capacity and relatively strong robustness.

Finally, the third group deals with the operation strategy to investigate the best time to use the energy flexibility potential of structure thermal energy storage, in order to receive the maximum CO_2 emission reduction and operation cost saving considering the impact of occupancy and operational scenarios. The results showed that staring ADR-event prior to periods with a high energy demand thus the heat stored in thermal mass by ADR-event can be directly recovered or periods with high electricity price since load can be shifted to periods with relatively lower price. It was found that in low PV production condition, ADR-event does not contribute to reducing CO_2 emission and operation cost. For scenarios with net metering, real-time electricity price scheme does not show the superiority to the fixed one due to the limited power shifting capacity and the small variation range of electricity price. Among the three operation scenarios with high PV production, the future-oriented scenario with real-time electricity price and without net metering presented a better operation cost saving potential, which means when the subsidy from net metering is stopped, ADR-event takes a more crucial role in saving operation cost. Additionally, in this scenario, both CO_2 emission reduction and operation cost saving reach the maximum of 8% when $T_{ADR-Starting} = 14\text{h}$.

Therefore, from design perspectives, building with usual renovated external insulation and 0.4 ACH infiltration rate is recommended since it has the best performance in exploiting energy flexibility. In the operation point of view, $T_{ADR-Starting} = 14\text{h}$ is regarded as the most profitable and environmentally-friendly time to start ADR-event. Combined these two options together, a 9% reduction both in CO_2 emission and operation cost can be achieved, which is higher than the average level of 8%.

5.2 Recommendation

Several paths for future research are summarized as follows:

- It is indicated that the CO_2 emission reduction and operation cost saving are closely related to the PV production, hence, the simulation period can be extended to the whole year and consider the climate change to assess the appropriate weather condition to use energy flexibility of building structural thermal storage by ADR-event.

- Domestic hot water system is not considered in this thesis to avoid the influence on heat pump working condition. In future research, two schemes related to DHW are put forward here. Firstly, DHW can be implemented in the existing model in this thesis to assess its impact on the energy flexibility of structural thermal storage. Secondly, instead of structural thermal energy storage, hot water storage tank can take the role as building storage, of which the energy flexibility potential is worth to be investigated as a comparison to that of structural thermal storage.

- ADR-event can be used to pre-cool the buildings by decreasing indoor temperature to realize power shifting.

- ADR-event can be also implemented to floor heating instead of radiators as the heat emission system.

- The same methodology of this thesis can be applied to other building types, such as terraced houses and flats, and buildings with different ages, to assess the corresponding energy flexibility potential.

- Optimized control strategy like Model Predict Control (MPC), which takes into account predictions of the future heat demand and ADR incentives, can be developed to control energy flexibility without jeopardizing indoor comfort.

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Yuan Ren
TU Delft, August 2017

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Appendix A

TRNSYS Model

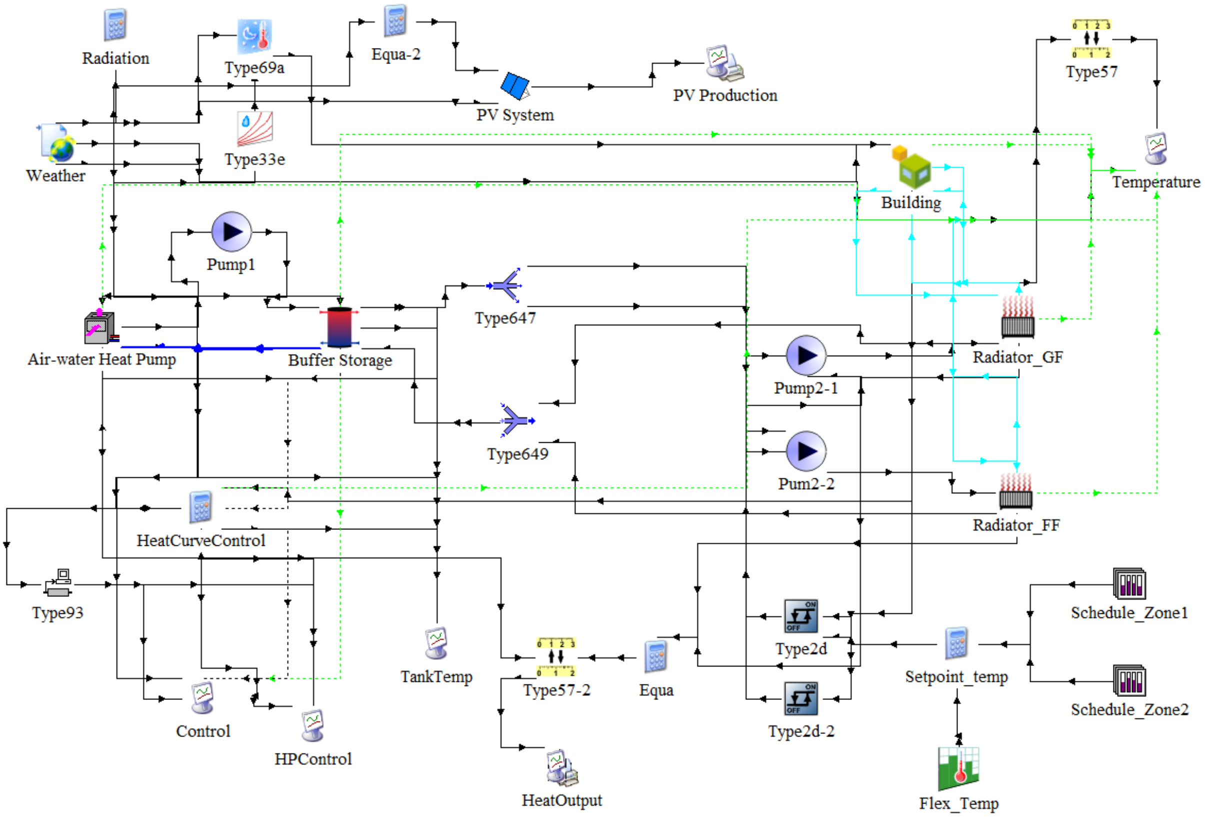


***Figure A.1:** TRNSYS model*

Appendix B

Building Properties

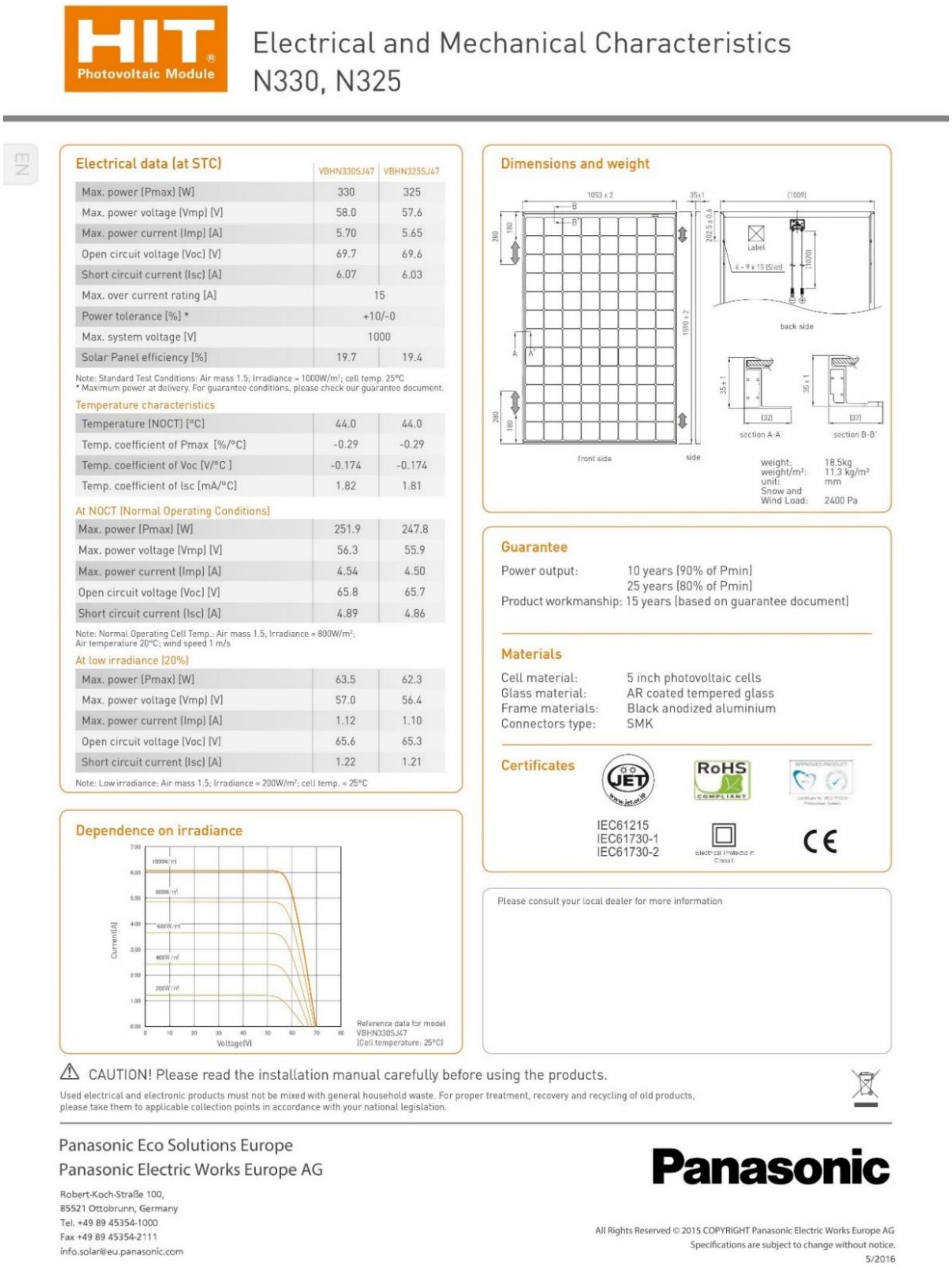
Table B.1: *Surface properties*

From zone	To zone	Construction type	Area [m^2]	Orientation
0	1	Wall External	53.83	North
0	1	Wall External	32.81	East
0	1	Wall External	51.06	South
0	1	Wall External	34.21	West
0	1	Window	11.34	North
0	1	Window	7.21	East
0	1	Window	14.11	South
0	1	Window	5.81	West
Ground	1	Floor	131.95	-
0	1	Roof	0	-
0	1	Door	4.75	South
0	1	Door	4.75	North
0	2	Wall External	0	North
0	2	Wall External	9.96	East
0	2	Wall External	0	South
0	2	Wall External	10.56	West
0	2	Window	0	North
0	2	Window	3.09	East
0	2	Window	0	South
0	2	Window	2.49	West
0	2	Roof	185	South + North
1	2	Floor Internal	131.95	-
1	1	Wall Internal	171.91	-
2	2	Wall Internal	45	-

*The boundaries 0, 1, 2 and 'ground' refer respectively to the ambient environment, the ground floor, the first floor and the ground.

Appendix C

PV Module Datasheet



HIT® Photovoltaic Module

Electrical and Mechanical Characteristics
N330, N325

EN

Electrical data (at STC)

	VBHN330SJ47	VBHN325SJ47
Max. power (Pmax) [W]	330	325
Max. power voltage (Vmp) [V]	58.0	57.6
Max. power current (Imp) [A]	5.70	5.65
Open circuit voltage (Voc) [V]	69.7	69.6
Short circuit current (Isc) [A]	6.07	6.03
Max. over current rating [A]	15	
Power tolerance [%] *	+10/-0	
Max. system voltage [V]	1000	
Solar Panel efficiency [%]	19.7	19.4

Note: Standard Test Conditions: Air mass 1.5; Irradiance = 1000W/m²; cell temp. 25°C
* Maximum power at delivery. For guarantee conditions, please check our guarantee document.

Temperature characteristics

Temperature (NOCT) [°C]	44.0	44.0
Temp. coefficient of Pmax [%/°C]	-0.29	-0.29
Temp. coefficient of Voc [V/°C]	-0.174	-0.174
Temp. coefficient of Isc [mA/°C]	1.82	1.81

At NOCT (Normal Operating Conditions)

Max. power (Pmax) [W]	251.9	247.8
Max. power voltage (Vmp) [V]	56.3	55.9
Max. power current (Imp) [A]	4.54	4.50
Open circuit voltage (Voc) [V]	65.8	65.7
Short circuit current (Isc) [A]	4.89	4.86

Note: Normal Operating Cell Temp.: Air mass 1.5; Irradiance = 800W/m²; Air temperature 20°C; wind speed 1 m/s

At low irradiance (20%)

Max. power (Pmax) [W]	63.5	62.3
Max. power voltage (Vmp) [V]	57.0	56.4
Max. power current (Imp) [A]	1.12	1.10
Open circuit voltage (Voc) [V]	65.6	65.3
Short circuit current (Isc) [A]	1.22	1.21

Note: Low irradiance: Air mass 1.5; Irradiance = 200W/m²; cell temp. = 25°C

Dependence on irradiance

Current[A]
Voltage[V]
Reference data for model VBHN330SJ47 (Cell temperature: 25°C)

Dimensions and weight

front side
side
back side
section A-A'
section B-B'
Label

weight:	18.5kg
weight/m²:	11.3 kg/m²
unit:	mm
Snow and Wind Load:	2400 Pa

Guarantee

Power output: 10 years (90% of Pmin)
25 years (80% of Pmin)
Product workmanship: 15 years (based on guarantee document)

Materials

Cell material:	5 inch photovoltaic cells
Glass material:	AR coated tempered glass
Frame materials:	Black anodized aluminium
Connectors type:	SMK

Certificates

JET
RoHS COMPLIANT
IEC61215
IEC61730-1
IEC61730-2
Electrical Protection Class I
CE

Please consult your local dealer for more information

⚠ CAUTION! Please read the installation manual carefully before using the products.

Used electrical and electronic products must not be mixed with general household waste. For proper treatment, recovery and recycling of old products, please take them to applicable collection points in accordance with your national legislation.

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Panasonic

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Specifications are subject to change without notice.
5/2016

***Figure C.1**: PV module datasheet – Panasonic HIT® VBHN330SJ47*

Appendix D

Internal Gains for Occupant Behavior Scenarios

Table D.1: *Internal gains for occupant behavior scenario 1 described in Table 4.1*

Days	Hours	Ground Floor [W]	First Floor [W]
Weekdays/Weekend	00:00-07:00	40	320
	07:00-09:00	1000	10
	09:00-18:00	700	10
	18:00-23:00	1000	10
	23:00-00:00	40	620

Table D.2: *Internal gains for occupant behavior scenario 2 described in Table 4.1*

Days	Hours	Ground Floor [W]	First Floor [W]
Weekdays/Weekend	00:00-07:00	40	160
	07:00-09:00	800	10
	09:00-18:00	500	10
	18:00-23:00	800	10
	23:00-00:00	40	460

Table D.3: *Internal gains for occupant behavior scenario 3 described in Table 4.1*

Days	Hours	Ground Floor [W]	First Floor [W]
Weekdays/Weekend	00:00-07:00	40	160
	07:00-09:00	800	10
	09:00-18:00	40/500	10
	18:00-23:00	800	10
	23:00-00:00	40	460

Table D.4: *Internal gains for occupant behavior scenario 4 described in Table 4.1*

Days	Hours	Ground Floor [W]	First Floor [W]
Weekdays/Weekend	00:00-07:00	40	320
	07:00-09:00	1000	10
	09:00-18:00	40/700	10
	18:00-23:00	1000	10
	23:00-00:00	40	620

Appendix E

Real-time Electricity Price Calculation Method

The detailed method to predict the RTP profile is described in this section. Day-ahead hourly electricity price of APX are used as the base of prediction. In Figure E.1, the corresponding electricity price in each hour for three days are used to calculated the hourly average which is connected as the pink curve. The daily average of the pink curve is 0.037 EUR/kWh. According to the Table 3.9, the daily average electricity price of energy and supply section is 0.065 EUR/kWh. Therefore, the daily electricity profile only taking into account energy and supply is predicted as the same variation trend of the average daily profile considering three typical days shown by the pink curve. By adding the fixed network cost and taxes, the real-time electricity price is shown as the red line in Figure 3.10.

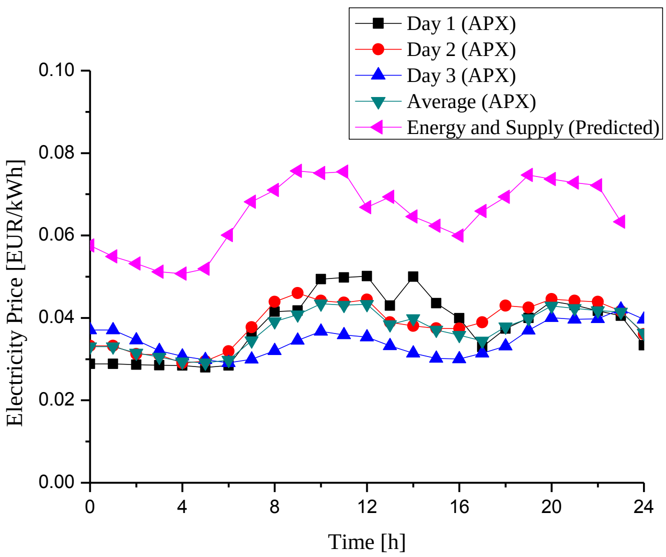

Figure E.1: *Electricity price profiles used to predict real-time electricity price*