Economic Feasibility of Achieving Net-Zero Energy in Residential Buildings in the USA

by

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DEDICATION

This dissertation is dedicated to everyone who devote themselves to create a sustainable future in the built environment.

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ABSTRACT

Over the past few decades, residential buildings have been one of the major sectors responsible for a large share of energy demand in the United States (EIA, 2020). However, such high energy demand from residential buildings will cause economic and environmental problems, eventually leading to the growing expectations for implementing net-zero energy buildings (NZEBs) in the near future.

Therefore, this study provides a financial framework for implementing NZEBs in the United States residential sector by utilizing two popular renewable energy systems, solar P.V. and geothermal heat pumps. A two-story single residential building in Ann Arbor, Michigan was simulated using the TRNSYS software tool. Specifically, this study analyzed the discounted payback periods of the following four different heating, ventilation, and air-conditioning (HVAC) systems; these are:

(1) air-source heat pump (ASHP)
(2) PV-integrated ASHP (PV+ASHP)
(3) ground-source heat pump (GSHP), and
(4) PV-integrated GSHP (PV+ GSHP).

In addition, each building's HVAC system has been subdivided into multiple scenarios based on the level of technological (i.e., P.V. energy conversion rate) and institutional (i.e., CO_2 equivalent price of ETS) improvements required to achieve the net-zero emission target by 2050.

First, this study reveals high expectations for installing PV-integrated GSHP in residential buildings because PV+GSHP generates electricity using solar and geothermal heat sources. The results clearly show that technological advancements, such as improving the performance of solar panels, have a much more significant effect on reducing the payback periods of heat pump systems compared with raising the CO_2 equivalent price of the emission trading scheme (ETS).

More specifically, installing a PV-integrated GSHP enables the implementation of NZEB with a payback period of fewer than ten years when the technology reaches a P.V. energy conversion rate of 32.5%. Second, this study highlights the growing demand for renewable energy sources by supporting the broader application of investment tax credits (ITC) to the United States residential sector. Specifically, this study presents reasonable tax credit rates that should be supported by the U.S. federal government when applying solar and geothermal heat sources to residential heat pump systems. Results show that the current 26% solar tax credit rate is reasonable under today's technological and institutional context. Meanwhile, the high investment cost of GSHP does not ensure economic investment but requires government subsidies that far exceed the current 26% geothermal heat pump tax credit rate.

In conclusion, this research framework clarifies the ambiguous issues related to technology and policy that must be addressed to allow NZEBs to become more economically feasible in the United States residential sector. Furthermore, implementing NZEBs with reasonable payback periods requires significant improvements in technology and policy. This goal can hardly be achieved with short-term efforts. Therefore, many building engineers, technicians, and policy makers are required to play the role as a frontier of this challenge and actively contribute to achieving the net-zero emission target by 2050.

Keywords:

Net-zero energy building (NZEB), emission trading scheme (ETS), investment tax credit (ITC), economic feasibility, P.V. energy conversion rate, CO_2 equivalent price

Note: The content of this dissertation is currently being reviewed in the journal of cleaner production. All authors of the study under review are aware of this copyright (This statement is signed by all the authors to indicate agreement that the above information is true and correct).

Author's signature Date

Hyeonsoo Kim March 27th, 2023

Lars Junghans March 27th, 2023

CHAPTER 1

Introduction

Throughout the past few decades, buildings have been one of the prime sectors responsible for a large share of energy demand and greenhouse gas (GHG) emissions worldwide (IEA, 2018). For example, in the United States, the residential sector alone accounts for 21.2% of the national primary energy demand (EIA, 2020) and 15.6% of the total GHG emissions (EPA, 2018). In general, an increase in building energy demand is accompanied by economic and environmental problems, such as increased electric utility costs and GHG emissions. Thus, it is essential to find reasonable solutions to reduce operating costs and GHG emissions associated with high energy demand from the residential sector. As a way to solve these problems, most countries around the world are targeting "net-zero emission" as a future governmental initiative (Mishra et al., 2022), which leads to the growing expectations for net zero energy buildings (NZEBs) (Zhang et al., 2021). More specifically, many developed countries have a carbon-neutral target set up for 2050, and most governments in these nations require all new constructions from then to be implemented as NZEBs (Zhang et al., 2020).

Furthermore, as a supportive measure, these leading countries offer tax credits to encourage many building owners to utilize renewable energy sources in their households. Therefore, this dissertation presents the economic feasibility of implementing NZEBs in the U.S. residential sector by installing two widely used renewable energy systems: solar P.V. and geothermal heat pumps. To be specific, this study strives to economically measure whether the 2050 net-zero target can be achieved promptly. In addition, this dissertation presents the payback period of several building HVAC systems depending on the improvement level of each factor, considering the technological (P.V. energy conversion rate) and institutional (CO_2 equivalent price of ETS) factors that promote the net-zero emission target.

In addition, these results are intended to propose the reasonable investment tax credit (ITC) rates for solar P.V. and geothermal heat pumps supported by the U.S. federal government. The recommended tax credit rates will help the government economically support many homeowners to utilize renewable energy sources. Conclusively, the research framework of this study clarifies the rather ambiguous issues related to technology and policy that must be addressed to allow NZEBs to become more economically feasible in the United States residential sector. Since the implementation of NZEBs with reasonable payback periods require significant improvements in both technology and policy, this goal can be hardly achieved with short-term efforts. Therefore, many building engineers, technicians, and policy makers should play the role as a frontier of this challenge and actively contribute to achieving the net-zero emission target by 2050.

CHAPTER 2

Literature Review

First, this section addresses the worldwide trend toward “net-zero emission” target. Figure 1 shows the time pledges for net-zero emission target by each country throughout the globe. Second, this chapter covers the literature review on previous studies that have analyzed the feasibility of NZEBs from an economic perspective. Finally, this study reviews the status of the U.S. federal support for solar and geothermal investment tax credits (ITC), which are the two renewable energy sources covered in this research.

2.1 Net-zero emission target worldwide

Figure 1 shows the global trend toward the time frame of carbon neutrality. For reference, “carbon neutrality” refers to “net-zero emission” in this study. According to the illustration, the target year for net-zero emission can be classified into three different time periods: carbon neutral (1) prior to 2050, (2) by 2050, and (3) by 2060. As shown in the figure, most developed countries (i.e., United States, United Kingdom, France, Germany, South Korea, Japan, Australia etc.) pledge to achieve the net-zero emission target by the year 2050. However, many developing countries (i.e., China, Russia, Indonesia, Brazil etc.) set their goals to meet the target by 2060.

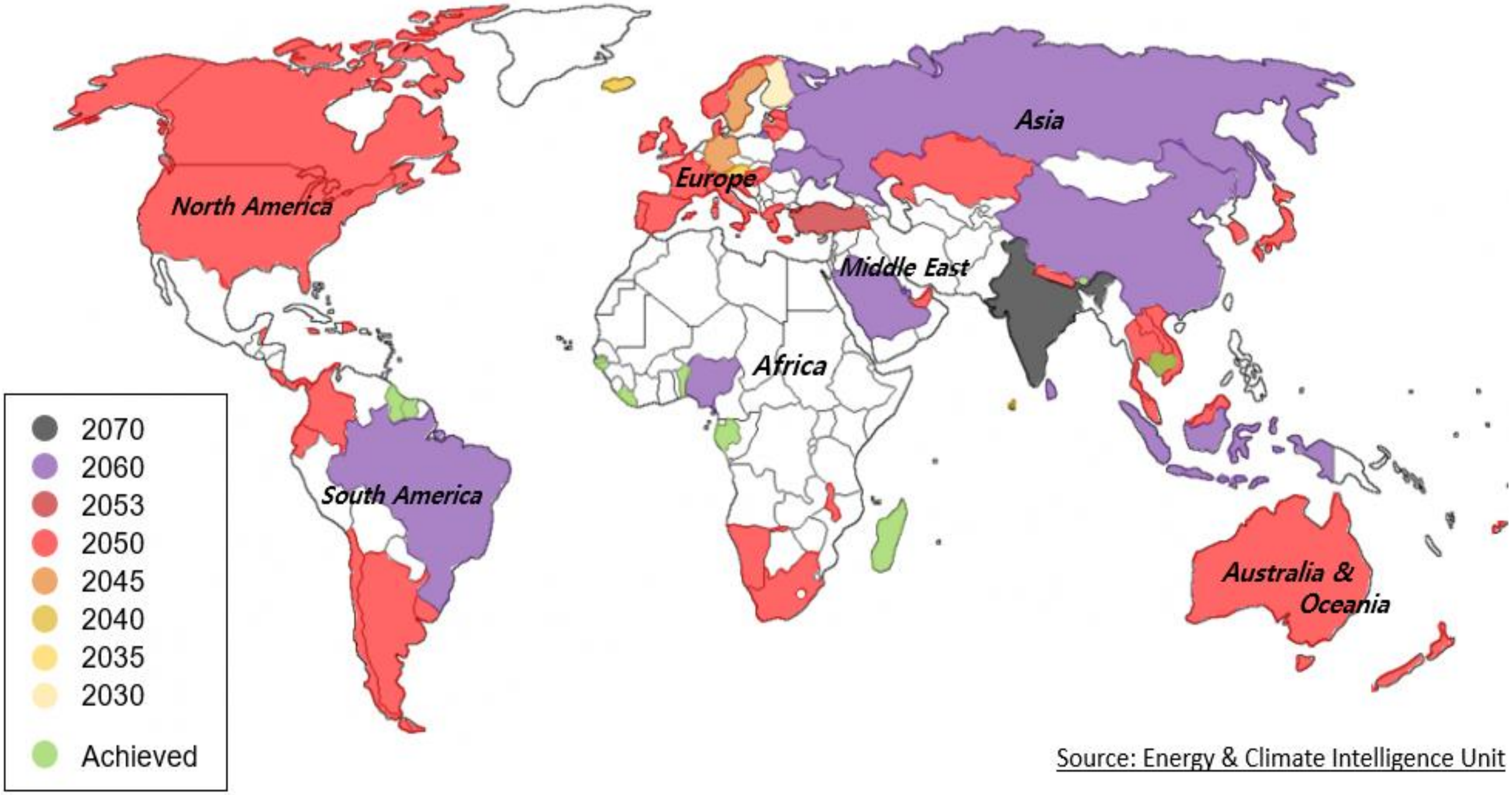


Figure 1. Concrete timed pledges for the net-zero emission target worldwide. Most developed countries pledge to achieve the net-zero emission target by 2050. However, many developing countries set their goals to meet the target by 2060.

2.1.1 Carbon neutral prior to 2050

According to the energy & climate intelligence unit, some developed countries, including Germany, Sweden, and Finland, are far ahead of their carbon neutrality targets compared with those of most other nations' (Energy & Climate Intelligence Unit, 2021). Especially, because 69% of the Swedish and 74% of the Finnish land areas are covered with dense forests, these countries have advantages in setting up ambitious goals against climate change (Lipiäinen et al., 2022). More surprisingly, owing to the prevalence of undeveloped nature and forests, Bhutan and Suriname are the two countries that have already achieved their net-zero emission targets as of the year 2021 (Ruffini et al., 2022).

2.1.2 Carbon neutral by 2050

Most developed countries, including the United States, Canada, Australia, Japan, South Korea and many European countries, pledge to achieve their carbon neutrality goal by 2050. According to a study conducted by Qin et al., the group of seven (G7) countries (United States, United Kingdom, Canada, France, Italy, Japan, and Germany) accounts for more than 60% of the global net wealth, which plays an essential role for setting up ambitious climate action (Qin et al., 2021). This study highlights that most of these developed nations require political stability and institutional quality to support stringent environmental policies to achieve the carbon neutrality goal by 2050.

2.1.3 Carbon neutral by 2060

Different from most developed nations, large developing countries including China, Russia, Indonesia, and Brazil have set their carbon neutrality goals by 2060. According to a report from the Center for Social and Economic Progress (CSEP), developing nations typically require longer than 2050 to achieve net-zero emission (Ahluwalia & Patel, 2021). For instance, Li et al., demonstrated that China is likely to reach carbon neutrality by 2060 if the increasing forest carbon sinks can reduce 768 $MtCO_2$/year during the next four decades (2021-2060) (Li et al, 2022). Similarly, the Ministry of Energy and Mineral Resources (MEMR) and National Electric Company of Indonesia have announced that the major policy head toward replacing the dominance of fossil fuels completely with renewable energy sources by 2060 (Permana et al, 2022).

2.2 Economic approach to NZEBs

Buildings are one of the three major sectors responsible for high energy demand and GHG emissions. In addition to the study of building energy optimization, analyzing the payback period of building energy systems is another emerging topic that characterizes the economic feasibility of implementing NZEBs. In fact, many building owners these days consider the “payback period” as a critical index for evaluating the worth of investment for their building systems. For instance, recently in 2021, Wang et al., evaluated the comprehensive performance of a new dual-source building energy system using photovoltaic-thermal (PV/T) technology, assuming that the use of renewable energy sources is essential to reduce both building energy demand and environmental loads (Wang et al., 2021). This study made use of the TRNSYS simulation tool. The results show that the dual-source energy system has a payback period of 3.66 years, which can save 10% of annual operation cost by using load forecasting data such as the real-time price of electricity.

In recent years, the investigation of the payback periods for building energy systems is being actively conducted as a part of economic analysis. This research approach will help many building designers to understand and support the knowledge of integrating such economic models into the built environment. First of all, this section classifies the previous studies that have analyzed the economic feasibility of implementing NZEBs. Table 1 illustrates the previous studies examining NZEBs from economic perspectives.

Table 1.
Literature review: previous studies analyzing the economic feasibility of NZEBs.

No.	Author(s) & Year	Title of paper	Research idea	Methodology	Limitations	Results & Major findings
1	Pacheco & Lambert (2013)	Assessment of technical and economic viability for large-scale conversion of single-family residential buildings into zero energy buildings in Brazil: Climatic and cultural considerations.	Addressing the economic feasibility of constructing NZEBs in Brazilian single residential sector.	Economic calculation (Internal Rate of Return; IRR) for PV technology based on simulation research: 1) high electricity tariffs and tax exemption, 2) low electricity tariffs and tax exemption, 3) low electricity tariffs and no tax exemption.	Higher residential electricity tariffs in Brazil than the developed nations, causing inconsistencies in applying the standard zero-energy building strategies.	Brazil must establish its own ZEB strategies, given that the climatic and economic conditions remarkably differ from those of the developed countries. The government should allow selling PV energy credits for economic gain.
2	Alirezaei et al. (2016)	Getting to net zero energy building: Investigating the role of vehicle to home technology.	Achieving NZEB by connecting vehicles, buildings, and renewable energy sources to work as a single techno-ecological system.	Simulation research based on Design-Builder software tool. Comparing building energy demand (heating, cooling, and lighting) and capital costs for different building scenarios.	High capital cost of installing solar panels, causing high life cycle cost in a complete sense.	Single techno-ecological system can help save on building operation costs and energy demand from the grid. The reduction in utility cost and grid energy demand is 62 and 68%, respectively, compared with that of regular buildings.
3	Hemmati (2017)	Technical and economic analysis of home energy management system incorporating small-scale wind turbine and battery energy storage system.	Home energy management system (HEMS) incorporated with wind turbine and battery will determine optimal capacity and electricity charging pattern for BESS.	Simulation research based on MATLAB software tool. Comparing building energy demand, annual operation cost, and GHG emissions for different HEMS scenarios.	HEMS utilizes energy storage systems (ESS) with multiple energy uncertainties.	HEMS integrated with wind turbine and BESS can reduce 14% of purchasing energy from the grid. In addition, fuel cell vehicle enables 40% drop in building energy operation cost.

No.	Author(s) & Year	Title of paper	Research idea	Methodology	Limitations	Results & Major findings
4	Wells et al. (2018)	A review of Net-Zero Energy Buildings with reflections on the Australian context.	Identifying the ambiguity of net-zero energy building (NZEB) by exploring the progression and potentials of the related research.	Case study of global trends in NZEBs based on literature review.	The term "net-zero energy building" still lacks a universally agreed definition. Thus, validating the economic feasibility of NZEB is impossible.	A universally agreed definition for NZEB develops clear polices for Australian context. In general, developed countries such as the USA, Canada, and European Union are leading the way in creating their own NZEB policy models.
5	Asaee et al. (2019)	Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings.	The techno-economic feasibility of adopting NZEB strategies for existing housings in the Canadian context.	Comprehensive analysis on building energy demand, operation cost, and GHG emissions using Canadian Hybrid Residential Energy and GHG emissions Model (CHREM) tool.	Difficult contexts for generalizing Canadian housing stocks, climate conditions, and geographical features.	Canadian housing stocks have high potentials for techno-economic feasibility, resulting in substantial savings for energy demand and GHG emissions.
6	Li et al. (2019)	Energetic and economic evaluation of hybrid solar energy systems in a residential net-zero energy building.	In the context of Singapore residential housings, NZEBs can be achieved by integrating solar PV systems with insulated solar glasses.	Energy and economic analysis on 12 different building scenarios in Singapore context. Validating between TRNSYS simulation results and standard test reports.	Lack of considering other renewable energy sources such as geo-thermal technology (e.g., ground-source heat pump).	Integrating solar PV, insulated solar glass, and air-source compression chiller turn out to be the most favorable solutions for reaching net-zero in Singapore residential sectors.
7	Qin & Pan (2020)	Energy use of subtropical high-rise public residential buildings and impacts of energy saving measures.	Enhancing the knowledge regarding the energy performance of high-rise residential areas in subtropical climates.	Sensitive analysis on multiple building energy saving measures (ECM) using Energy-Plus simulation tool.	The study results may vary depending on various factors (e.g., climatic conditions, building shape, and building type).	Among the 13 ESMs covered in this study, 1) Human behavior (operation schedule), 2) HVAC system type, and 3) renewable energy sources were the three impactful measures for controlling building energy demand.

No.	Author(s) & Year	Title of paper	Research idea	Methodology	Limitations	Results & Major findings
8	Arabkoohsar et al. (2021)	A highly innovative yet cost-effective multi-generation energy system for net-zero energy buildings.	Making progressive steps toward the actual definition of NZEB. Innovation in energy performance and cost effectiveness.	Simulation research based on MATLAB software tool. Performing multi-objective optimization (energy, economic, and environmental perspectives) on different building configurations using genetic algorithm.	The payback period for each building system excluded the discount rate. In this study, only simple payback period was considered in the economic analysis.	The electrical capacity of batteries and cold storage systems were the two most effective parameters for improving the overall performance of building energy systems.
9	Zhang et al. (2021)	Methodology for developing economically efficient strategies for net-zero energy buildings: A case study of a prototype building in Yangtze River, China.	Establishing a systematic guideline for selecting the most economical design option towards NZEB.	Systematic economic analysis on building energy optimization including LCC and benefit-cost analysis. A study based on dynamic building performance simulation.	Some minor cost and benefit elements have been completely ignored for simplifying the calculation process of life cycle benefit-cost analysis.	Most economical design options for a prototype building in YRD region of China are as follows: 1) HVAC unit: VRF system 2) Wall thickness (XPS): 20mm 3) Roof thickness (XPS): 60mm 4) Glazing type: Low-E double 5) Renewables: Rooftop PV

2.2.1 Previous approach toward NZEBs

Recent studies analyzing NZEBs from an economic perspective are progressing in the direction of optimizing: 1) energy performance, 2) cost effectiveness, and 3) environmental impact, of building HVAC systems. For instance, Asaee et al., conducted a holistic approach toward optimizing energy demand, operation cost, and GHG emissions for residential housings in the Canadian context (Asaee et al., 2019). More recently, in 2021, Arabkoohsar et al., used genetic algorithms to find optimal solutions for the energy, economic, and environmental impacts of several building configurations (Arabkoohsar et al., 2021). These multi-objective elements are ultimately used to calculate the economic payback period for each building HVAC systems. Similarly, Zhang et al., established systematic guidelines for selecting the most economical NZEB design option (Zhang et al., 2021). More specifically, the economic decision criteria included the simple payback period as well as the life-cycle cost (LCC) and benefit-cost ratio (BCR) of the building scenarios covered in the study. However, in the field of NZEB, few studies have focused on the level of technological and institutional improvements urgently required to achieve the carbon neutrality goal on time. Therefore, the following section will discuss the research approach to which economic studies on NZEB should proceed.

2.2.2 Integrative approach toward NZEB

The term “net-zero energy building (NZEB)” completely lacks a universally agreed definition, only creating uncertainties and abstract purposes (Moghaddasi et al., 2021). To understand the goal of designing NZEB, a variety of technical, economical, and environment perspectives should be considered during its development process (Ahmed et al., 2022). The criteria to achieve “net-zero” can be classified into three categories, depending on the energy flow stage that needs to be identified: 1) net-zero emission building (i.e., environmental target considering the elements of primary energy demand), 2) net-zero operation cost building (i.e., economic target considering the elements of secondary energy demand), and 3) net-zero ~~emission~~ energy building (i.e., technological target merely considering the elements of use energy demand) (Cellura et al., 2014).

The primary energy demand is the gross energy including all the losses resulting from energy transportation and power plant inefficiencies. The amount of energy delivered to the grid must be traceable to the form of primary energy when quantifying the actual amount of the GHG emissions. As a result, understanding the broader concept of energy flow is essential for developing the strategies to reduce the GHG emissions more effectively.

Second, the building energy operation cost is a quantitative indicator that can be calculated by the secondary energy demand, which still includes the loss factors resulting from electric distribution and HVAC system efficiencies. The building energy operation cost provides the building occupants with basic information, including the breakdown of their electricity bills and daily usage patterns (Shakouri & Kazemi, 2017).

Finally, the grid energy demand is one of the fundamental outputs that can be calculated directly from the use energy demand. The term ‘use energy demand’ refers to the amount of thermal energy necessary for the occupants to maintain comfort inside a building. Energy at this stage does not include the loss factors resulting from electricity transmission or distribution to each individual household.

In general, “net-zero emission”, associated with the most comprehensive phase of energy (primary energy), has been the ultimate goal for implementing NZEBs (Cielo & Subiantoro, 2021). When the objectives of the research field have been clearly identified, studies should be directed toward considering realistic measures to meet the carbon neutrality goal on time. Specifically, this study proposes the level of technological and institutional advancements required to successfully achieve the 2050 net-zero emission target in the U.S. residential sector. In addition, this study considers the economic benefits resulting from renewable tax credits supported by the federal government. The next section briefly discusses the federal tax credits for the renewable energy sources covered in this study.

2.3 Governmental support for renewable energy sources

In the United States, “Investment Tax Credits (ITC)” for supporting energy efficiency were first enacted by the Energy Policy Act (EPACT) of 2005 (Gold & Nadel, 2011). During the early stages, most tax credits supported up to 10% of the energy system investment costs, which have been significantly increased to 26% since 2009 (U.S. DOE). To this day, the 26% investment tax credit has been continuously extended by the federal government, encouraging many residential owners to install renewable energy sources. More specifically, the following section will discuss the investment tax credits for the two renewable energy sources mainly covered in this study: solar and geothermal heat pump tax credits.

2.3.1 Solar tax credit

The “Solar Investment Tax Credit (ITC)” is one of the best-known federal policy operations to support the widespread of solar power in the United States (Solar Energy Industries Association). An extension of the solar tax credit was passed by the congress in December 2020. According to the recent policy, the government offers a 26% tax credit rate for any solar systems installed in residential housings between 2020 and 2022. However, the ITC support will be reduced to 22% for systems installed by the end of 2023. In addition, the tax credit will completely expire from the beginning of 2024 unless the congress takes any further action (U.S.DOE). Solar power is one of the most common renewable energy sources utilized across the United States; Therefore, extending the solar tax credit will be an important policy action to support the implementation of NZEB by the target period, 2050.

2.3.2 Geothermal heat pump tax credit

Geothermal energy is another popular type of renewable energy source, which uses heat from the earth to produce electricity. Similar to the use of solar power, the federal government allows building owners to claim financial support for installing HVAC systems running based on ground-source heat. Currently, the tax credit stands at 26% of the total investment cost by the end of 2022. However, this credit rate will decrease to 22% from the beginning of 2023 and will eventually expire in 2024 unless a new ITC is passed by the U.S. congress (Climate Master). Since the upfront cost of ground-source heat pump (GSHP) is still very high, extending the geothermal heat pump tax credit at a reasonable rate will encourage many residential owners to practice net-zero emission with less economic burden.

CHAPTER 3

Methodology

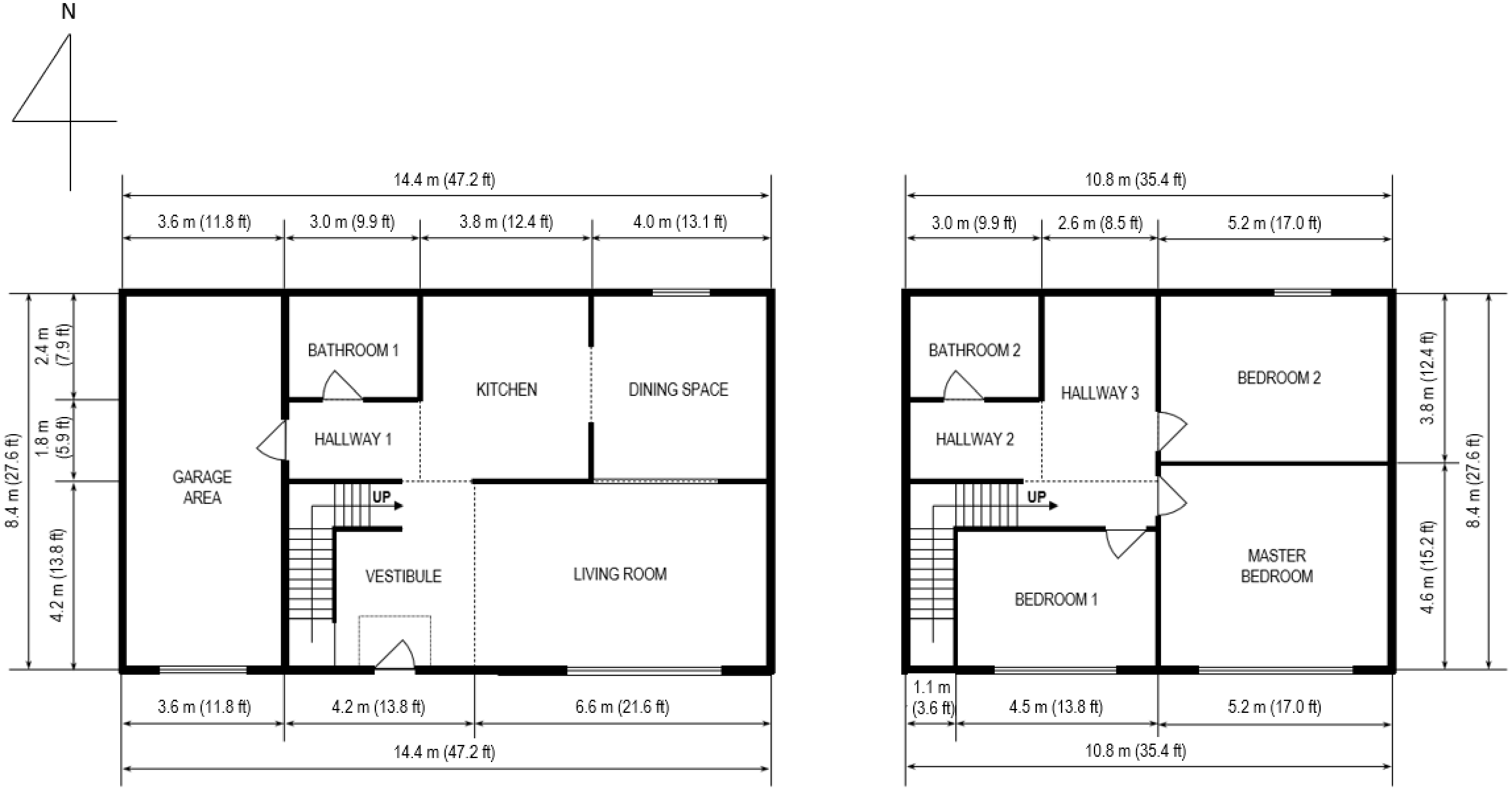
This section describes the methods used to analyze the economic feasibility of net-zero energy building (NZEB) covered in this study. The first subsection explains the basic setup of the simulated building. This setup includes the components of passive and active systems within the building. The second subsection discusses technological and institutional improvements, which are the key external factors that can be considered to accelerate the implementation of NZEBs. Finally, the third subsection deals with the calculation process of optimizing building performance from energy, economic, and environmental perspectives.

3.1 Research setup

3.1.1 Research object: residential building

In this study, a typical two-story residential house in Ann Arbor, Michigan was simulated using the TRNSYS software tool. More specifically, the residential building has a thermal zone area of 181.44 (m^2) excluding the garage space on the main floor. As shown in Figure 2, this typical home has most of the common areas located on the first floor. On the other hand, most of the private spaces are located on the second floor, running based on completely different energy operation schedules. For reference, Figure 3 shows the schematic design of the technical systems of the object building. To be specific, the HVAC system is operated by utilizing two renewable energy sources (i.e., solar P.V. and geothermal heat pump), which are directly connected to the warm water storage system. The hot water from the warm water storage tank is then used to heat each thermal zone via a radiant floor heating system. In terms of air movement, the mechanical ventilation system circulates fresh air by utilizing the heat recovery ventilator (HRV). In summary, Figure 4 represents the schematic drawing of the object building, showing the 3-Dimentional view of the layout including architectural sections, HVAC systems, and renewable energy sources (i.e., solar P.V. and geothermal heat pump).

Table 2 describes the passive design characteristics of the target building. These passive design elements include not only the dimensions, but also the physical conditions of the residential building. In this study, all the passive design components are set as unchangeable values including the insulation level (U-value) of the building structure. In accordance with the building code of climate zone 5, the insulation level of walls, floors, and ceilings are 0.27, 0.19, and 0.12W/m^2·K, respectively (IECC, 2021).



(a)

(b)

Figure 2. Floor plan of the object building. (a) First floor with common areas (kitchen, dining room, living room, and vestibule). (b) Second floor with private areas (bathroom, hallways, and three bedrooms).

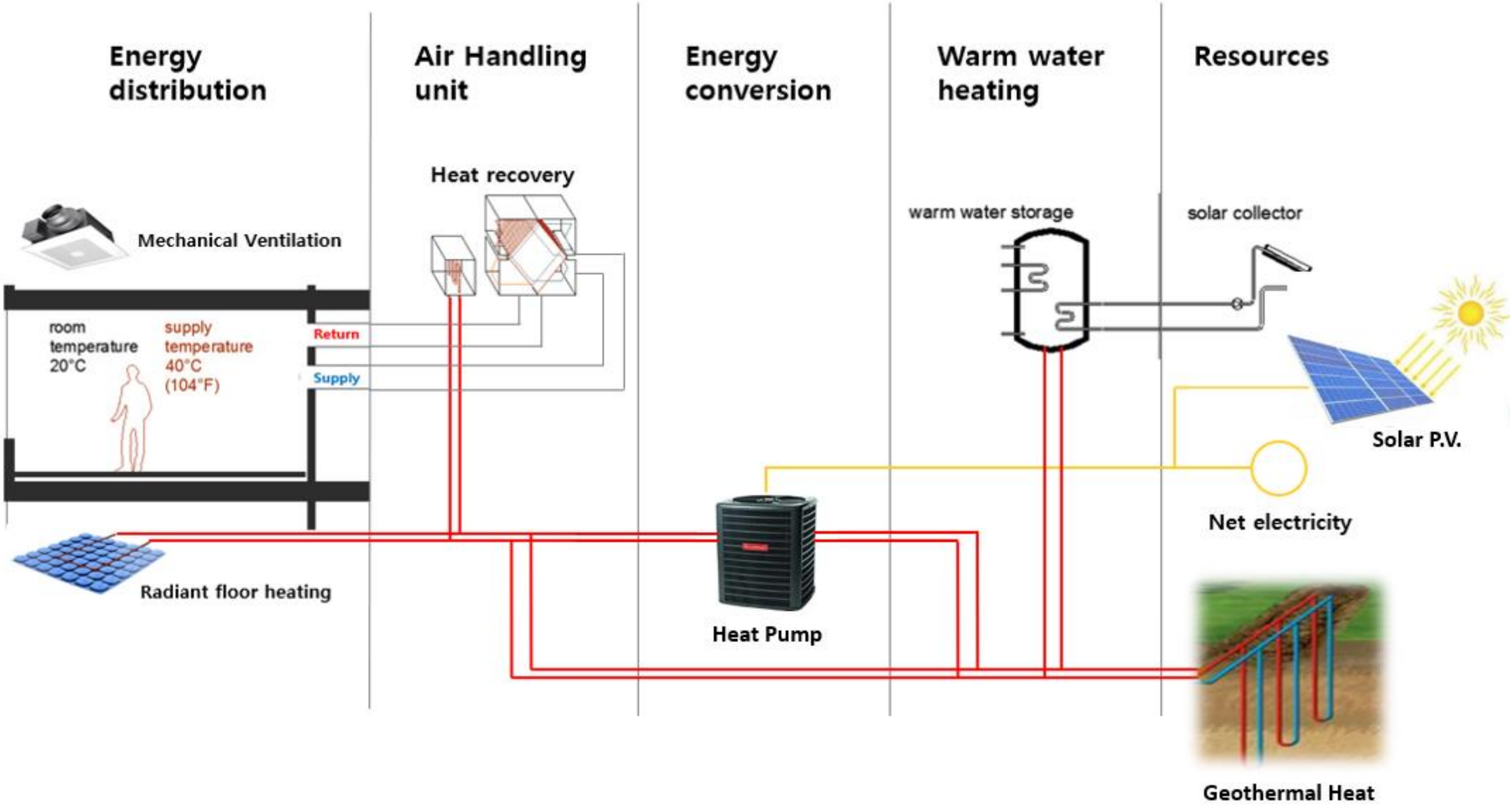


Figure 3. Schematic design of the technical systems. The HVAC system is composed of radiant floor heating, heat recovery system, warm water storage, heat pump, and two renewable energy sources (i.e., solar P.V. and geothermal heat).

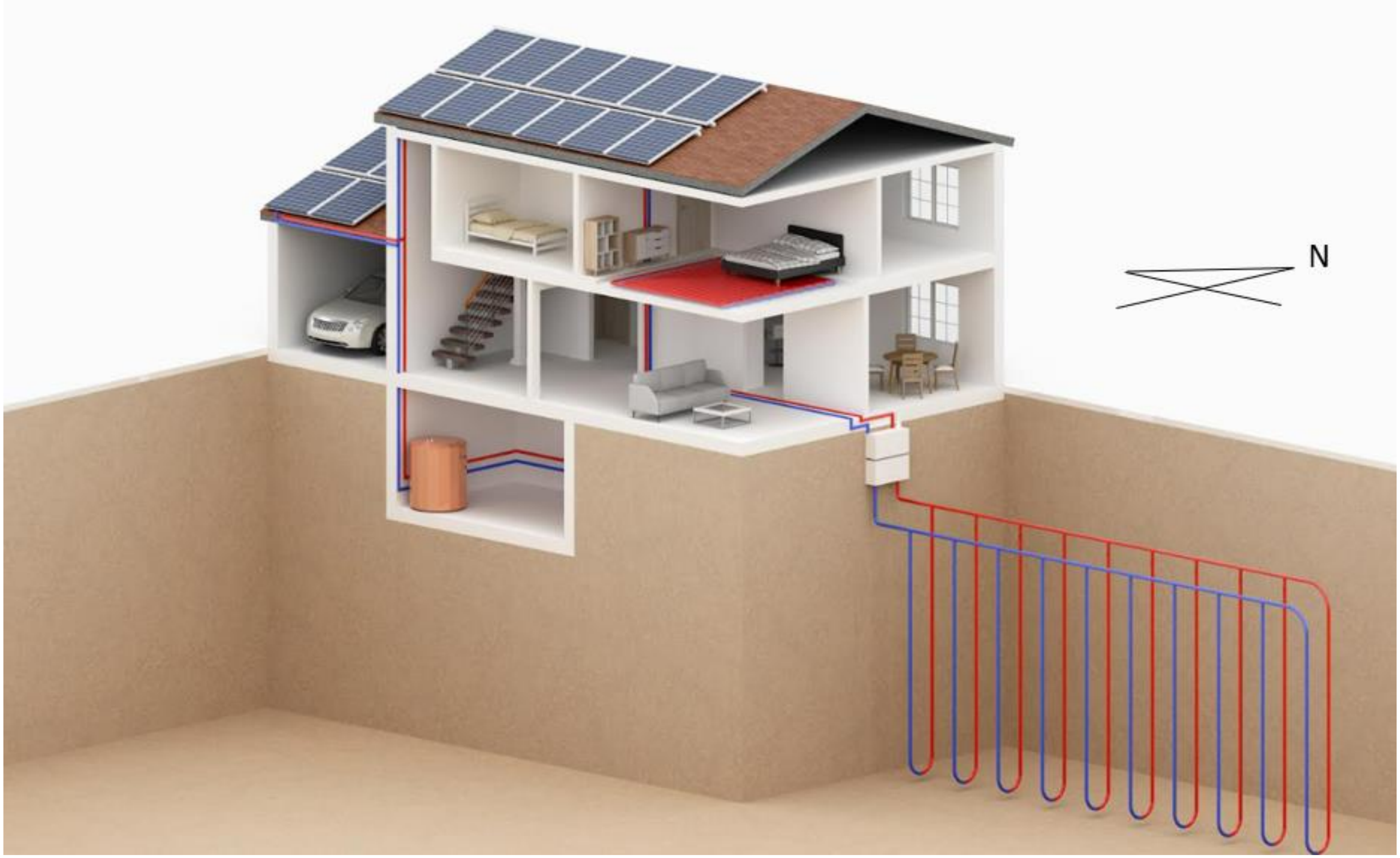


Figure 4. Schematic drawing of the object building (3-Dimensional), including the HVAC systems and renewable energy sources (i.e., solar P.V. and geothermal heat pump).

Table 2.
Passive design components of the target building (Ann Arbor). All the information shown in the table are unchangeable values, corresponding to the fixed variables of this study.

Building specifics	
Thermal zone area	181.44 (m^2)
Roof area	104.76 (m^2)
Number of floors	2
Height	6.0 (m)
Building orientation	0° (main entrance facing directly towards south)
U-value (wall)	0.27W/m^2·K (R-21)
U-value (floor)	0.19W/m^2·K (R-30)
U-value (ceiling)	0.12W/m^2·K (R-49)
U-value (glazing)	1.20W/m^2·K (Low-E double glazing)
Window to wall ratio	South façade (40%) / North façade (15%) / East façade (20%) / West façade (20%)
Shading coefficient (SC)	0.15 (exterior venetian blind)
Infiltration rate	0.10 (ACH)
Natural ventilation rate	32 (m^3 / person / hour)

3.1.2 HVAC systems

This section deals with the type of HVAC systems considered in this study. In this ~~paper~~ dissertation, the HVAC systems are categorized into four scenarios, all of which include heat recovery systems. Specifically, these HVAC systems include: (1) air-source heat pump (ASHP), (2) PV-integrated ASHP (PV+ASHP), (3) geothermal or ground-source heat pump (GSHP), and (4) PV-integrated GSHP (PV+GSHP). These scenarios deal with all cases of combining the most common types of heat pump systems with two different renewable energy sources: solar and geothermal heat. Each system will be described in detail in the following section.

(1) Air-source heat pump (ASHP)

Air-source heat pump (ASHP) is one of the most common types of heat pump systems in nearly all regions of the United States. One of the important characteristics of ASHP is that the system can be used for both heating and cooling purposes without installing independent cooling appliances (Udovichenko & Zhong, 2020). In this study, ASHP was used as a benchmark for comparison with the other HVAC systems integrated with renewable energy sources. More specifically, the ASHP applied in this study is an "air-to-air split unit system" in which the supply- and return-air ducts are directly connected to the indoor central fan. The most important aspect to describe the performance of all heat pump systems is the coefficient of performance value (COP-value). This technical value represents the ratio of useful heat supplied (or removed) to the energy input required by the system (COP 1.0 = 100%), and the efficiency is highly dependent on the difference between the outside-air and the supply-air temperatures.

Although the efficiency of heat pump systems highly depends on the temperature difference between the outdoor- and supply-air, the COP-value of ASHP was set to 2.0 ~ 3.0 for heating, and 1.3 ~ 2.8 for cooling (Aprianti et al., 2021). For reference, the figure below represents the dynamic performance map of ASHP depending on the heat source temperature (Figure 5). As illustrated from the graph, the COP-value of ASHP shows a large deviation depending on the temperature of the heat source.

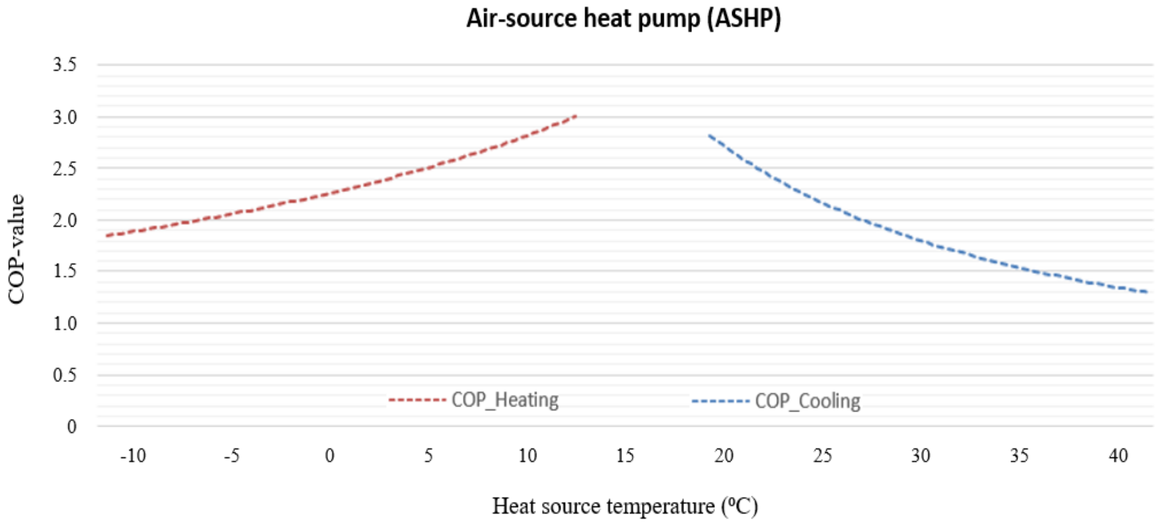


Figure 5. Performance map of ASHP depending on the heat source temperature.

(2) PV-integrated ASHP (PV+ASHP)

The first renewable energy source considered in this study is the photovoltaic (PV) system which generates electricity by converting the solar energy. Solar PV, which generates power by converting solar energy into direct current electricity, is one of the most widely implemented technologies compared to any other renewable sources (Baccoli et al., 2021). In response to the increasing demand for renewable energy these days, building engineers have made huge efforts to reduce energy supply from the grid by placing PV panels on the building elements (wall, roof, shading devices). Also, many national governments around the world are offering financial incentives to encourage building owners to install PV panels (Zambrano-Asanza et al., 2021), and this approach is expected to be worth investing in reducing the payback periods of building energy systems. For these reasons, the residential building covered in the present study also incorporates the scenario that combines 'photovoltaic systems' with 'air-source heat pump (ASHP)'.

In this study, the PV-integrated system is also connected to an energy storage system (ESS) to efficiently balance the energy supply and demand. To be specific, in the TRNSYS software tool, P.V. panels and electric batteries were simulated using "Type 94a" and "Type 47", respectively (Mazzeo et al., 2020). For reference, the P.V. module applied to the software is a mono-crystalline with an area of 0.89 (m^2) per panel. The tilt angle of the P.V. array was fixed at 30 degrees, since "Type 94a" does not include a solar tracking sensor. In terms of the energy storage system (ESS), Type 47 is a lead-acid battery with an electric capacity of 1.20 (kWh). In this system, energy is first supplied from the PV, then transferred to the storage system. This stored energy can be kept for later use, and the energy exceeding the capacity of the electric storage (1.20kWh) is sold back to the grid. This process significantly contributes to reducing not only the utility bills but also the need for energy supply from the grid (Kim & Junghans, 2022).

For experimental purposes, this study assumes that the rooftop area of the object building is heavily installed with solar PV (100% solar rooftop on both sides of the sloped roof). In summary, utilizing the PV-integrated ASHP is suitable for the climate of Ann Arbor, Michigan which receives sufficient solar radiation during the summer season.

(3) Ground-source heat pump (GSHP)

Ground-source heat pump (GSHP), commonly known as the geothermal heat pump, generates electricity by collecting the heat underneath the ground. More specifically, the GSHP covered in this study is a vertical loop water-to-water heat pump which draws heat from nearly 120 meters below the ground level. Since the temperature underneath the ground is relatively constant throughout the year (10 ~ 15°C (i.e., 50 ~ 60°F)), heat transfer between the earth and the heat pump is much more efficient than most of the conventional HVAC systems. Generally, the COP-value of GSHP can be well maintained at a level between 3.5 and 5.0 (Aprianti et al., 2021). The seasonal COP-value of the GSHP is calculated by averaging the COP-values over the heating season. Unlike the COP-value of ASHP, which varies depending on the outside air temperature, the COP-value of GSHP is relatively constant like the temperature of the underground heat source. However, the vertical loop GSHP is also well-known for its high upfront cost due to the expense of drilling boreholes deeply underneath the ground. This economic drawback usually gives geothermal heat pumps having a long payback period (Mensah et al., 2017).

(4) PV-integrated GSHP (PV+GSHP)

In this study, PV+GSHP is the most integrated type of HVAC system, which is combined with both solar and geothermal heat sources. This system was also simulated by integrating with the ESS to efficiently balance the energy supply and demand. In this integrative system, supplied energy from both solar and geothermal heat can be transferred to the storage system for later use. As a result, the use of batteries in the residential sector can significantly reduce the reliance on electricity grid (Tumminia et al., 2020). From an economic perspective, energy exceeding the capacity of ESS (1.20kWh) is automatically sold back to the grid.

In summary, the PV+GSHP is structurally designed to optimally reduce 1) energy demand, 2) utility cost, and 3) GHG emissions of the residential building. These challenges correspond to the three major aspects pursed by net-zero energy buildings (NZEBs) as follows: energy, economic, and environmental perspectives.

3.2 External factors

This section addresses two external factors, the level of technological and institutional advancements, required to satisfy the 2050 carbon neutrality goal in the U.S. residential sector. For reference, carbon neutrality refers to a state in which the actual amount of CO_2 emission is reduced to zero by having a balance between emitting CO_2 and absorbing CO_2 from the atmosphere (European Parliament). In this dissertation, the technological and institutional improvements are represented by the "energy conversion rate of P.V. panels" and "CO_2 equivalent price of emission trading scheme (ETS)", respectively. Each factor will be discussed in detail in the following section.

3.2.1 Technological factor: energy conversion rate of PV

The objective of using photovoltaic system is to supply the building energy demand with solar panels as much as possible within the PV capacity range. However, when energy demands exceed the PV capacity, the system will, like a conventional system, draw supply from the grid, and this energy draw will affect both building operation cost and GHG emissions. In this study, the PV-panel applied to the TRNSYS simulation tool is a mono-crystalline type which has an energy conversion rate of 15.0%. This energy efficiency of the PV-panel is regarded as the current technological level and has been set as a benchmark. According to a study conducted by Peng et al., the electric output of PV-panels can be significantly increased by cooling down its surface temperature. More specifically, the results show that PV electric output can increase up to 35% with a payback period of 12.1 years (Peng et al., 2017). Therefore, by targeting carbon neutral 2050, this study analyzes the economic feasibility (payback period) of NZEBs when the current 15.0% P.V. energy conversion rate is gradually increased to 35.0%.

3.2.2 Institutional factor: CO_2 equivalent price of ETS

Although recent studies have deeply considered building energy optimization in terms of environmental perspectives, few of these previous works have investigated the influence of green policies on reducing both the economic and environmental costs of operating residential buildings. The first ‘Emission Trading Scheme (EU-ETS)’ was enacted by the European Parliament in 2003. Therefore, European Union has presented the standard for all ETS around the world, based on having the longest history of this policy.

In addition to Europe, Cielo & Subiantoro investigated the socio-economic factors that challenge the implementation of net-zero energy buildings (NZEBs) in New Zealand (Cielo & Subiantoro, 2021). An economic analysis, calculating the net-present value (NPV) and payback period of NZEB, was conducted through the collection of secondary data and a systematic literature review. According to the calculation results, NZEB have NPV and payback period of 14 and 18 years, respectively. In conclusion, this research demonstrates that even though New Zealand has suitable conditions for constructing NZEB in terms of climatic, technical, and economic perspectives, the development of NZEBs highly requires the adoption of environmental policies and legislations (i.e., ETS).

In the United States, 14 out of 50 states have adopted the emission trading scheme (ETS) as of 2020 (Figure 7). According to the U.S. Energy Information Administration (U.S. EIA), California has become one of the leading states actively implementing this environmental policy, with a CO_2 equivalent price of $28.26 USD per ton (i.e., $28.26 USD/t$CO_2$) in April 2022. To be specific, the figure below represents the CO_2 equivalent prices of California cap and trade (ETS) in quarterly intervals (Figure 6). As shown in the figure, different from the gradual increase over the past decade, the auction price has risen sharply during the most recent years. For reference, the CO_2 equivalent price of California cap and trade was $17.71 USD/t$CO_2$ in Q3 of 2021. The increase in CO_2 equivalent price results from the growing demand for such green policies. Therefore, along with the technological improvement, this study deals with the effect of adopting ETS on improving the economic feasibility of NZEBs.

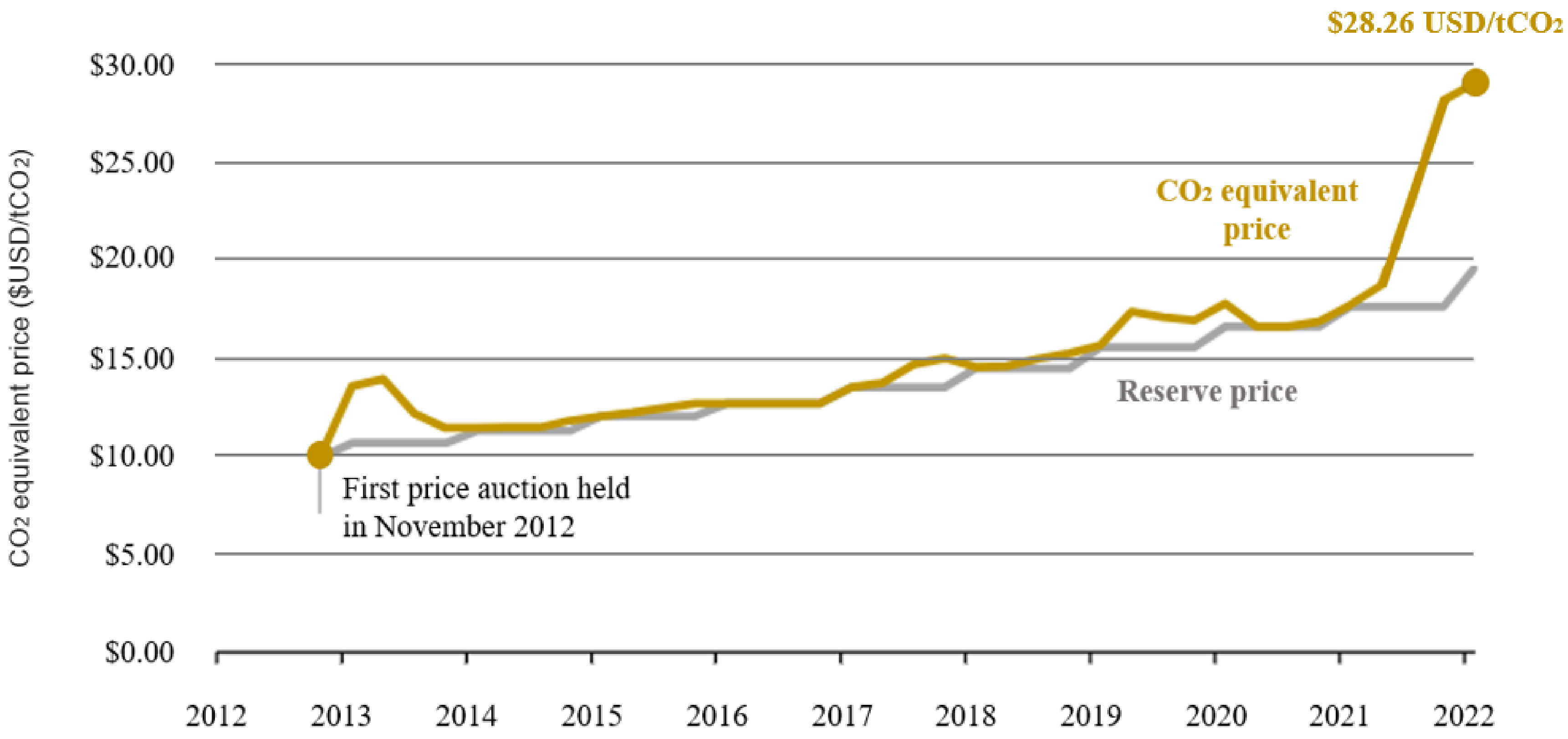


Figure 6. CO_2 equivalent price of California cap and trade ($28.26 USD/t$CO_2$)
(U.S. Energy Information Administration, 2022.04).

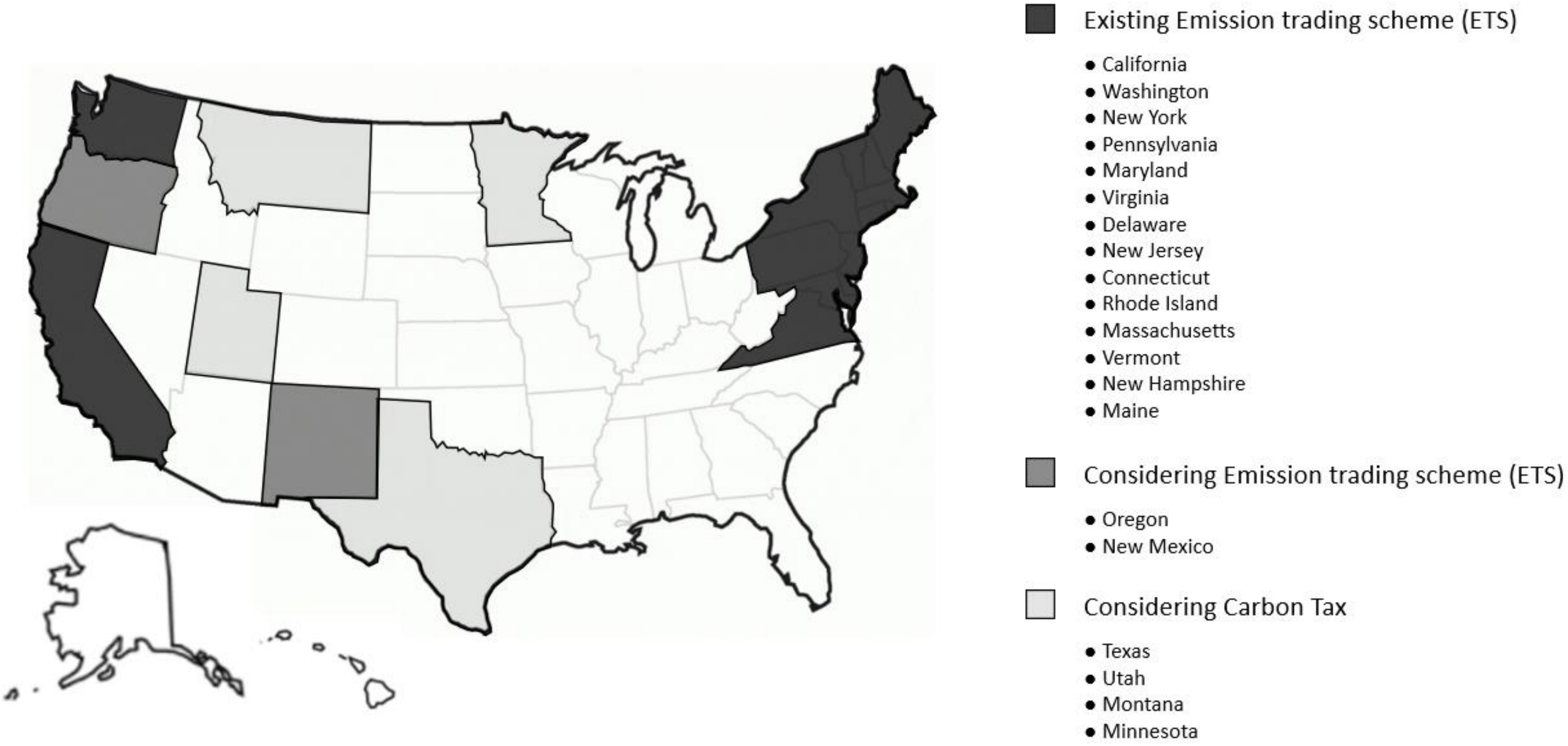


Figure 7. Environmental policies in the United States (U.S.EPA, 2020). As of 2020, 14 out of 50 states have adopted the 'Emission Trading Scheme (ETS)'.

3.3 Calculations

In recent years, there have been numerous efforts to reduce the building energy demand in residential buildings (Karunathilake et al., 2018). However, most of the conventional studies in building energy optimization merely deal with the final energy outcome, the use energy demand, without deeply considering the fundamental energy state concepts such as primary and secondary (site) energy demands (Figure 8). For this reason, the current research intends to simultaneously address the three major challenges of building energy optimization: energy demand, operation cost and GHG emissions. Once the three topics are covered, this study goes on to calculate the payback periods of several building scenarios with different renewable energy sources integrated to a heat pump system. Such an integrative approach to find economic feasibility of NZEBs can provide the public with deeper understanding of sustainable building design, leading to increase public awareness of the global energy issues and their negative impact, climate change (Nejat et al., 2015). Therefore, taking action towards this worldwide issue requires the development of technology and policy at the national government level.

The main challenge for implementing net-zero energy buildings (NZEBs) is to achieve “carbon neutrality” by optimizing three perspectives: 1) grid energy demand, 2) operation cost, and 3) GHG emissions. Each task is directly related to energy, economic, and environmental concerns resulting from building operations. This simultaneous analysis in turn results in a more integrative economic analysis. Economic support can be provided through various options including tax credit, direct subsidy or market-based compensation when building owners are aiming to reduce the payback period of each building system by adopting green policies (Gan et al., 2007). Clearly, under this analytical framework, environmental policies for building energy optimization will promote not only economic benefits for individual building owners, but also positive environmental impacts for the entire society. Therefore, this section introduces the calculation procedure for the three major factors, which are subsequently used to analyze the economic feasibility (e.g., payback period) of NZEBs.

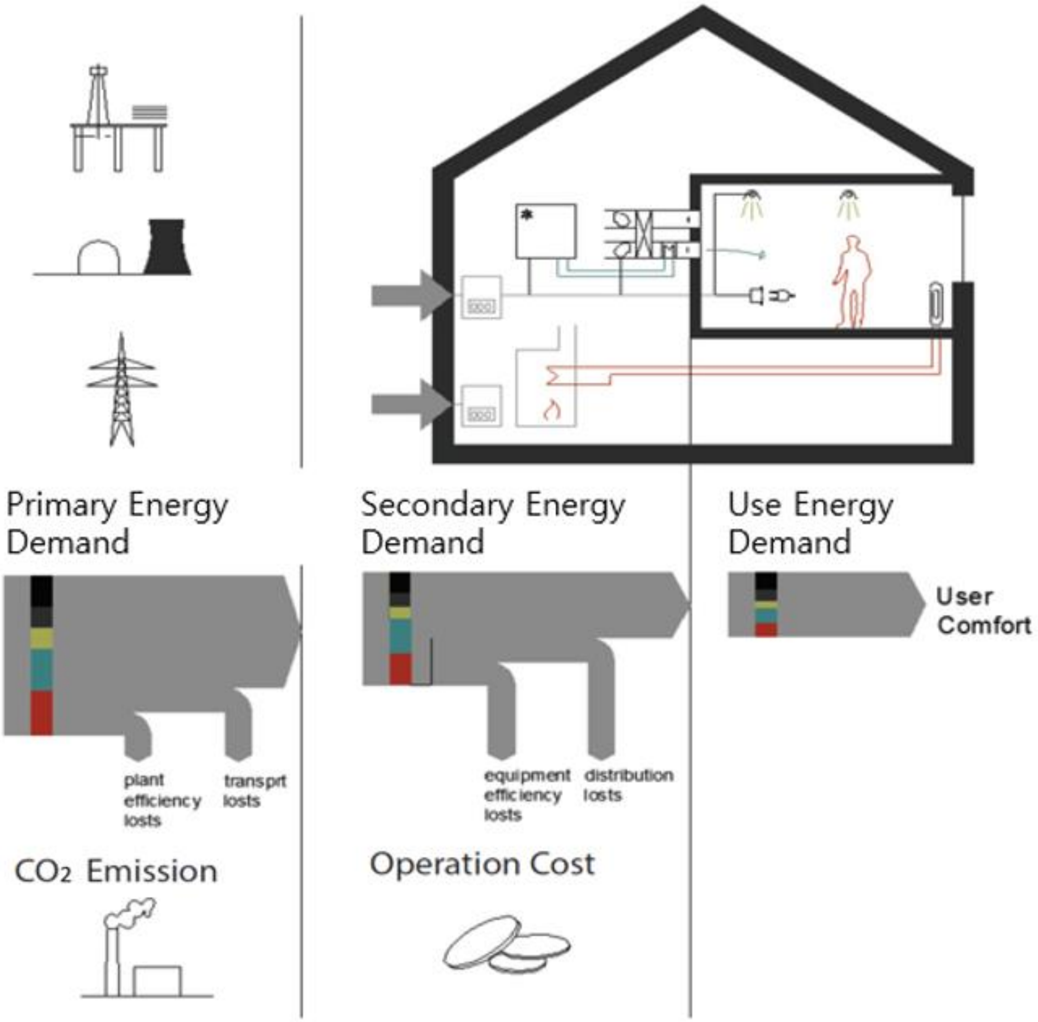


Figure 8. Concept diagram of electricity flow (primary, secondary, and use energy demand). The three major challenges of building energy optimization: GHG emissions, operation cost, and grid energy demand are derived from primary, secondary, and use energy demand, respectively.

3.3.1 Technical perspective: grid energy demand

The annual building energy demand eventually refers to the energy demand from the electricity grid. More specifically, grid energy demand is the final consumer energy used by building occupants, which consider various loss factors such as transportation and distribution losses from the power plant (Casals et al., 2016). In this study, electricity demands for heating and cooling were analyzed using the TRNSYS software tool. The set-point temperatures for heating and cooling were made at the room temperatures below 20 ℃ and above 26 ℃, respectively. The use energy demand for heating and cooling were expressed in the unit of "kWh/(m^2·**y**ear)" to precisely diagnose the energy demand intensity of the object building.

3.3.2 Economic perspective: building operation costs

Most residential owners are familiar with the building energy operation cost given that the electricity bills directly indicate the economic load of each household. Specifically, building operation costs are utility bills paid to local energy companies, which still count the loss factors incurred during the process of generating and transporting electricity from the power plant. However, these utility rates do not include energy losses resulting from insufficient performance of the HVAC systems within the building (Pino-Mejías et al., 2017). Therefore, building energy operation costs are calculated by dividing heating and cooling energy demands by the COP-value of each HVAC system, and then multiplying that value with the real-time price of electricity (equations (1) and (2)) (Kim et al., 2022). Table 3 represents the dynamic peak price of electricity in Ann Arbor (DTE energy, 2022). For reference, the peak electricity rate is the sum of peak charge and distribution charge at each time of the day.

$$E_{heat,\ annual} = \sum_{t=1}^{8760} \frac{Q_{heat,\ t}}{COP_{heat,\ t}} \times (E_{PC} + E_{DC}) \tag{1}$$

$$E_{cool,\ annual} = \sum_{t=1}^{8760} \frac{Q_{cool,\ t}}{COP_{cool,\ t}} \times (E_{PC} + E_{DC}) \tag{2}$$

$E_{heat,\ annual}$ = annual building operation cost for heating

$E_{cool,\ annual}$ = annual building operation cost for cooling

E_{PC} = peak charge of electricity

E_{DC} = distribution charge of electricity

Q_{heat} = building energy demand for heating

Q_{cool} = building energy demand for cooling

COP_{heat} = COP-value of heat pumps (heating)

COP_{cool} = COP-value of heat pumps (cooling)

t = hourly time sequence throughout the year ($0 < t \leq 8760$)

Table 3.
Dynamic peak price of electricity in Ann Arbor, Michigan (DTE energy, 2022)

	Monday – Friday				Weekends & holidays
	Off-peak	Mid-peak	On-peak	Critical peak	
Peak charge (cent/kWh)	4.8	9.2	16.6	95.0	4.8
Distribution charge (cent/kWh)	6.6	6.6	6.6	6.6	6.6
Total peak rate (cent/kWh)	**11.4**	**15.8**	**23.2**	**101.6**	**11.4**

3.3.3 Environmental perspective: building GHG emissions

The main purpose of implementing NZEBs is to minimize the environmental impact resulting from operating buildings (Attia et al., 2013). The amount of GHG emissions include CO_2 produced during the process of generating, transporting, and distributing electricity from power plants to each residential area. Figure 9 below shows the average mixing ratio of each fuel source per month when generating electricity in Ann Arbor, Michigan. Specifically, the data have been collected from the electricity produced by Mid-continent Independent System Operator (MISO), an energy market which is responsible for electricity generation and energy balance in the region where Ann Arbor is located. In addition, Table 4 shows the CO_2 emission factors by each fuel source (IPCC, 2021). The total emission factor of electricity can be calculated by averaging the emission factor of each electrical fuel source according to their quantitative ratio (equation (3)). Finally, the total GHG emissions from a building is the product of heating (and cooling) energy demand and the real-time CO_2 emission factor of electricity (equation (4)).

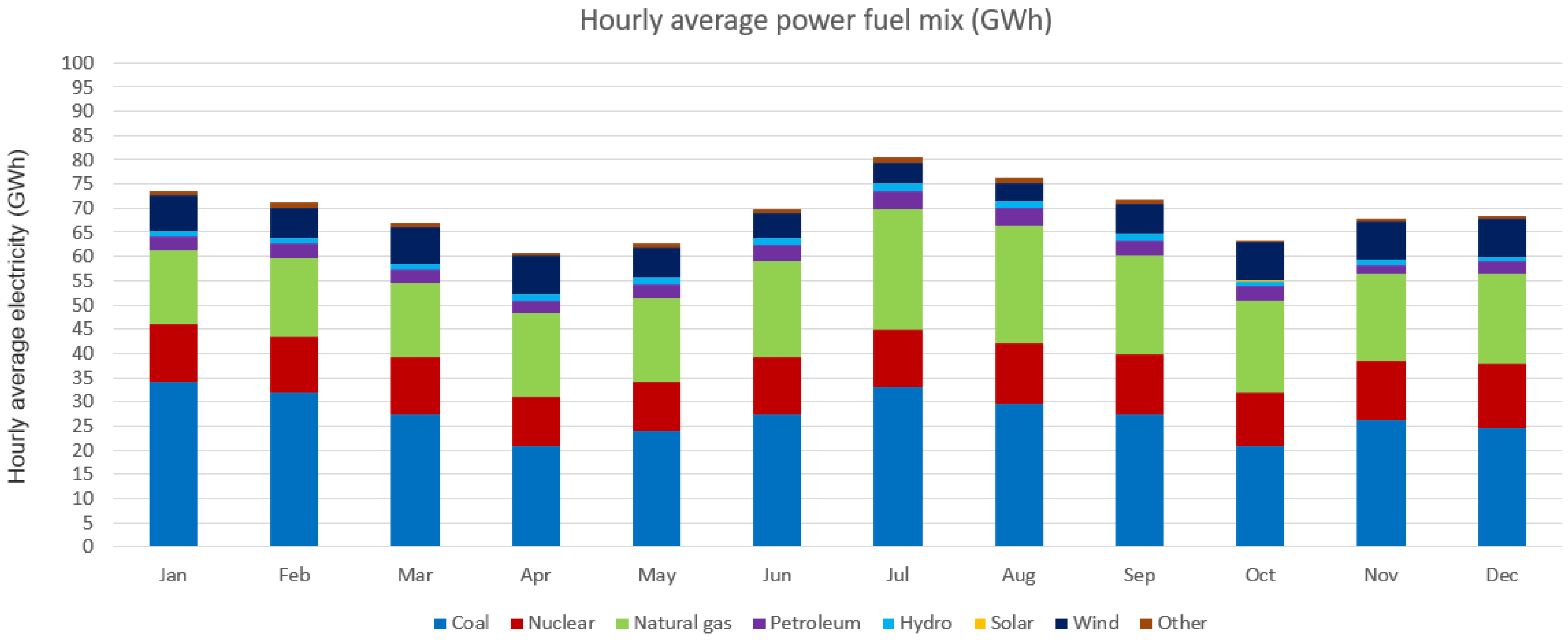


Figure 9. Hourly average power fuel mix per each month in Ann Arbor, Michigan (EIA, 2021). This figure shows the average mixing ratio of each fuel source per month when generating electricity. MISO is responsible for generating (and distributing) electricity in the state of Michigan.

Table 4.

Life-cycle CO_2 equivalent emissions by different fuel sources (IPCC, 2021)

Fuel Source	Emission Factor (gCO_2e/kWh)							
	Coal	Nuclear	Natural gas	Petroleum	Hydro	Solar PV	Wind	Other
	820	12	490	740	24	89	23	268

$$EF_{CO_2\_total} = \sum EF_{CO_2\_fuel\,source} \times \delta_{fuel\,source} \tag{3}$$

$$GHG_{CO_2\_total} = \sum_{t=1}^{8760} EF_{CO_2\_total,\ t} \times (Q_{heat,\ t} + Q_{cool,\ t}) \tag{4}$$

$EF_{CO2\_fuel\ source}$ = CO_2 emission factor by each fuel source (tCO_2e/MWh)

$\delta_{fuel\ source}$ = weighted proportion of each fuel source

Q_{heat} = building energy demand for heating

Q_{cool} = building energy demand for cooling

t = hourly time sequence throughout the year ($0 < t \leq 8760$)

3.3.4 Discounted payback period

This study evaluates the economic feasibility of each NZEB scenario based on a discounted payback period. This economic indicator, which reflects the discount rate of residential facilities, serves as a reasonable criterion for many building owners to consider their long-term investment plans (Shinoda, 2010). The equation below shows the method for calculating the discounted payback period (equation (5)). Specifically, the annual discount rate for the 15-year fixed mortgage loan in the state of Michigan is 4.250(%) as of June 2022 (T&I Credit Union). Conclusively, the economic feasibility of implementing NZEBs is expected to be highly reliable when considering these realistic variables.

$$DPP = \ln\left(\frac{1}{1 - \frac{O_1 \times r}{CF}}\right) \div \ln(1 + r) \tag{5}$$

DPP = discounted payback period

O_1 = Investment cost (outflow)

r = discount rate (= 4.250%)

CF = periodic cash flow

CHAPTER 4

Results

Based on the calculation procedure described in the previous chapter, this section introduces the economic feasibility of several building HVAC systems. More specifically, the results show the potential for achieving net-zero energy building (NZEB) when two renewable energy sources, solar and geothermal, are combined with a typical air-source heat pump (ASHP). First, this study presents the number of solar panels required to achieve the net-zero critical point for 1) energy, 2) economic, and 3) environmental perspectives. For reference, the "net-zero critical point" refers to the point at which the electricity supply from renewable energy sources (solar and geothermal) equals the electricity demand from the grid. Second, this study introduces the economic feasibility of two building HVAC systems, ASHP and GSHP, by calculating the payback period of each unit according to technological and institutional improvements. ~~Specifically,~~ Precisely, the discounted payback period (DPP) was calculated by comparing (1) the investment (material + installation) cost and (2) the building operation cost of each system applied in the study. This study then further analyzes the effect of improving the technological (i.e., P.V. energy conversion rate) and institutional (i.e., CO_2 equivalent price of ETS) factors on reducing the payback period of each building scenario. Especially for GSHP, this section presents the technological improvement (P.V. energy conversion rate) required to achieve the net-zero emission target on time. Finally, this study proposes reasonable tax credit rates for solar and geothermal heat sources to provide economic guidelines for implementing NZEBs.

4.1 Net-zero critical point

The net-zero critical point is derived from the three different perspectives of building energy optimization: 1) energy (grid energy demand), 2) economic (building operation cost), and 3) environmental (GHG emissions). Although this section covers two types of HVAC systems, ASHP and GSHP, the results only present the quantity of solar panels required for GSHP, which is relatively favorable to achieve net-zero in all three standpoints.

4.1.1 Grid energy demand

This section presents the quantity of solar panels required to reach a net-zero critical point, where the energy demand from the grid matches the amount of energy supply from the renewable energy sources. Figure 10 shows the comparison between “grid energy demand” and “renewable energy supply” when ASHP and GSHP are installed in the target building, respectively. In addition to heating and cooling, building energy demand includes electricity use for lighting, electric consumer, and warm water heating. In terms of the energy supply, both “solar” and “geothermal” provide energy to GSHP, whereas “solar” is the only renewable source supplying energy to ASHP.

The unit of grid energy demand is presented in “kWh/($m^2 \cdot$year)”, and the total amount of grid energy demand is shown on the right axis of the graph. For the PV-integrated GSHP, the results show that the critical point for net-zero energy appears when the solar installation area is 110% of the total thermal zone area (181.44 m^2). Meanwhile, for the case of PV-integrated ASHP, net-zero energy cannot be achieved with the same amounts of solar panels since the ground-source heat does not support the energy supply.

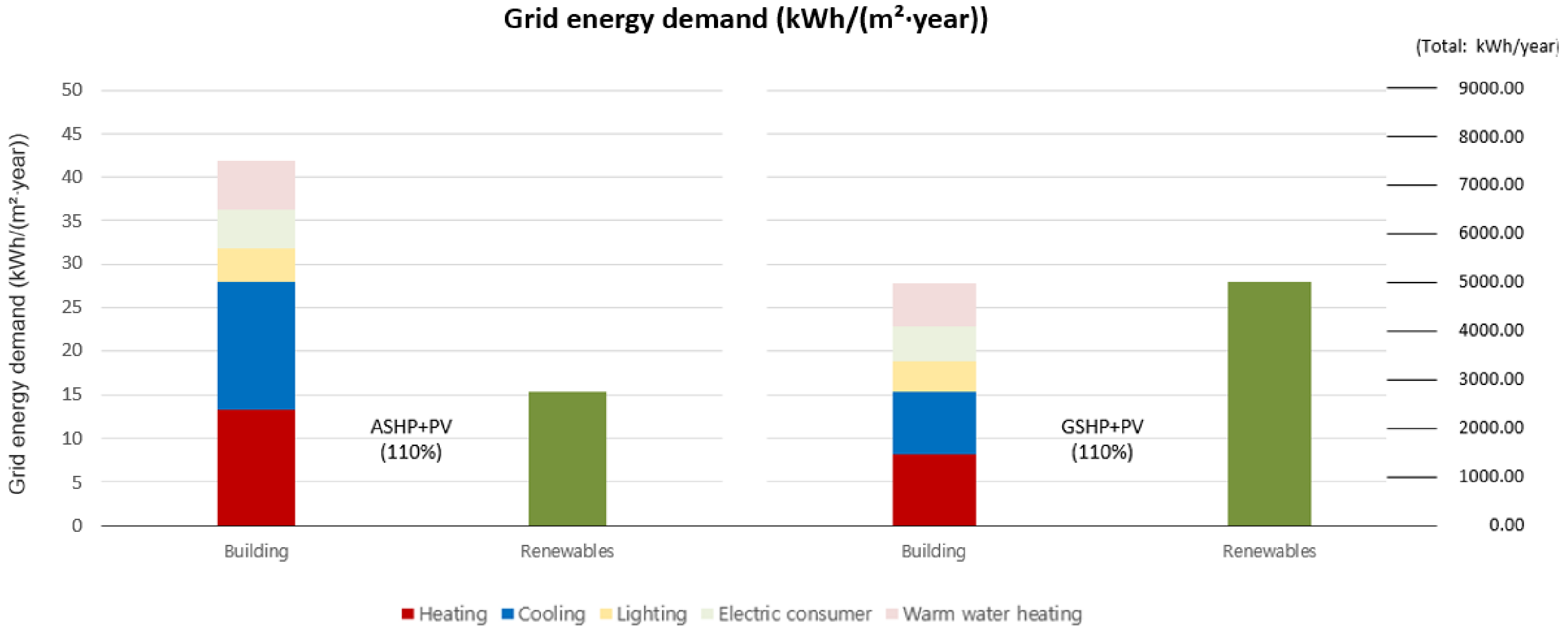


Figure 10. Net-zero critical point for grid energy demand (kWh/(m^2·year)). For the PV-integrated GSHP, net-zero occurs when the solar installation area is 110% of the total thermal zone area. Meanwhile, for the case of PV-integrated ASHP, net-zero can hardly be achieved with the same quantity of solar panels.

4.1.2 Building operation costs

Building operation costs have been one of the main concerns of NZEBs from an economic perspective. Electricity bills from building energy operation is a quantitative indicator that can be calculated from secondary energy demand, which includes the loss factors resulting from energy distribution and HVAC system efficiencies. The building energy operation cost provides the building occupants with basic information, including the breakdown of their electricity bills and daily usage patterns (Shakouri & Kazemi, 2017). Thus, a number of recent studies have considered both building energy demand and energy operation cost while implementing net-zero energy buildings (NZEBs).

This section analyzes the net-zero critical point at which the total energy costs supplied from renewable energy sources can offset the building operation costs. Figure 11 presents the operation costs from "building energy demand" as well as the operation cost savings from "renewable energy supply". Specifically, building operation costs include the use of electricity for heating, cooling, lighting, electric consumer, and warm water heating. Meanwhile, both ASHP and GSHP can achieve energy cost savings by utilizing the renewable energy sources.

The unit of building operation cost is presented in "\$USD/(m^2·**y**ear)", and the total energy cost is also shown on the right axis. For GSHP, the results show that the critical point for net-zero cost occurs when the amount of solar installation is 125% of the total thermal zone area (181.44 m^2). However, for the case without the supply from geothermal energy, net-zero is hardly achievable by using the same amount of solar installation.

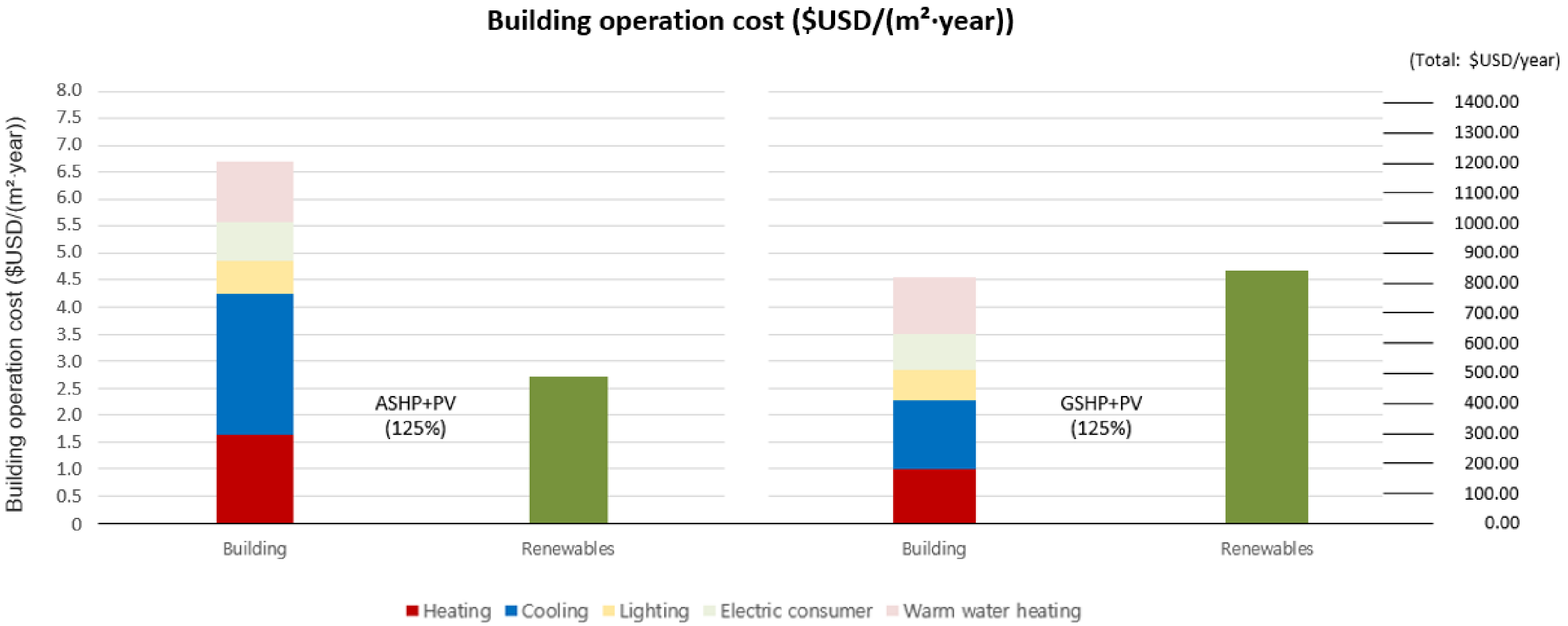


Figure 11. Net-zero critical point for building operation cost ($USD/(m^2·year)). For the PV-integrated GSHP, net-zero occurs when the solar installation area is 125% of the total thermal zone area. Meanwhile, for the case of PV-integrated ASHP, net-zero cannot be achieved with the same quantity of solar panels.

4.1.3 Building GHG emissions

Along with considering building energy demand and operation cost, building energy optimization studies have not been commonly extended to the scope of analyzing primary energy demand and, more crucially, greenhouse gas (GHG) emissions. The primary energy demand is the gross energy including all the losses resulting from energy transportation and power plant inefficiencies. The amount of energy delivered to the grid must be traceable to the form of primary energy when quantifying the actual amount of the GHG emissions. As a result, understanding the broader concept of energy flow is essential for developing the strategies to reduce the GHG emissions more effectively.

GHG emissions are generally understood as the major cause of global warming. Therefore, significant efforts are being made in the building sector to focus on such environmental concern. Since fossil fuels are still the major source of electricity production in most of the developed countries, the amount of GHG emissions from residential buildings continue to grow at a rapid speed (Khan et al., 2016).

For most of the recent studies in the field, the ultimate challenge of NZEB is to achieve net-zero emissions as an environmental task. Therefore, this study also presents a critical point for “net-zero emissions” where the reduction in GHG emissions resulting from the use of renewable energy sources equals the GHG emissions from building operation. Figure 12 describes the amount of GHG emissions produced by the target building when ASHP and GSHP are installed respectively. The figure also shows the amount of GHG emissions that can be reduced by utilizing the renewable energy sources. For reference, the reduction in GHG emissions from non-HVAC sources (lighting, electric consumer, and warm water heating) is relatively minimal because ASHP and GSHP primarily control energy demands for heating and cooling.

The units of GHG emissions are presented in “$kgCO_2/(m^2 \cdot year)$” and “$kgCO_2/year$” to diagnose both the relative and absolute environmental impact of the target building. For both HVAC systems, the results clearly show that the critical point for net-zero emission is hardly achievable even when the quantity of solar installation is over 200% of the total thermal zone area (181.44 m^2). In conclusion, this study demonstrates that “net-zero emission” is the most challenging task among the three target perspectives of NZEB, namely, energy, economy, and environment (Bourrelle et al., 2013).

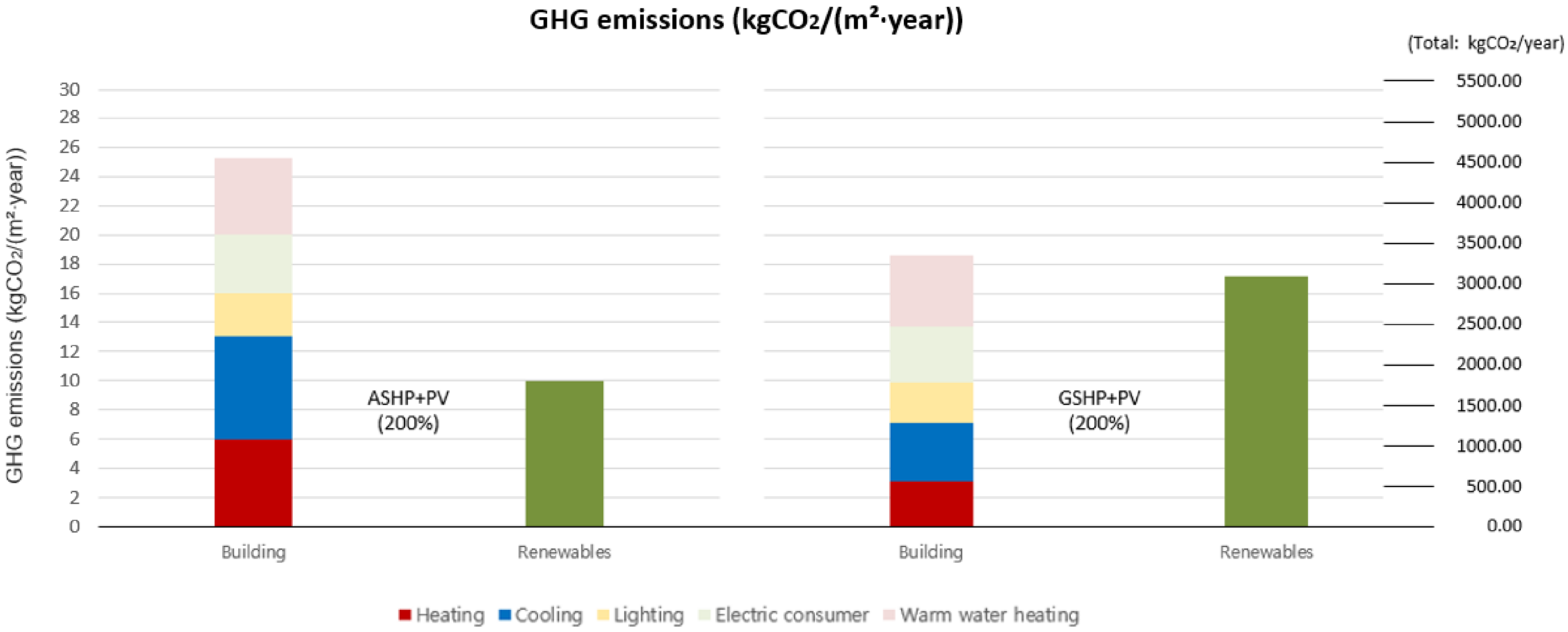


Figure 12. Net-zero critical point for GHG emissions (kgCO$_2$/(m^2·year)). For the PV-integrated GSHP, net-zero cannot be achieved even when the solar installation area is over 200% of the total thermal zone area. This finding clearly shows that “net-zero emission” is the most challenging target among the energy, economic, and environmental perspectives.

4.2 Payback periods

In this section, the payback period for each residential heat pump system is calculated based on the technological (i.e., P.V. energy conversion rate) and institutional (i.e., CO_2 equivalent price of ETS) improvements. First, the discounted payback period (DPP) was calculated by comparing between (1) the investment (material + installation) cost and (2) the building operation cost of each system applied in the study.

4.2.1 No-policy scenario

The payback period of each building system was first calculated without the consideration of Emission Trading Scheme (ETS). In this study, the discounted payback period was calculated for all systems, and the discount rate was set to 4.250% in accordance with a 15-year term fixed rate mortgage in Ann Arbor. For reference, Table 5 represents the total investment costs for each HVAC system applied in this study.

Table 5.
Total investment cost for each HVAC system ($USD). Costs in the parentheses reflect the 26% tax credit rate applied to the use of renewable energy sources (solar and geothermal).

HVAC system types	Mechanical + Installation cost ($USD)			**Total ($USD)**
ASHP	15,000	-	-	15,000
GSHP	25,000 (18,500)	-	-	25,000 (18,500)
GSHP+PV	25,000 (18,500)	5,000 (3,700)	-	30,000 (22,200)
GSHP+PV+ESS	25,000 (18,500)	5,000 (3,700)	1,500	31,500 (23,700)
Heat Recovery	1,750	-	-	1,750

4.2.2 Emission Trading Scheme (ETS)

The institutional solution considered in this study is the application of ‘Emission Trading Scheme (ETS)’. ETS is an environmental policy that provides building owners with economic benefits corresponding to the amount of CO_2 emissions reduced from their buildings. The results of the payback period for each building system are represented in Figures 13 through 17. Except for the benchmark case (Figure 13), Figures 14 through 17 show the results of discounted payback periods when the ETS is applied to each system with incremental CO_2 equivalent prices. As shown in the results, the payback periods for both heat pump systems (ASHP and GSHP) gradually decrease with the improvement of P.V. energy conversion rate. In other words, for solar integrated systems, the reduction in payback period becomes significant with the improvement of its technological performance.

The CO_2 equivalent price of ETS applied in this study provides building owners with an economic benefit of \$28.26 per reducing 1 ton of CO_2 emission (California cap and trade). This economic support can increase with higher demand for ETS throughout the country. For reference, Figures 15 to 17 show the payback period for each heat pump system when the CO_2 equivalent price rises to \$40.00, \$50.00, and \$60.00, similar to the price level of the European Union Emission Trading Scheme (EU–ETS) in March 2022 (Statista, 2022). The growing demand for ETS will result in shorter payback periods for many building HVAC systems, especially by encouraging the use of renewable energy sources.

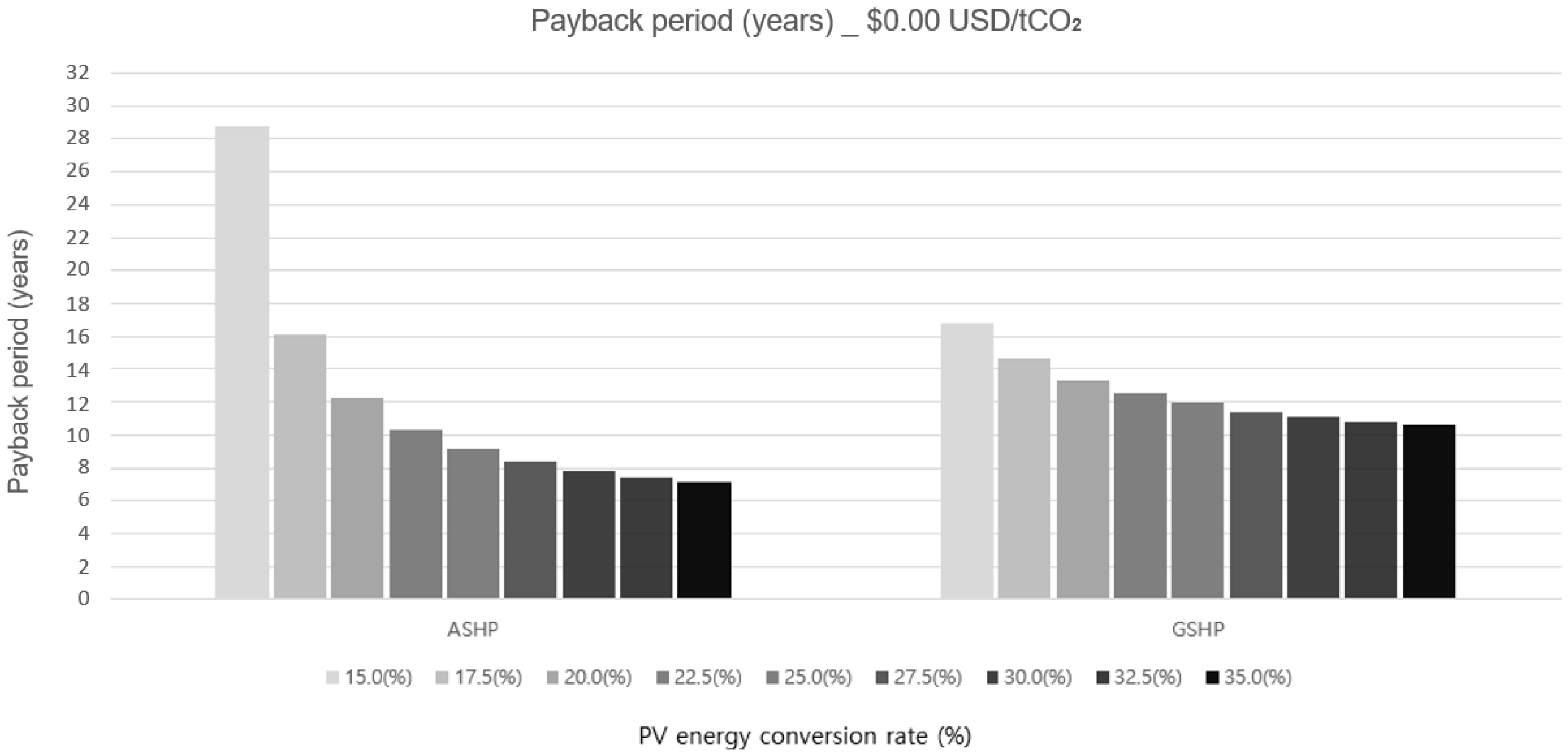


Figure 13. Payback period of heat pump systems without ETS. The payback periods for both heat pump systems gradually decrease with the improvement of P.V. energy conversion rate.

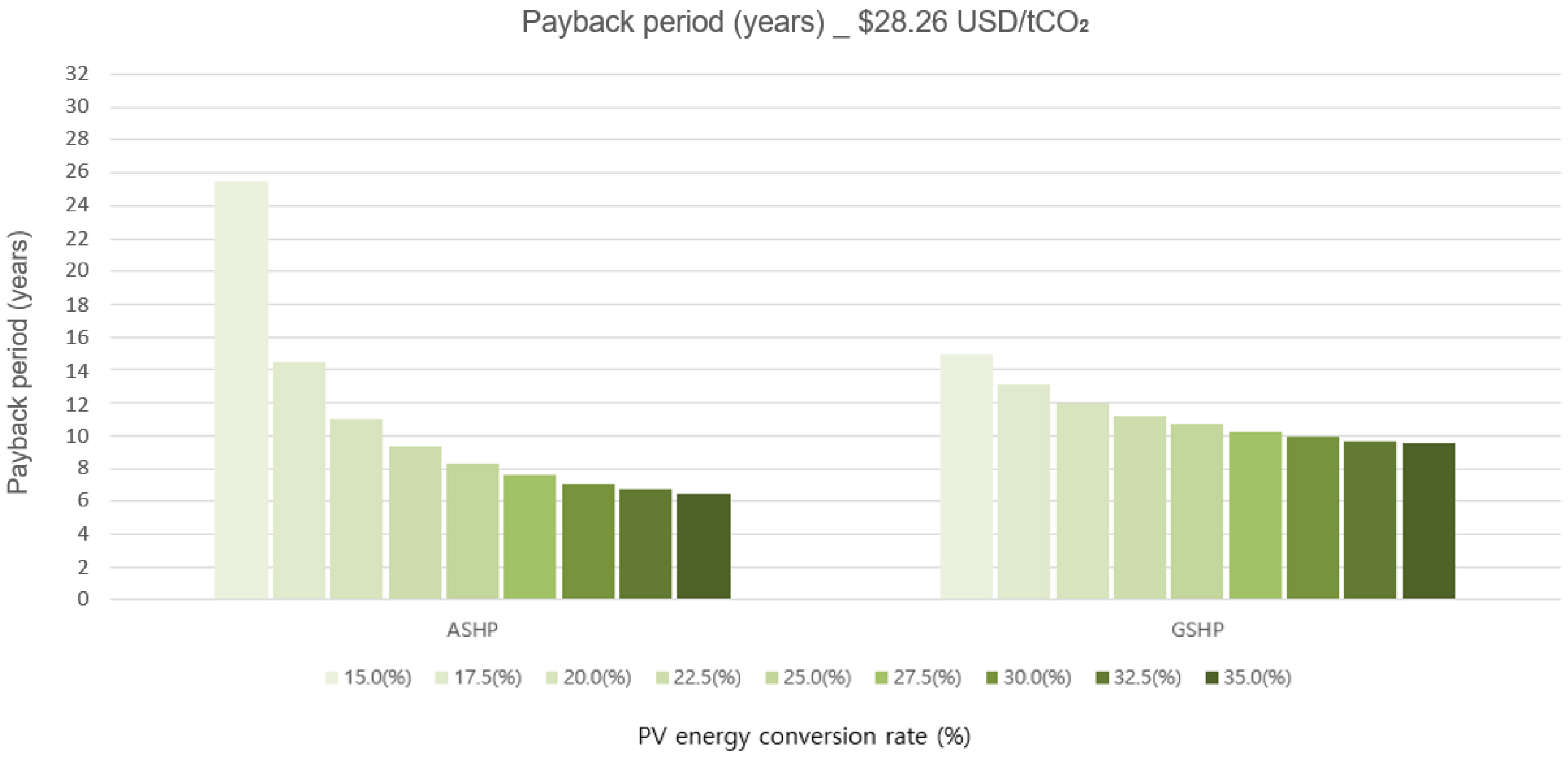


Figure 14. Payback period of heat pump systems with the current CO_2 equivalent price. The payback periods for both heat pump systems gradually decrease with the improvement of P.V. energy conversion rate.

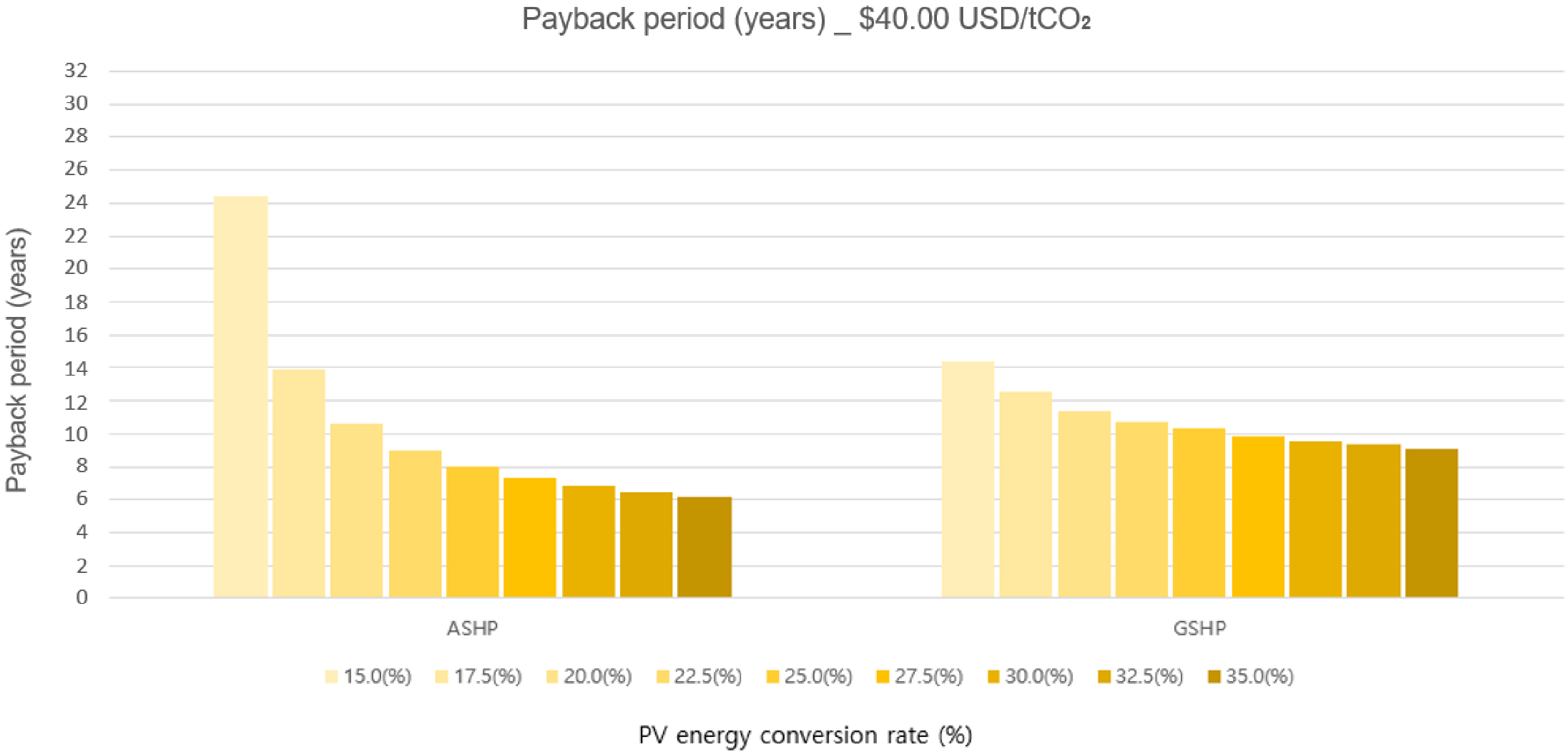


Figure 15. Payback period of heat pump systems with ETS ($40.00 USD/tCO$_2$). The payback periods for both heat pump systems gradually decrease with the improvement of P.V. energy conversion rate.

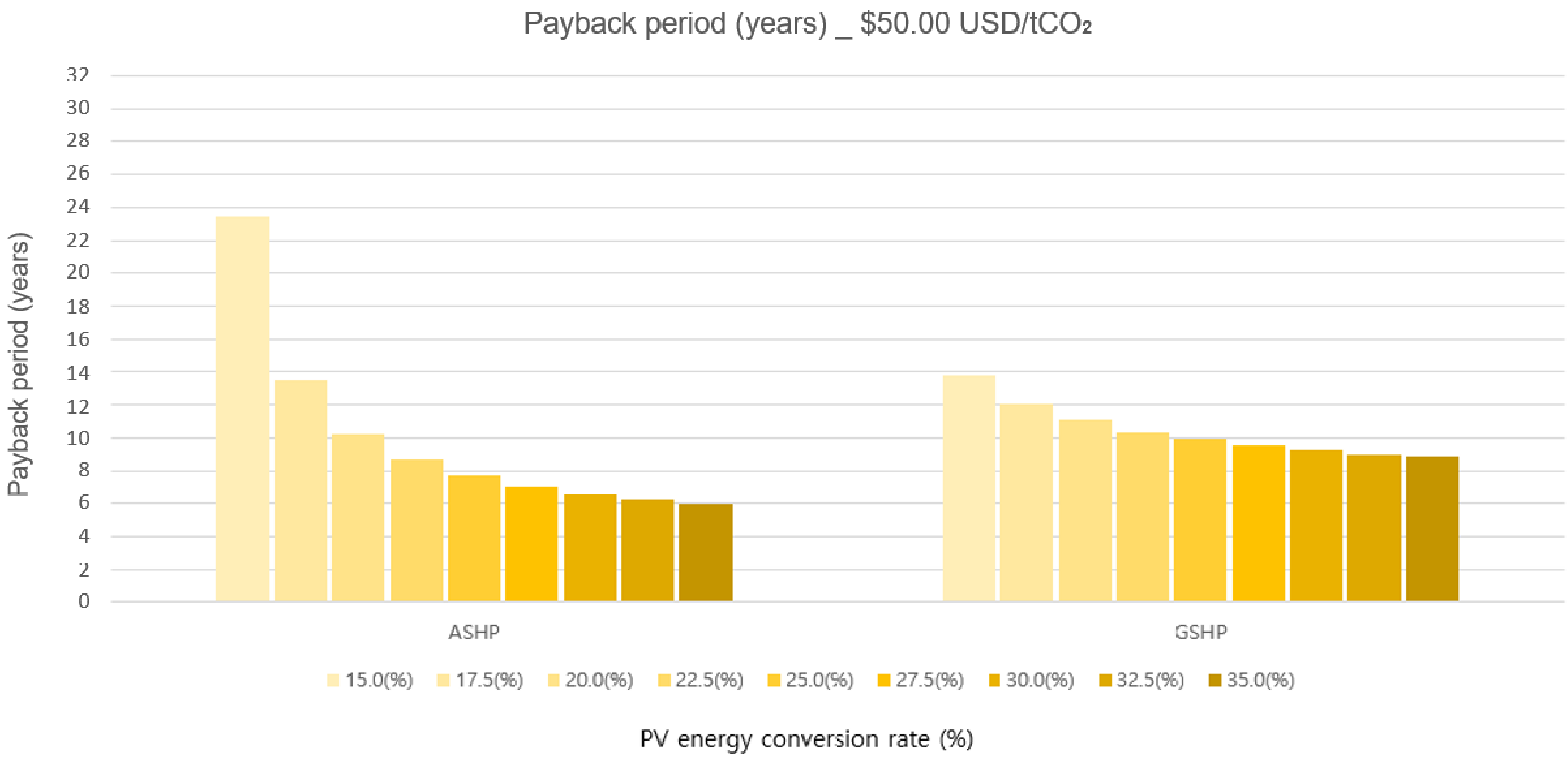


Figure 16. Payback period of heat pump systems with ETS ($50.00 USD/tCO$_2$). The payback periods for both heat pump systems gradually decrease with the improvement of P.V. energy conversion rate.

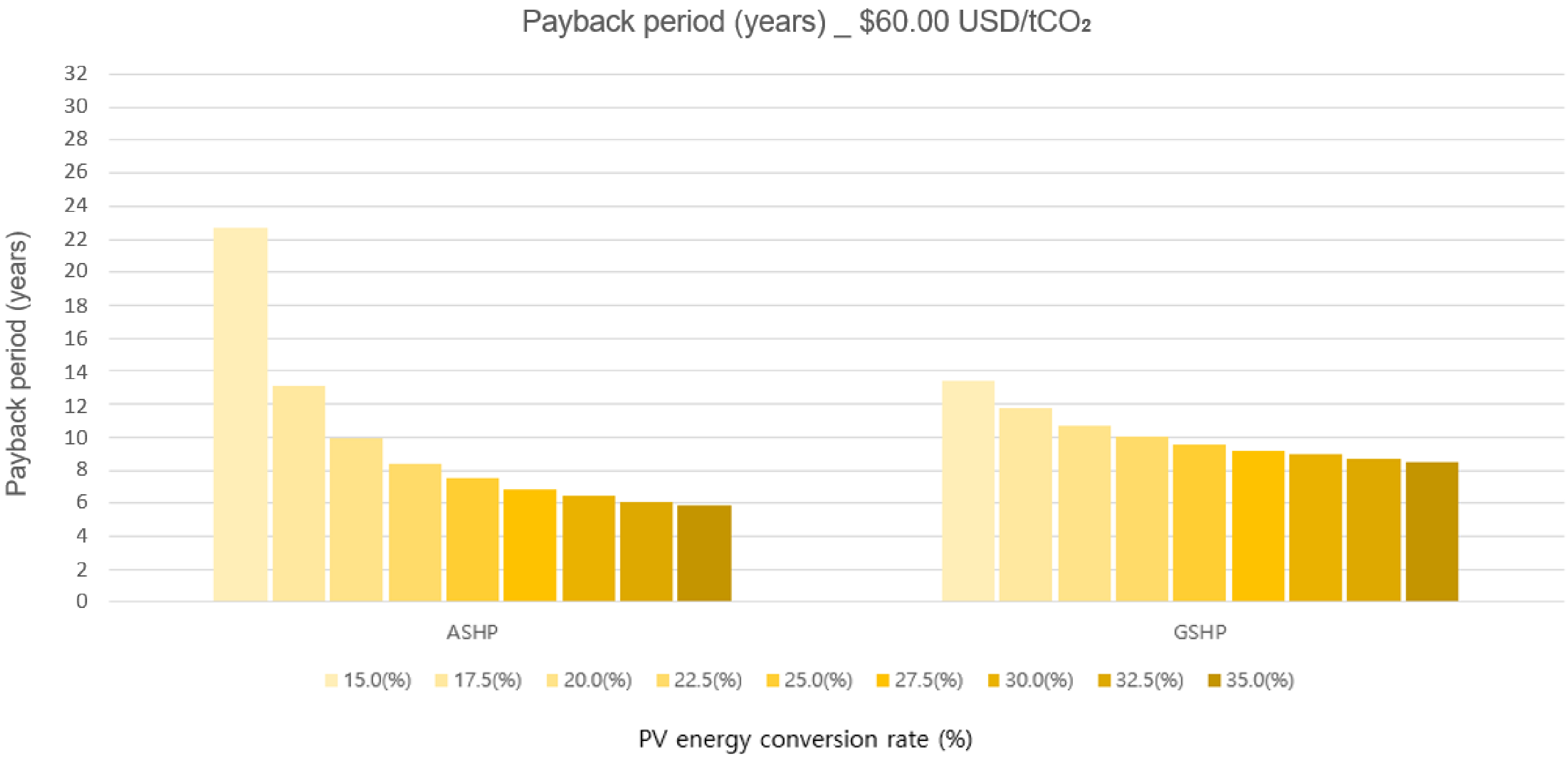


Figure 17. Payback period of heat pump systems with ETS ($60.00 USD/$tCO_2$). The payback periods for both heat pump systems gradually decrease with the improvement of P.V. energy conversion rate.

4.3 Economic feasibility of NZEBs

This section presents the economic feasibility of two HVAC systems, ASHP and GSHP. More specifically, the economic calculation of each heat pump system was subdivided into multiple scenarios in consideration of gradual improvements made in technological and institutional perspectives. In addition, the results show reasonable tax credit rates for the two widely used renewable energy sources, solar and geothermal heat, to establish economic guidelines for implementing NZEBs.

4.3.1 Economic feasibility of installing ASHP

For experimental purposes, this study assumes that the solar installation area is equal to the rooftop area of the object building (100% solar rooftop). Figure 18 and Table 6 show the payback periods for multiple ASHP scenarios, depending on the level of technical and institutional improvements. Particularly, scenarios with payback periods of less than 7 years are highlighted in bold. For reference, the average home ownership in the United States is approximately 7 years (Real trends, 2019). Therefore, in this study, the national average length of residence was assumed to be the main threshold for a reasonable payback in residential heat pump systems. Similarly, HVAC scenarios with payback periods between 7 and 10 years were highlighted as the secondary benchmark for reasonable investment.

The result clearly shows that technological improvement, such as increasing the energy conversion rate of the solar panel, is highly essential for reducing the payback period of ASHP. Specifically, compared with the current technological status, a 10% increase in P.V. energy conversion rate (i.e., 25%) will allow the heat pump system to have a payback period of less than 10 years even without any institutional support. Similarly, the payback period of ASHP can be reduced by increasing the CO_2 equivalent price. However, such institutional improvement has relatively small impact on reducing the payback period of the HVAC system.

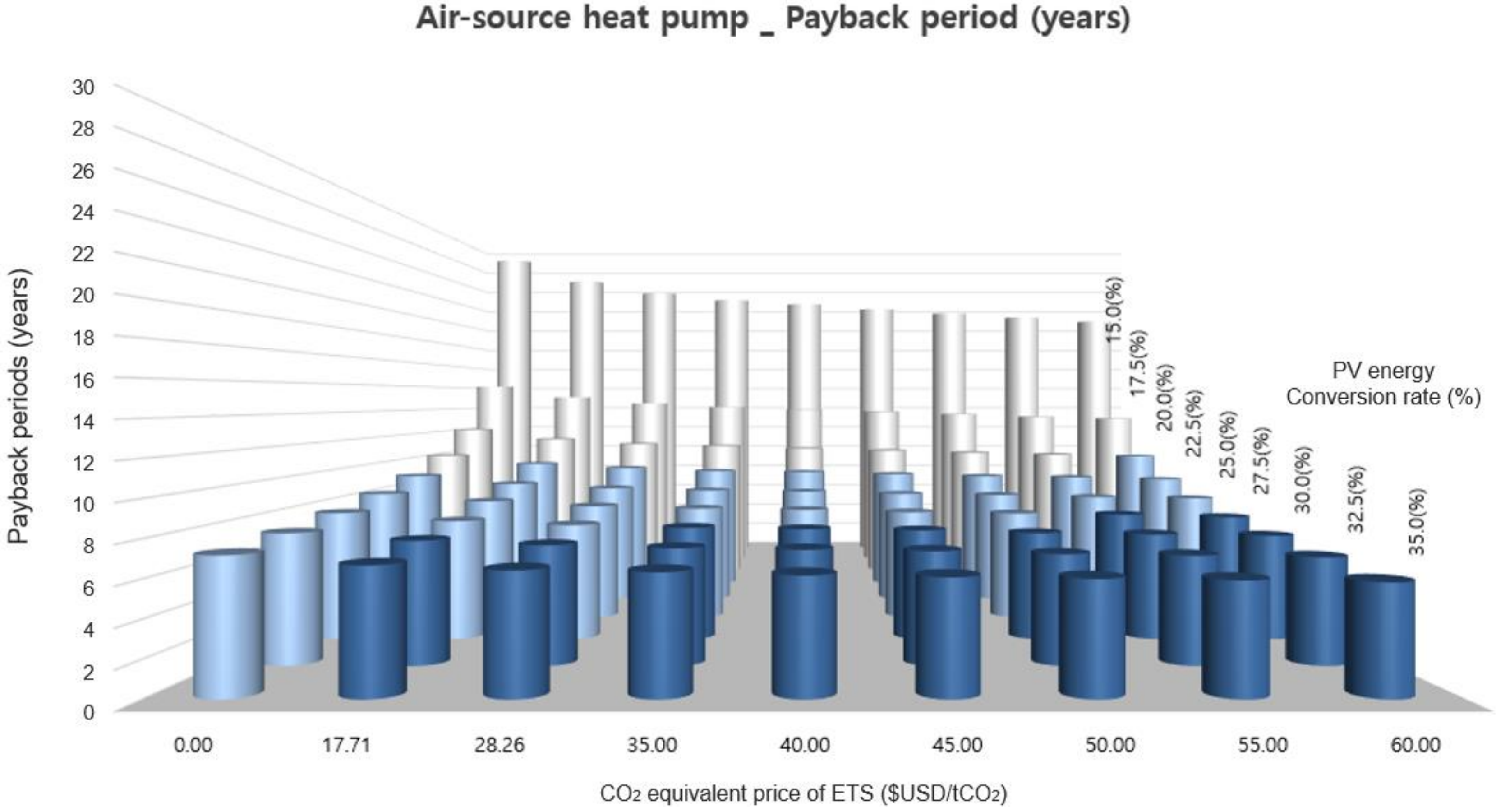


Figure 18. Payback periods for various air-source heat pump (ASHP) scenarios. The graph shows the discounted payback periods for ASHP when the energy conversion rate of PV (technological factor) and CO_2 equivalent price of ETS (institutional factor) improve progressively. Scenarios with payback periods less than 7 years are presented in bold. Similarly, scenarios with payback periods between 7 and 10 years are colored in light.

Table 6.
Payback periods for the various ASHP scenarios depending on the improvements in technical and institutional factors.

ASHP	CO_2 equivalent price (USD/tCO_2$)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	28.75	26.67	25.50	24.83	24.42	23.92	23.50	23.08	22.67
17.5	16.08	15.08	14.50	14.17	13.92	13.75	13.50	13.25	13.08
20.0	12.25	11.42	11.00	10.83	10.58	10.42	10.25	10.08	9.92
22.5	10.33	9.67	9.33	9.08	9.00	8.83	8.67	8.58	8.42
25.0	9.17	8.58	8.25	8.08	8.00	7.83	7.75	7.58	7.50
27.5	8.42	7.92	7.58	7.42	7.33	7.17	7.08	7.00	6.83
30.0	7.83	7.33	7.08	6.92	6.83	6.75	6.58	6.50	6.42
32.5	7.42	7.00	6.75	6.58	6.50	6.42	6.25	6.17	6.08
35.0	7.17	6.67	6.42	6.33	6.17	6.08	6.00	5.92	5.83

4.3.2 Economic feasibility of installing GSHP

For calculating the payback period of GSHP, this study assumes that the rooftop area of the object building is completely installed with solar panels (100% solar rooftop). Figure 19 and Table 7 present the payback periods for different GSHP scenarios based on the potentials for technological and institutional improvements, respectively. The result shows that none of the scenarios can meet the payback period within 7 years due to the high investment cost of geothermal heat pump. However, although reducing the payback period of GSHP is relatively challenging, building owners can reap the value of their investment within 10 years when the technological and institutional improvements are properly balanced. Specifically, if the CO_2 equivalent price remains at \$28.26 USD/tCO_2, there will be technical pressure to improve the P.V. energy conversion rate above 30% to achieve a payback period within 10 years. Therefore, although improving this policy seems to have minor impact on reducing the payback period of GSHP, the increase of CO_2 equivalent price will reduce the technological burden to some extent.

In addition to payback period analysis, this renewable heat pump system can be discussed in terms of the feasibility of achieving net-zero energy. GSHP is much more advantageous in terms of achieving the net-zero emission target compared to ASHP, since the geothermal heat pump itself generates electricity by utilizing a renewable energy source. For reference, Figure 20 represents the feasibility of net-zero energy for multiple GSHP scenarios. Provided that the object building has a 100% solar rooftop, NZEB can be implemented when the P.V. energy conversion rate reaches 32.5% or higher. Furthermore, Figure 21 emphasizes the overlapping scenarios between Figure 19 and Figure 20. In other words, these overlapping scenarios represent the cost-effective options for GSHP that can achieve the net-zero emission target within 10 years of payback period.

In general, this study reveals high expectation for expanding the installation of GSHP in residential buildings due to the feasibility of implementing NZEBs. This clearly demonstrates the synergistic effect of utilizing two different renewable energy sources, solar and geothermal heat. Referring to the findings of this study, many building engineers, technicians, and policy makers should contribute to improving the technological and institutional drivers to economically achieve the net-zero emission target in the U.S. residential sector.

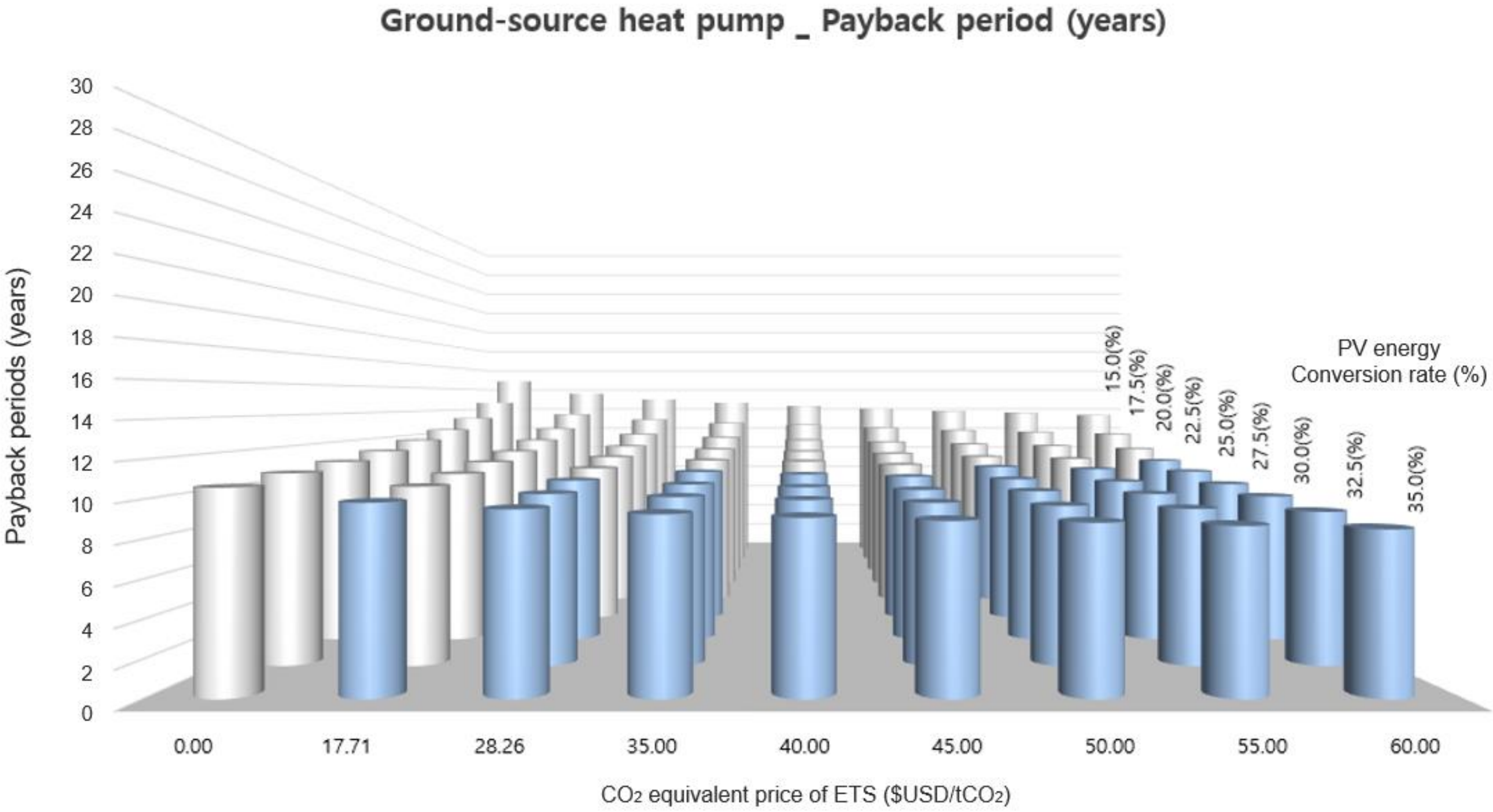


Figure 19. Payback periods for the various ground-source heat pump (GSHP) scenarios. The graph shows the discounted payback periods for GSHP when the P.V. energy conversion rate (technological factor) and CO_2 equivalent price of ETS (institutional factor) improve progressively. None of the scenarios satisfy the payback period within 7 years. Scenarios with payback periods between 7 and 10 years are colored in light.

Table 7.
Payback periods for the various GSHP scenarios depending on the improvements in technical and institutional factors.

GSHP	CO$_2$ equivalent price (USD/tCO_2$)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	16.83	15.58	15.00	14.67	14.33	14.08	13.83	13.67	13.42
17.5	14.67	13.58	13.08	12.75	12.58	12.33	12.08	11.92	11.75
20.0	13.33	12.42	11.92	11.67	11.42	11.25	11.08	10.92	10.67
22.5	12.50	11.67	11.17	10.92	10.75	10.58	10.33	10.17	10.00
25.0	11.92	11.08	10.67	10.42	10.33	10.08	9.92	9.75	9.58
27.5	11.42	10.67	10.25	10.00	9.83	9.67	9.50	9.33	9.17
30.0	11.08	10.33	9.92	9.67	9.50	9.33	9.25	9.08	8.92
32.5	10.83	10.08	9.67	9.50	9.33	9.17	9.00	8.83	8.67
35.0	10.58	9.83	9.50	9.25	9.08	8.92	8.83	8.67	8.50

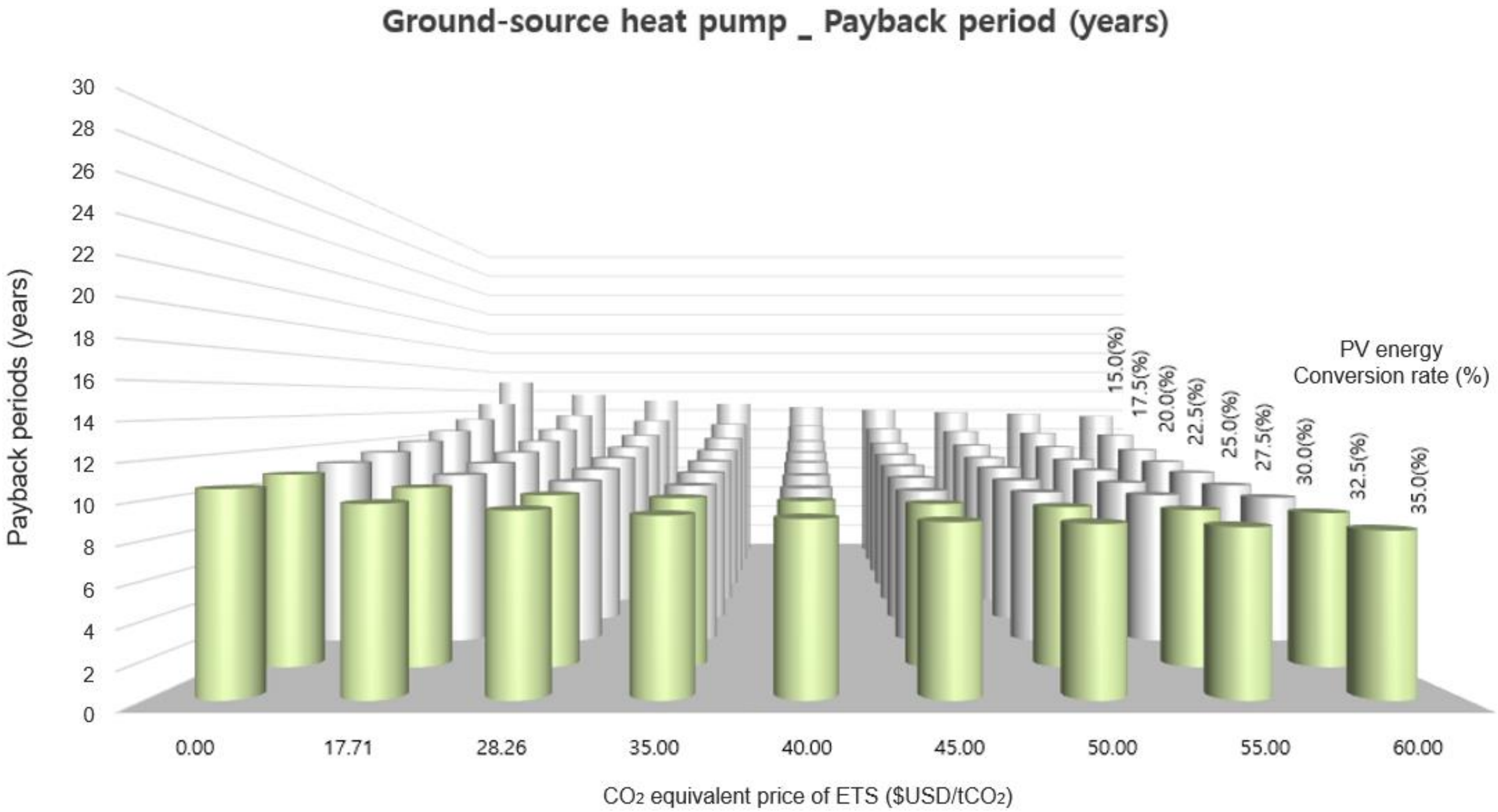


Figure 20. Feasibility of "net-zero energy" for the various ground-source heat pump (GSHP) scenarios. The graph above shows various scenarios where net-zero emission target is met. Under the condition where PV installation area equals the rooftop area, a net-zero energy can be achieved when the P.V. energy conversion rate is improved to at least 32.5%.

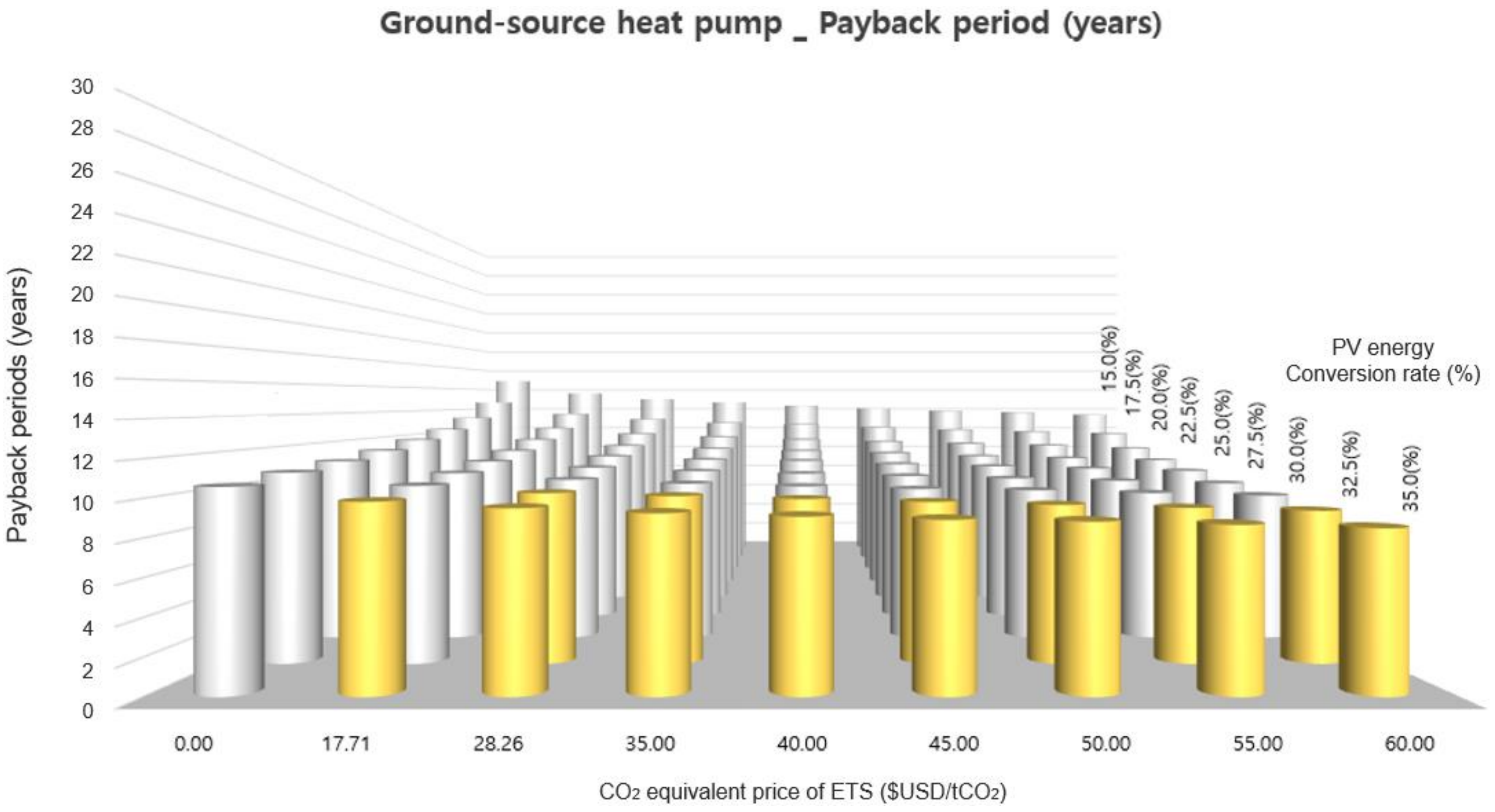


Figure 21. Economic feasibility of the various ground-source heat pump (GSHP) scenarios. The graph represents the overlap between Figure 19 and Figure 20. In other words, the scenarios marked with color show the conditions that satisfy net-zero emission target with a payback period of less than 10 years.

4.4 Plausible incentives for renewable tax credits

Following the economic analysis of two different types of heat pumps, this section presents reasonable tax credit rates for solar and geothermal heat sources, respectively. Over the past few years, the federal government has consistently extended the investment tax credit at a fixed rate of 26%. As a result, these government subsidies have so far encouraged many homeowners to install renewable energy sources. However, considering the investment costs of solar and geothermal energy systems, this study proposes reasonable tax credit rates for the two widely used renewable energy sources. For reference, the solar and geothermal heat pump tax credit rates analyzed in this study only apply to the case when GSHP is installed, and not ASHP.

4.4.1 Solar tax credit rates

With reasonable solar tax credit rates, the federal government will be able to economically subsidize many homeowners. This section presents a series of solar tax credit rates recommended for GSHP, depending on the level of technological and institutional improvements. Figure 22 and Table 8 show the recommended solar tax credit rates to satisfy a 10-year payback period in all scenarios. Specifically, the solar tax credit rate of 26% seems reasonable at the current level of technological and institutional conditions. However, with improvements in technology and policy, the 10-year payback target can be achieved at a much lower solar tax credit rate. For reference, Figure 22 highlights the scenarios where the recommended tax solar credit rate is less than 20%. Furthermore, scenarios where the solar tax credit rate can be less than 10% are emphasized in bold. Under the condition where CO_2 equivalent price is maintained at \$28.26 USD/tCO_2 (U.S. Energy

Information Administration, 2022.04), the result shows that P.V. energy conversion rates of 17.5% and 27.5% require solar tax credit rates of less than 20% and 10%, respectively.

Similarly, Figure 23 and Table 9 present a series of reasonable tax credit rates for the geothermal heat pump to satisfy a 7-year payback period. In summary, the results clearly show that achieving a payback period of 7 years is incomparably more challenging than the 10-year payback target. More specifically, under the current CO_2 equivalent price at $28.26 USD/$tCO_2$, the solar tax credit rate is still recommended to be over 20% even though the P.V. energy conversion rate reaches 35%. Therefore, significant improvements in both technology and policy are required to meet the 7-year payback target with a solar tax credit rate of less than 20%. Under the current technological and institutional conditions, a 26% solar tax credit may be considered a proper support to help many homeowners install GSHPs with a payback period of less than 10 years. However, perceiving the gradual improvements in technology and policy will enable the federal government to manage subsidies more economically, accelerating the implementation of NZEBs. For reference, assuming that the geothermal heat pump tax credit is zero, these results represent the economic performance that can be achieved with the solar tax credit alone.

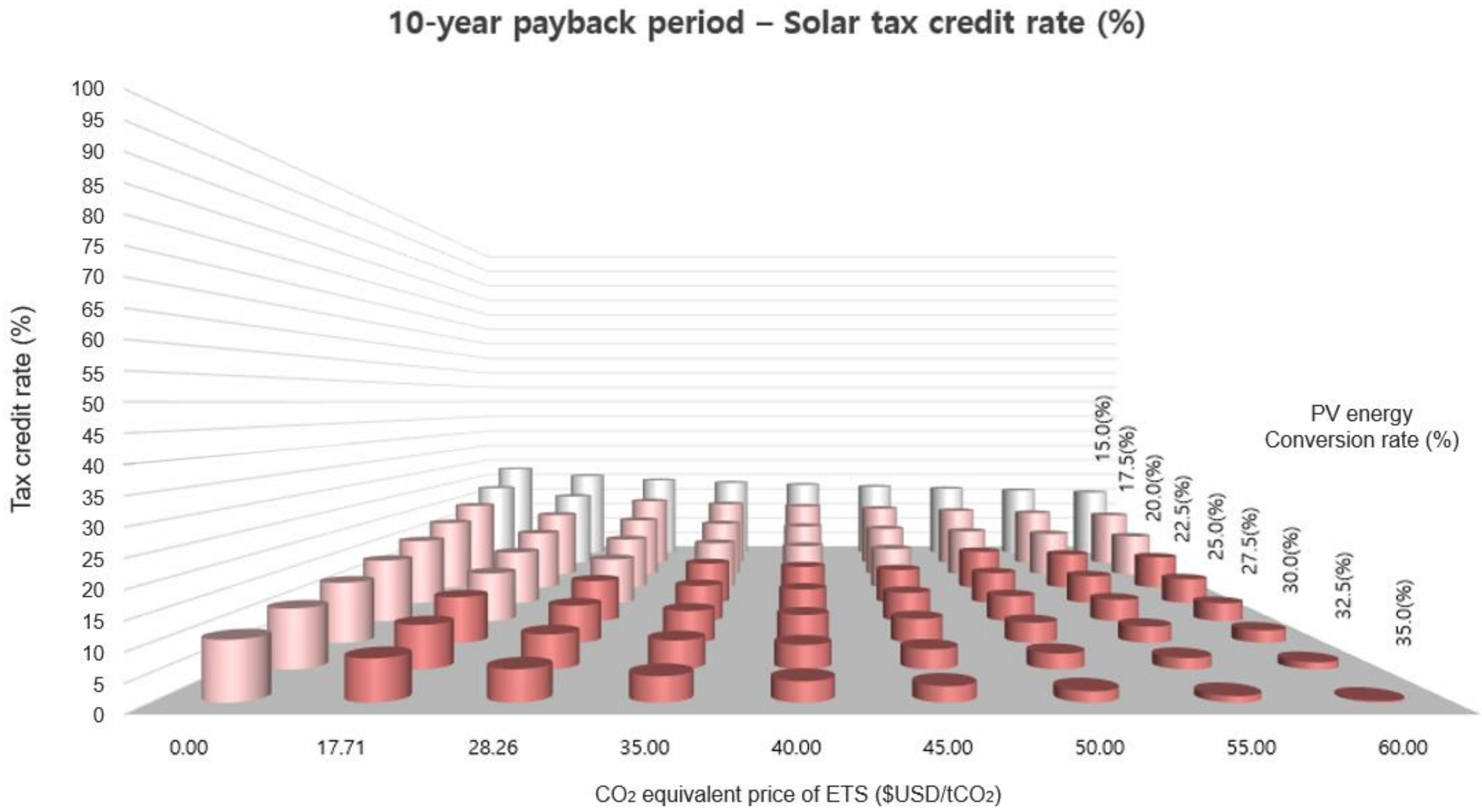


Figure 22. Recommended tax credit rates for solar PV (10-year payback period). The graph presents the recommended solar tax credit rates under the condition where geothermal heat pump tax credit is assumed to be zero. Scenarios with recommended tax credit rates of less than 10% are marked in bold. Similarly, scenarios with recommended tax credit rates between 10% and 20% are colored in light.

Table 8.

Recommended tax credit rates for solar PV depending on the improvements in technical and institutional factors. The table below shows the recommended solar tax credit rates for targeting a "10-year payback period" with the GSHP.

GSHP	CO_2 equivalent price (\$USD/tCO_2)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	27.79	25.43	24.05	23.18	22.53	21.89	21.27	20.63	20.01
17.5	23.18	20.62	19.13	18.18	17.49	16.80	16.11	15.43	14.75
20.0	19.86	17.15	15.58	14.58	13.85	13.12	12.39	11.68	10.96
22.5	17.34	14.54	12.89	11.86	11.10	10.34	9.59	8.84	8.10
25.0	15.37	12.48	10.79	9.72	8.94	8.17	7.39	6.62	5.86
27.5	13.78	10.83	9.10	8.01	7.20	6.41	5.62	4.83	4.05
30.0	12.47	9.46	7.71	6.60	5.78	4.97	4.17	3.37	2.57
32.5	11.38	8.32	6.54	5.41	4.59	3.76	2.95	2.13	1.33
35.0	10.45	7.35	5.55	4.41	3.57	2.74	1.91	1.09	0.27

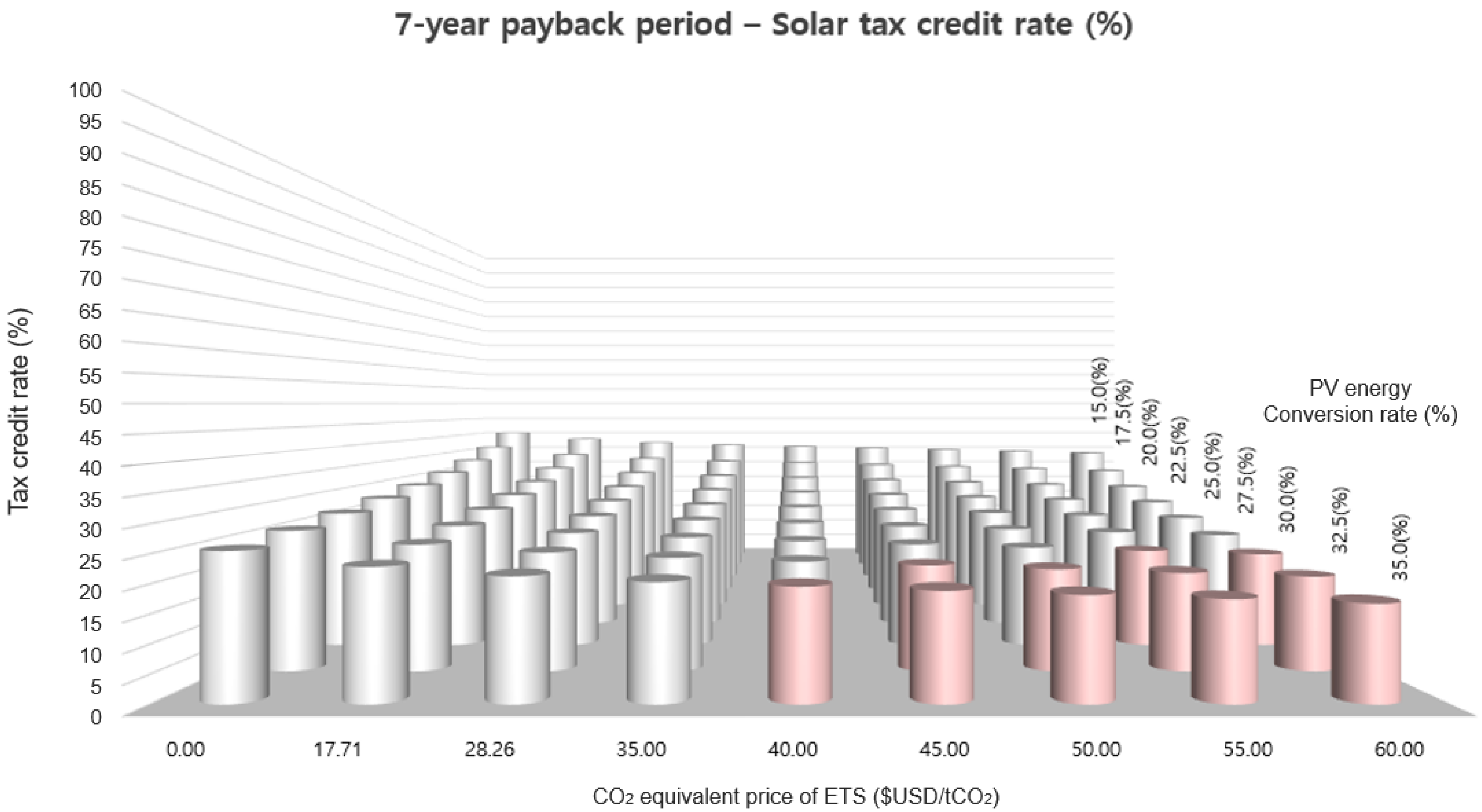


Figure 23. Recommended tax credit rates for solar PV (7-year payback period). The graph presents the recommended solar tax credit rates under the condition where geothermal heat pump tax credit is assumed to be zero. No scenario recommends a tax credit rate of less than 10%. Scenarios with recommended tax credit rates between 10% and 20% are colored in light.

Table 9.
Recommended tax credit rates for solar PV depending on the improvements in technical and institutional factors. The table below shows the recommended solar tax credit rates for targeting a "7-year payback period" with the GSHP.

GSHP	CO$_2$ equivalent price (\$USD/tCO$_2$)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	40.28	38.27	37.10	36.35	35.81	35.26	34.72	34.19	33.65
17.5	36.36	34.17	32.89	32.09	31.50	30.90	30.32	29.73	29.15
20.0	33.52	31.21	29.87	29.01	28.39	27.76	27.15	26.53	25.91
22.5	31.37	28.97	27.57	26.68	26.03	25.39	24.74	24.10	23.47
25.0	29.68	27.21	25.77	24.86	24.19	23.53	22.86	22.20	21.55
27.5	28.32	25.80	24.32	23.39	22.70	22.03	21.35	20.67	20.01
30.0	27.21	24.63	23.13	22.18	21.49	20.79	20.10	19.42	18.73
32.5	26.27	23.66	22.14	21.17	20.46	19.76	19.06	18.37	17.67
35.0	25.48	22.83	21.29	20.31	19.59	18.88	18.17	17.47	16.77

4.4.2 Geothermal heat pump tax credit rates

Geothermal heat pump tax credit is another government subsidy addressed in this study to encourage homeowners to use renewable energy sources. The results presented in this section show that economic performance is achievable by applying the geothermal heat pump tax credit alone given that the solar tax credit is assumed to be zero. Figure 24 and Table 10 show the recommended geothermal heat pump tax credit rates for different GSHP scenarios to satisfy a 10-year payback period. However, since the upfront cost of GSHP is incomparably higher than that of the solar panel, the results clearly show that support from geothermal heat pump tax credit alone cannot guarantee economical investment.

Furthermore, Figure 25 and Table 11 present the geothermal heat pump tax credit rates recommended for achieving the 7-year payback target. The results show that a tax credit rate of over 35% is recommended for geothermal, regardless of the significant improvement in technological and institutional factors. In summary, for the geothermal heat pump tax credit to support economical investments at a proper tax credit rate, the investment cost of geothermal heat pump must be significantly reduced to be comparable to the cost of solar PV (Litjens et al., 2018). However, considering the simultaneous application with the solar tax credit, the 26% tax credit for GSHP is considered a reasonable support from the government.

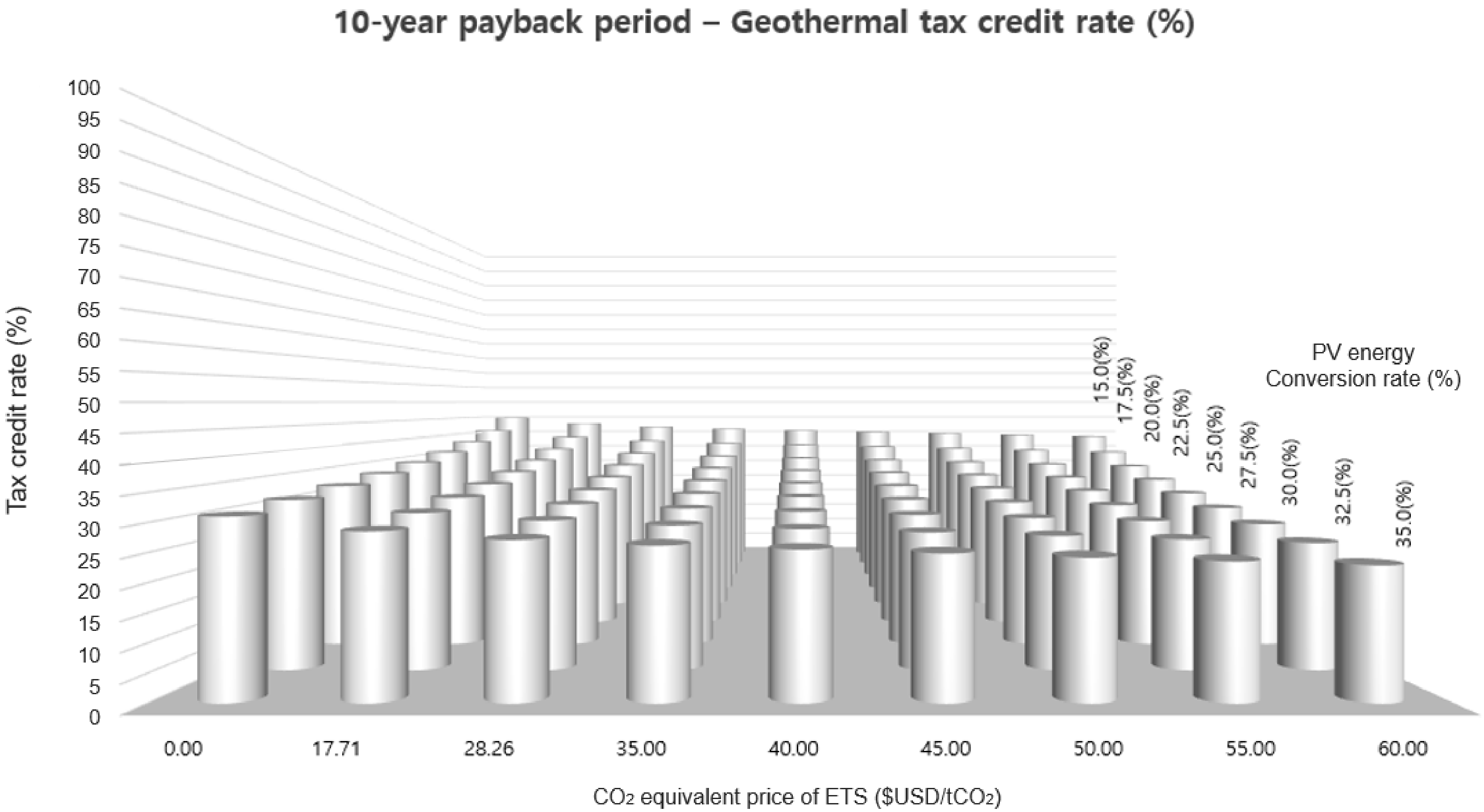


Figure 24. Recommended tax credit rates for geothermal heat pumps (10-year payback period). The graph presents the recommended geothermal heat pump tax credit rates under the condition where solar tax credit is assumed to be zero. No scenario recommends a tax credit rate of less than 20% for geothermal energy source.

Table 10.

Recommended tax credit rates for geothermal heat pumps depending on the improvements in technical and institutional factors. The table below shows the recommended geothermal heat pump tax credit rates for targeting “10-year payback period” with the GSHP.

GSHP	CO_2 equivalent price (\$USD/tCO_2)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	44.80	42.93	41.83	41.14	40.63	40.12	39.62	39.12	38.62
17.5	41.15	39.11	37.92	37.17	36.62	36.07	35.52	34.98	34.44
20.0	38.50	36.35	35.10	34.30	33.72	33.14	32.56	31.99	31.42
22.5	36.50	34.27	32.96	32.13	31.53	30.93	30.32	29.73	29.14
25.0	34.93	32.63	31.28	30.43	29.81	29.19	28.57	27.96	27.35
27.5	33.66	31.31	29.93	29.07	28.42	27.79	27.16	26.53	25.91
30.0	32.62	30.22	28.82	27.94	27.29	26.64	26.00	25.36	24.73
32.5	31.75	29.31	27.89	26.99	26.34	25.68	25.03	24.38	23.74
35.0	31.01	28.54	27.11	26.20	25.53	24.86	24.20	23.55	22.89

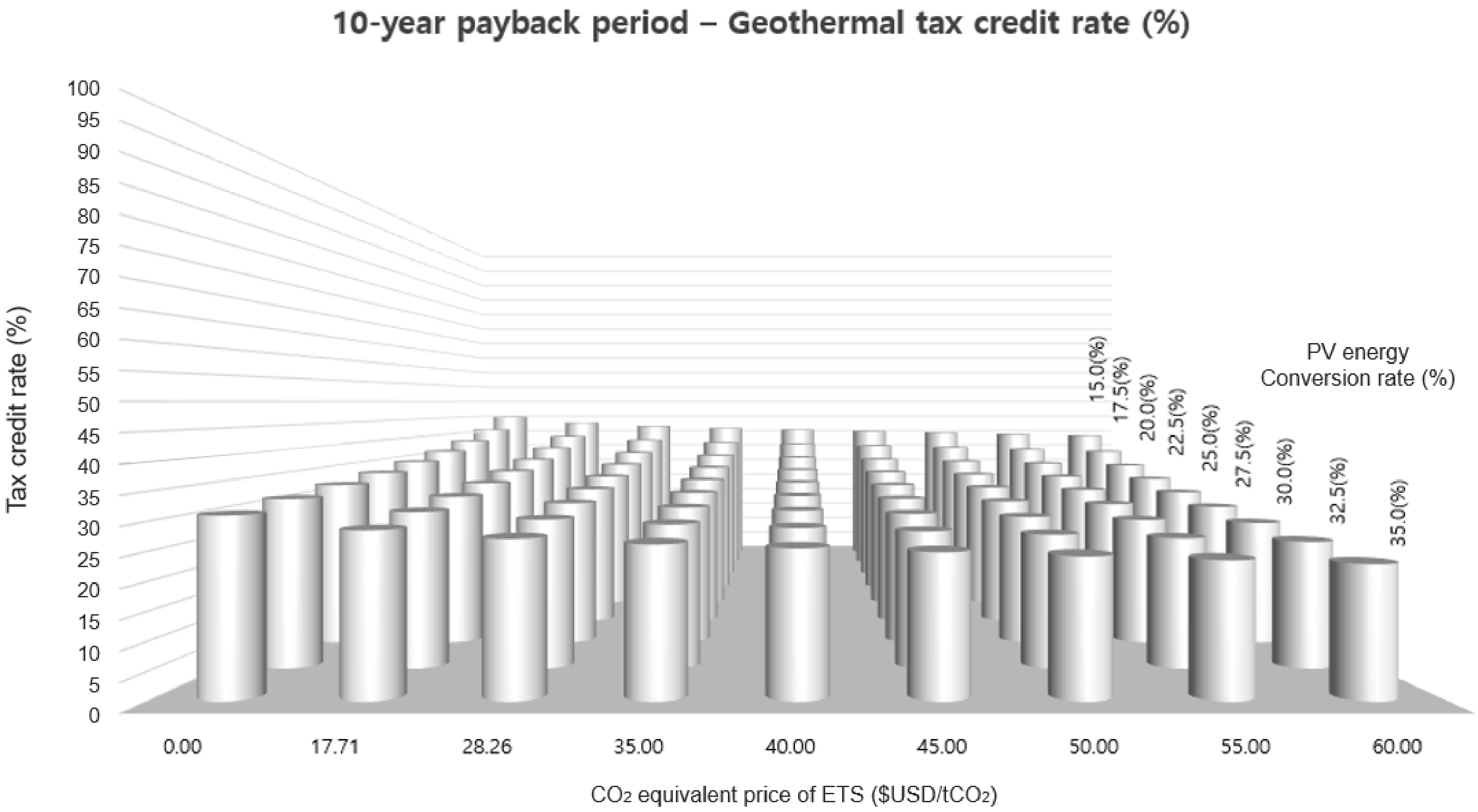


Figure 25. Recommended tax credit rates for geothermal heat pumps (7-year payback period). The graph presents the recommended geothermal heat pump tax credit rates under the condition where solar tax credit is assumed to be zero. No scenario recommends a tax credit rate of less than 20% for geothermal energy source.

Table 11.

Recommended tax credit rates for geothermal heat pumps depending on the improvements in technical and institutional factors. The table below shows the recommended geothermal heat pump tax credit rates for targeting “7-year payback period” with the GSHP.

GSHP	CO_2 equivalent price (\$USD/tCO_2)								
P.V. energy conversion rate (%)	0.00	17.71	28.26	35.00	40.00	45.00	50.00	55.00	60.00
15.0	54.70	53.11	52.18	51.59	51.16	50.73	50.30	49.88	49.45
17.5	51.60	49.86	48.85	48.21	47.74	47.27	46.81	46.34	45.89
20.0	49.34	47.52	46.45	45.78	45.28	44.78	44.29	43.81	43.31
22.5	47.64	45.74	44.63	43.93	43.41	42.90	42.38	41.88	41.37
25.0	46.31	44.35	43.20	42.48	41.95	41.42	40.89	40.37	39.85
27.5	45.23	43.22	42.05	41.31	40.77	40.23	39.69	39.15	38.62
30.0	44.34	42.30	41.11	40.35	39.80	29.24	38.70	38.15	37.61
32.5	43.60	41.53	40.31	39.55	38.98	38.42	37.87	37.32	36.76
35.0	42.97	40.86	39.64	38.86	38.29	37.73	37.16	36.60	36.04

CHAPTER 5

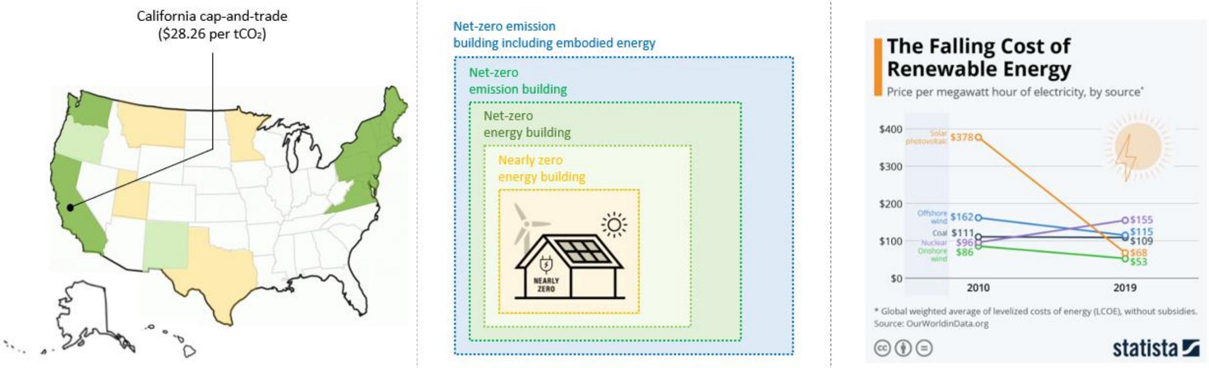
Discussion and Limitations

This study investigated the economic feasibility of implementing net-zero energy buildings (NZEBs) in the United States residential sector. Specifically, this study analyzed the discounted payback period for several building energy scenarios when PV-integrated GSHPs were installed in typical residential housing in Ann Arbor, Michigan. These scenarios have been classified according to the expected level of technological (i.e., P.V. energy conversion rate) and institutional (i.e., CO_2 equivalent price of ETS) improvements required to achieve NZEBs by 2050. The results show that technological advancement has a much more significant effect on reducing the payback period of the PV-integrated GSHP than institutional improvement. However, though the CO_2 equivalent price of ETS seems to have a relatively small impact on reducing the payback period of the heat pump system, adopting this policy still alleviates the technological burden to some extent. In terms of institutional improvement, this study proposes calculating the payback periods for several heat pump systems by applying two environmental policies that are ~~not entirely~~ unfamiliar to the public. While there are no solutions to eradicate GHG emissions from residential buildings altogether, the most feasible way to reduce CO_2 emissions is to promote applying green policies that encourage homeowners to reduce their environmental impacts (Balcombe et al., 2019). Currently, the application of ITC (i.e., renewable tax credit) and ETS to the residential building sector is increasing in many countries in Europe and Asia (Zhang et al., 2018). However, incorporating these environmental policies into building energy systems is still new in the U.S. residential sector.

The current research framework can fill this gap to some extent by helping many building owners across the country to understand the benefits of applying both ITC and ETS to residential heat pump systems integrated with renewable energy sources. In the future, the United States policy makers will need to incentivize and reward the incorporation of ITC and ETS into the process of selecting building HVAC systems. The application of such environmental policies will encourage many building owners to reduce both economic and environmental impacts in the residential sector.

As a practical application, this study presented reasonable tax credit rates for solar and geothermal heat sources, which are the two renewable energy sources applied to PV-integrated GSHPs. The results indicate that the current 26% solar tax credit rate seems a reasonable support from the federal government. Meanwhile, the high initial costs of GSHP require government subsidies that far exceed the current 26% geothermal heat pump tax credit to satisfy its 10-year (or 7-year) payback target (Lim et al., 2016). In summary, the investment tax credit (ITC) rates proposed in consideration of the economics of each renewable energy source will serve as an important indicator for the government to support many homeowners across the United States. Therefore, this study clarifies the rather ambiguous technological and institutional challenges that must be achieved to implement NZEBs by 2050.

However, this study has several limitations. To be specific, Figure 26 shows the major limitations of the current research approach. First, this study generalizes the economic feasibility of implementing NZEB in the United States residential sector only by selecting Ann Arbor as the study location. The United States has multiple climate zones and electricity market situations across the nation. Therefore, to prevent hasty generalization, the number of residentials subject to the study should be expanded throughout the country. In addition, the state of Michigan should also adopt the ETS policy as soon as possible.



(1) Hasty Generalization

(2) Ambiguity Error

(3) Dicto Simpliciter Fallacy

Figure 26. Limitations of the current research approach.

Second, the definition of NZEB is lacking a universally agreed definition and has created numerous uncertainties across the field of building energy optimization (Zhang et al., 2021). For instance, the task becomes increasingly challenging in the order of 1) Nearly zero energy building, 2) Net-zero energy building, 3) Net-zero emission building, and 4) Net-zero emission building including embodied energy. Therefore, to alleviate this confusion, many future studies should seek a universally agreed definition of NZEBs and clarify its actual purpose.

Finally, the technological costs associated with the increase in P.V. energy conversion rate was not deeply considered in this study. For simplicity, the investment cost of the solar panel was considered identical throughout the study, regardless of the P.V. energy conversion rate. However, a study conducted by Shahsavari & Akbari found that despite significant improvements in PV technology, the price of solar panel has continuously declined due to market growth and large-scale production (Shahsavari & Akbari, 2018). For these reasons, future studies should focus more on the economic perspective of PV-integrated systems and deeply consider the costs associated with technological improvements and market conditions over time. Additionally, this study did not consider the degradation of PV efficiency over time, which negatively affects the performance of the heat pump systems. Therefore, for a more accurate analysis, the technical tolerance of the PV panels should be examined and reflected in calculating the economic payback periods of such residential HVAC systems.

CHAPTER 6

Conclusion

Buildings are one of the prime sectors responsible for high energy demand and GHG emissions; therefore, the expectation for net-zero energy building (NZEB) is continuously increasing worldwide. For this reason, the current study presents the economic feasibility of implementing NZEBs in the U.S. residential sector by applying two renewable energy sources, solar and geothermal heat. Specifically, this study proposes the technological (i.e., P.V. energy conversion rate) and institutional (i.e., CO_2 equivalent price of ETS) improvements required to achieve the net-zero emission target by 2050. A typical two-story residential building in Ann Arbor, Michigan was simulated using the TRNSYS software tool.

Although all passive design elements were set as unchangeable values, the building HVAC systems were classified into four different scenarios: (1) air-source heat pump (ASHP), (2) PV-integrated ASHP (PV+ ASHP), (3) ground-source heat pump (GSHP), and (4) PV-integrated GSHP (PV+ GSHP). First, this study presents the number of solar panels required to achieve each target: 1) net-zero energy building, 2) net-zero cost building, and 3) net-zero emission building. The results clearly demonstrate that achieving the "net-zero emission" target is the most challenging task among the three targets.

The critical point for "carbon neutrality" can hardly be reached even when the solar installation area is over 200% of the thermal zone area (181.44 m^2). Second, this study analyzed the discounted payback periods for multiple building scenarios, especially when PV-integrated GSHPs were installed in the simulated building. Third, the economic calculation of each

PV+GSHP method was performed according to the level of improvements in technology (P.V. energy conversion rate) and environmental policy (CO_2 equivalent price of ETS). Some important takeaways are as follows:

- Technological improvement, such as increasing the P.V. energy conversion rate, is essential for the economical use of both ASHP and GSHP systems. However, raising the CO_2 equivalent price (i.e., institutional improvement) has a relatively small impact on reducing the payback periods for both HVAC systems.
- Regardless of the CO_2 equivalent price of emission trading scheme (ETS), a 10% increase in solar energy conversion rate (i.e., 25%) will significantly reduce the payback period of P.V.-integrated ASHP to less than ten years.
- Installing a PV-integrated GSHP enables the implementation of NZEB with a payback period of fewer than ten years when the P.V. energy conversion rate reaches 32.5%.

In addition, this study proposes reasonable investment tax credit (ITC) rates for the two renewable energy systems applied in the study: solar P.V. and geothermal heat pumps. Both renewable tax credit rates recommended in this study only apply to the case when installing PV-integrated GSHPs. Some significant findings include:

- Under the current technological and institutional context, a solar tax credit rate of 26% seems ~~a~~ reasonable to support achieving the 10-year payback target.

- However, the high initial cost of GSHP does not ensure economical investment and requires government subsidies that far exceed the current 26% geothermal heat pump tax credit rate.

- Overall, implementing NZEB with a 7-year payback target requires significant improvements in technology and policy; this goal can hardly be achieved with short-term support from renewable tax credits.

In conclusion, this research framework will clarify the technological and institutional challenges that should be addressed to allow NZEBs to become economically feasible in the U.S. residential sector. Therefore, many building engineers, technicians, and policy makers are required to play the role as a frontier of this challenge and actively contribute to achieving the net-zero emission target by 2050.

Abbreviations

NZEB	Net-Zero Energy Building
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air-Conditioning
ASHP	Air-Source Heat Pump
GSHP	Ground-Source Heat Pump
COP	Coefficient of Performance
PV	Photovoltaic
ESS	Energy Storage System
ETS	Emission Trading Scheme
ITC	Investment Tax Credit
DPP	Discounted Payback Period

APPENDICES

Appendix A

The tables below present the TRNSYS 17 component types (Table A.1), and parametric outputs (Table A.2) applied in this study.

Table A.1
Component types in TRNSYS 17

Type number	Description
Type 25	Printer
Type 33	Psychrometric analysis
Type 47	Battery storage
Type 48	Regulator & inverter
Type 56	Multi-zone building
Type 65	Online plotter
Type 69	Sky-temperature
Type 94	Photovoltaic panel
Type 109	Weather data
Type 557	Vertical ground heat exchanger
Type 665	Air-to-air heat pump
Type 927	Water-to-water heat pump

Table A.2
Parametric outputs in TRNSYS 17

N Type number	Label code	Description	Unit
N Type 1	TAIR	Air temperature within the zone	[°C]
N Type 30	QHEAT	Sensible heating load within the zone	[kW]
N Type 31	QCOOL	Sensible cooling load within the zone	[kW]
N Type 90	THEAT	Set-point temperature (heating) within the zone	[°C]
N Type 93	TCOOL	Set-point temperature (cooling) within the zone	[°C]

Appendix B

The payback periods of the various building HVAC systems depending on the insulation thickness of the walls (mm) and CO_2 equivalent price of ETS (Figure B.1~6 and Table B.1~6).

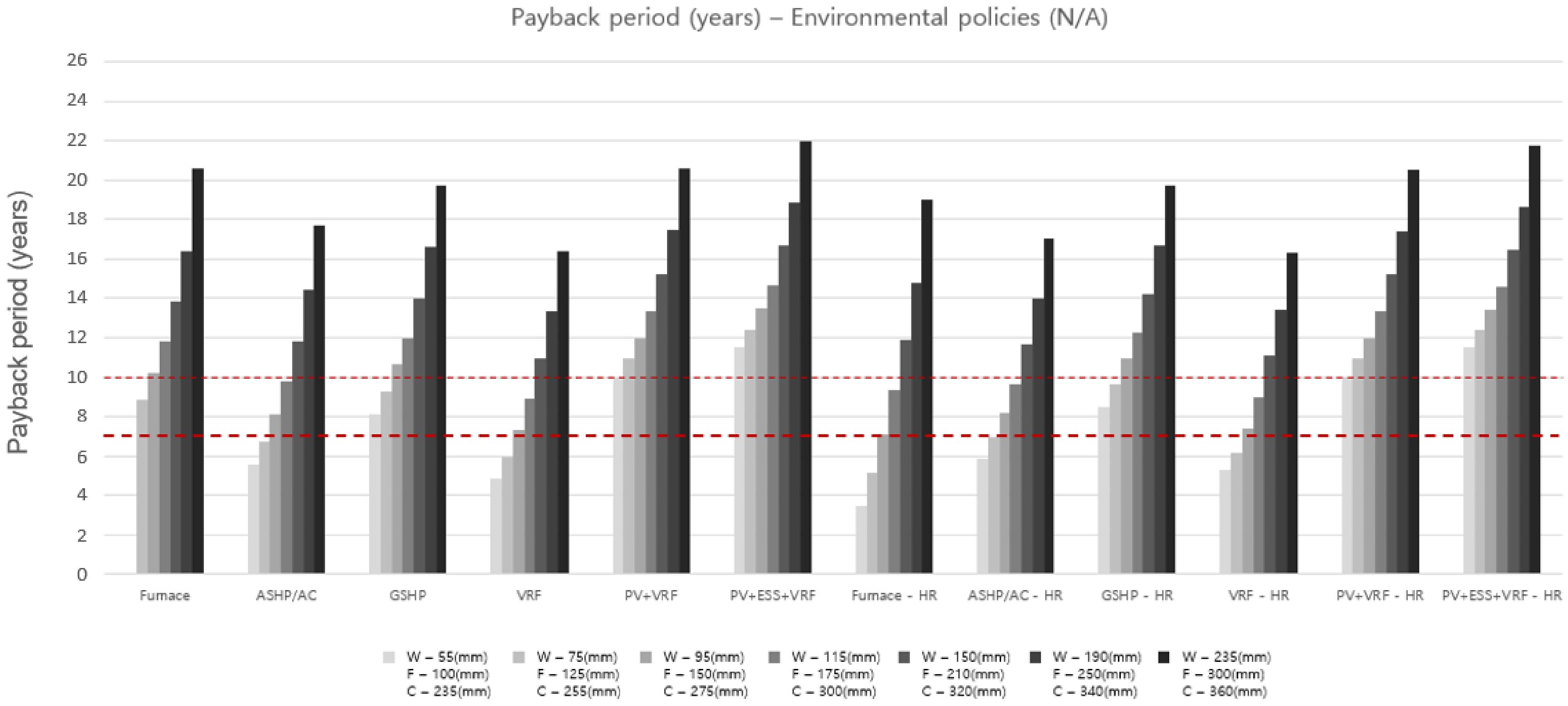


Figure B.1 Payback periods of the various building HVAC systems with no-policy support (years)

Table B.1
Payback periods of the various building HVAC systems considering neither ITC nor ETS (years)

	System	55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	8.83	10.25	11.83	13.83	16.42	20.58
	ASHP / AC	5.58	6.75	8.08	9.75	11.83	14.42	17.67
	GSHP	8.08	9.25	10.67	12.00	14.00	16.58	19.75
	VRF	4.83	5.92	7.33	8.92	10.92	13.33	16.42
	PV+VRF	9.92	10.92	12.00	13.33	15.25	17.50	20.58
	PV+ESS+VRF	11.50	12.42	13.50	14.67	16.67	18.83	22.00
HR	Furnace / window cooling unit	3.50	5.17	7.08	9.33	11.92	14.83	19.00
	ASHP / AC	5.83	6.92	8.17	9.67	11.67	14.00	17.08
	GSHP	8.50	9.67	10.92	12.25	14.25	16.67	19.75
	VRF	5.25	6.17	7.42	9.00	11.08	13.42	16.33
	PV+VRF	10.00	10.92	12.00	13.33	15.25	17.42	20.50
	PV+ESS+VRF	11.50	12.42	13.42	14.58	16.50	18.67	21.75

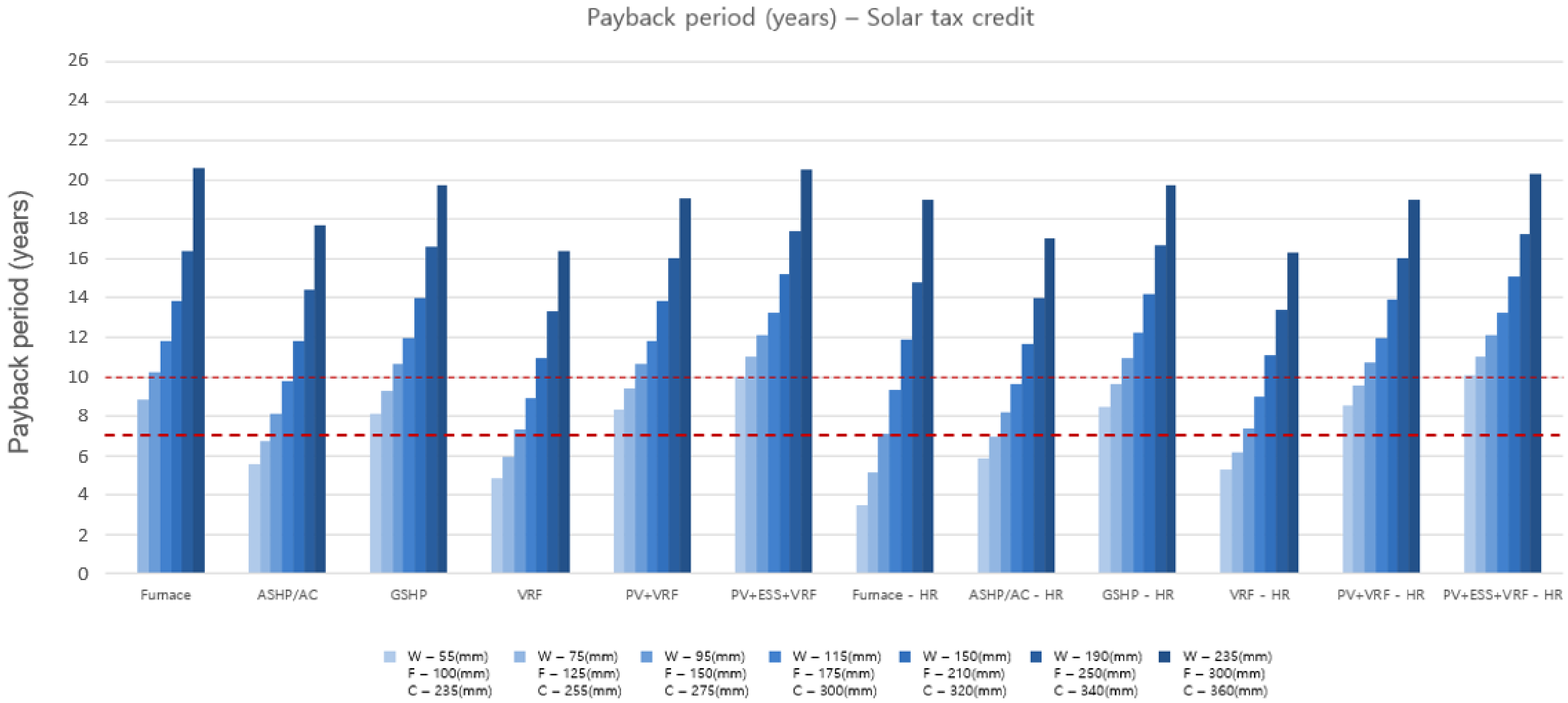


Figure B.2 Payback periods of the various building HVAC systems by applying the solar tax credit (years)

Table B.2

Payback periods of the various building HVAC systems by applying the solar tax credit (years)

System		55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	8.83	10.25	11.83	13.83	16.42	20.58
	ASHP / AC	5.58	6.75	8.08	9.75	11.83	14.42	17.67
	GSHP	8.08	9.25	10.67	12.00	14.00	16.58	19.75
	VRF	4.83	5.92	7.33	8.92	10.92	13.33	16.42
	PV+VRF	8.33	9.42	10.67	11.83	13.83	16.00	19.08
	PV+ESS+VRF	10.00	11.00	12.08	13.25	15.25	14.72	20.50
HR	Furnace / window cooling unit	3.50	5.17	7.08	9.33	11.92	14.83	19.00
	ASHP / AC	5.83	6.92	8.17	9.67	11.67	14.00	17.08
	GSHP	8.50	9.67	10.92	12.25	14.25	16.67	19.75
	VRF	5.25	6.17	7.42	9.00	11.08	13.42	16.33
	PV+VRF	8.58	9.58	10.75	12.00	13.92	16.00	19.00
	PV+ESS+VRF	10.08	11.00	12.08	13.25	15.08	17.25	20.33

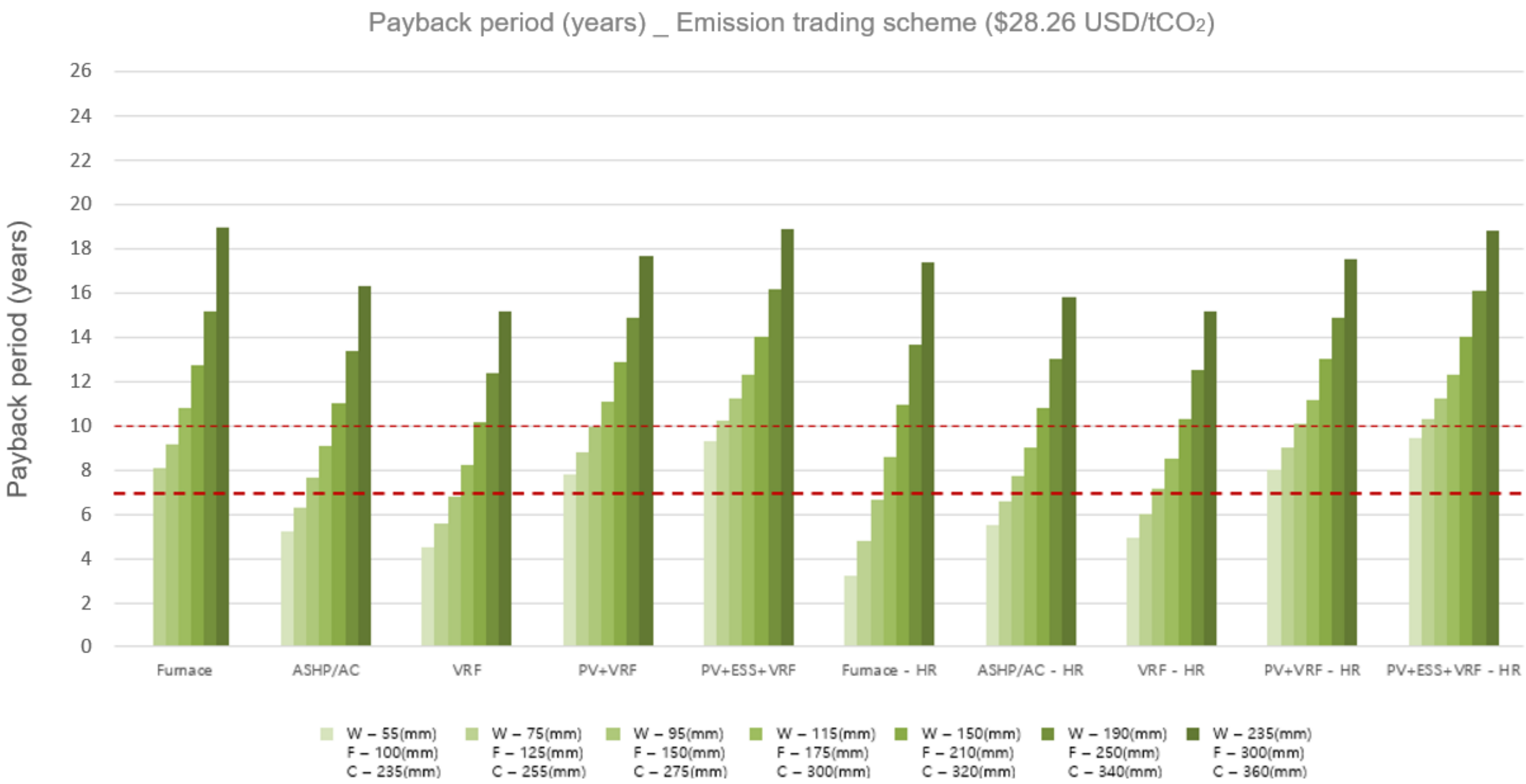


Figure B.3 Payback periods of the various building HVAC systems by applying the ETS (years) ($28.26 USD/tCO$_2$)

Table B.3
Payback periods of the various building HVAC systems by applying the ETS (years) ($28.26 USD/tCO$_2$)

	System	55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	8.08	9.17	10.83	12.75	15.17	19.00
	ASHP / AC	5.25	6.33	7.67	9.08	11.00	13.42	16.33
	GSHP	7.50	8.67	9.92	11.17	13.00	15.33	18.25
	VRF	4.50	5.58	6.83	8.25	10.17	12.42	15.17
	PV+VRF	7.83	8.83	9.92	11.08	12.92	14.92	17.67
	PV+ESS+VRF	9.33	10.25	11.25	12.33	14.00	16.17	18.92
HR	Furnace / window cooling unit	3.25	4.83	6.67	8.58	10.92	13.67	17.42
	ASHP / AC	5.50	6.58	7.75	9.00	10.83	13.00	15.83
	GSHP	7.92	9.08	10.25	11.42	13.25	15.50	18.33
	VRF	4.92	6.00	7.17	8.50	10.33	12.50	15.17
	PV+VRF	8.00	9.00	10.08	11.17	13.00	14.92	17.58
	PV+ESS+VRF	9.42	10.33	11.25	12.33	14.00	16.08	18.83

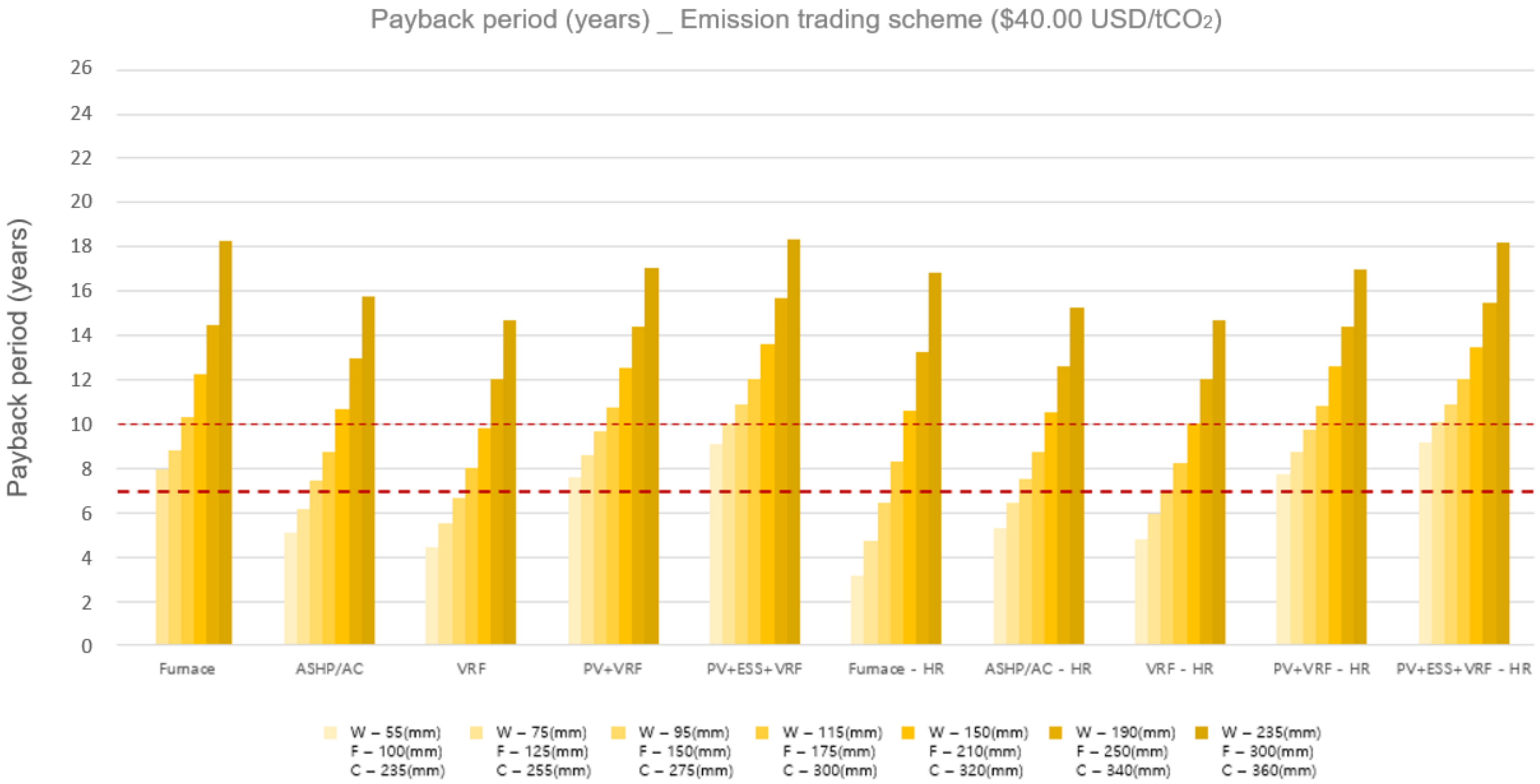


Figure B.4 Payback periods of the various building HVAC systems by applying the ETS (years) ($40.00 USD/tCO$_2$)

Table B.4

Payback periods of the various building HVAC systems by applying the ETS (years) ($40.00 USD/tCO$_2$)

System		55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	7.92	8.83	10.33	12.25	14.50	18.25
	ASHP / AC	5.08	6.17	7.42	8.75	10.67	13.00	15.75
	GSHP	7.33	8.42	9.58	10.83	12.58	14.83	17.58
	VRF	4.42	5.50	6.67	8.00	9.83	12.00	14.67
	PV+VRF	7.58	8.58	9.67	10.75	12.50	14.42	17.08
	PV+ESS+VRF	9.08	10.00	10.92	12.00	13.58	15.67	18.33
HR	Furnace / window cooling unit	3.17	4.75	6.42	8.33	10.58	13.25	16.83
	ASHP / AC	5.33	6.42	7.50	8.75	10.50	12.58	15.25
	GSHP	7.67	8.75	9.92	11.08	12.83	15.00	17.67
	VRF	4.83	5.92	7.00	8.25	10.00	12.00	14.67
	PV+VRF	7.75	8.75	9.75	10.83	12.58	14.42	17.00
	PV+ESS+VRF	9.17	10.08	10.92	12.00	13.50	15.50	18.17

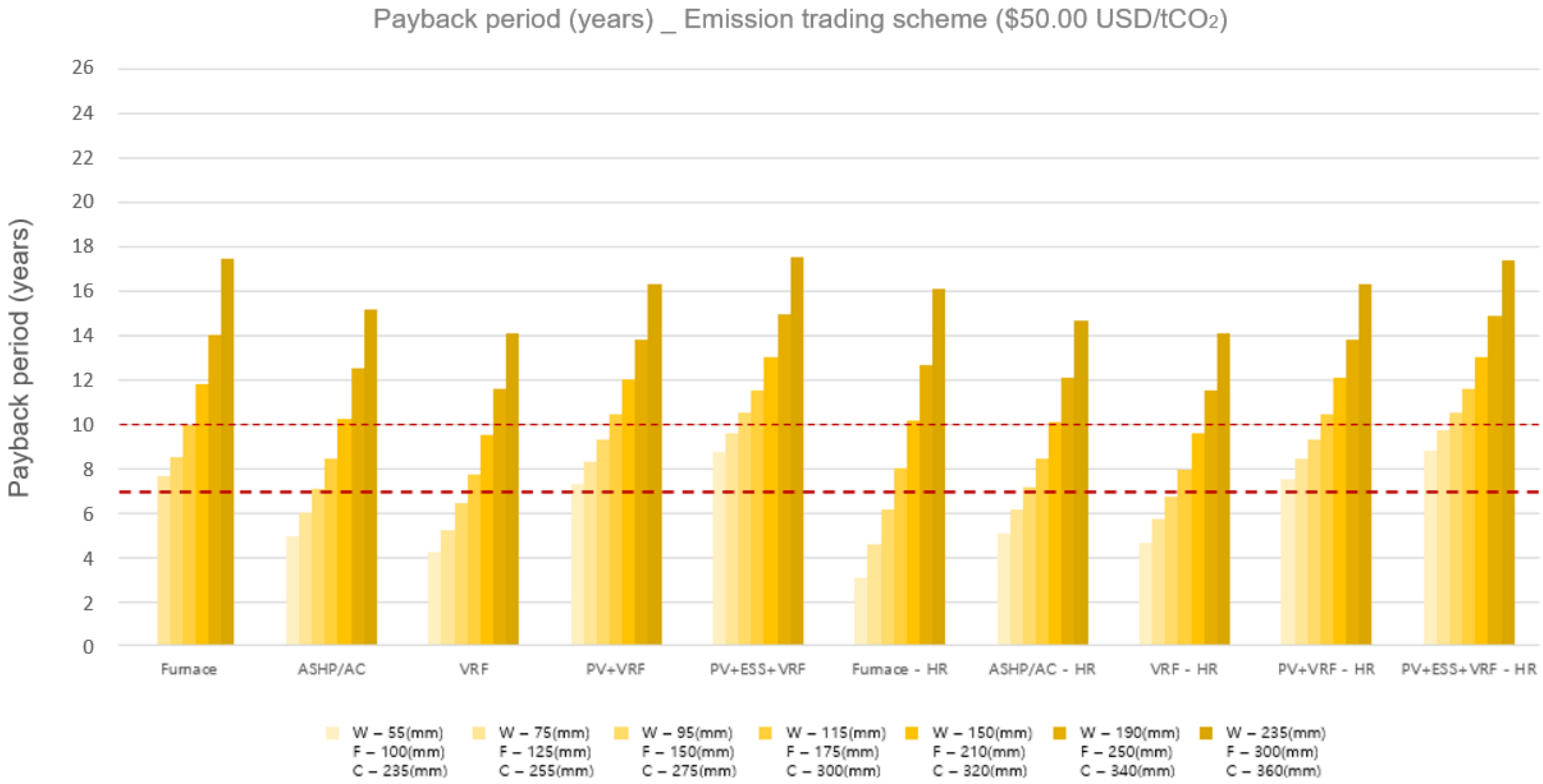


Figure B.5 Payback periods of the various building HVAC systems by applying the ETS (years) ($50.00 USD/tCO$_2$)

Table B.5

Payback periods of the various building HVAC systems by applying the ETS (years) ($50.00 USD/$tCO_2$)

	System	55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	7.67	8.50	9.92	11.83	14.00	17.50
	ASHP / AC	4.92	6.00	7.08	8.42	10.25	12.50	15.17
	GSHP	7.00	8.08	9.25	10.42	12.17	14.25	16.92
	VRF	4.25	5.25	6.42	7.75	9.50	11.58	14.08
	PV+VRF	7.33	8.33	9.33	10.42	12.00	13.83	16.33
	PV+ESS+VRF	8.75	9.58	10.50	11.50	13.00	15.00	17.58
HR	Furnace / window cooling unit	3.08	4.58	6.17	8.00	10.17	12.67	16.08
	ASHP / AC	5.08	6.17	7.17	8.42	10.08	12.08	14.67
	GSHP	7.42	8.42	9.50	10.67	12.33	14.33	16.92
	VRF	4.67	5.75	6.75	7.92	9.58	11.50	14.08
	PV+VRF	7.50	8.42	9.33	10.42	12.08	13.83	16.33
	PV+ESS+VRF	8.83	9.75	10.50	11.58	13.00	14.92	17.42

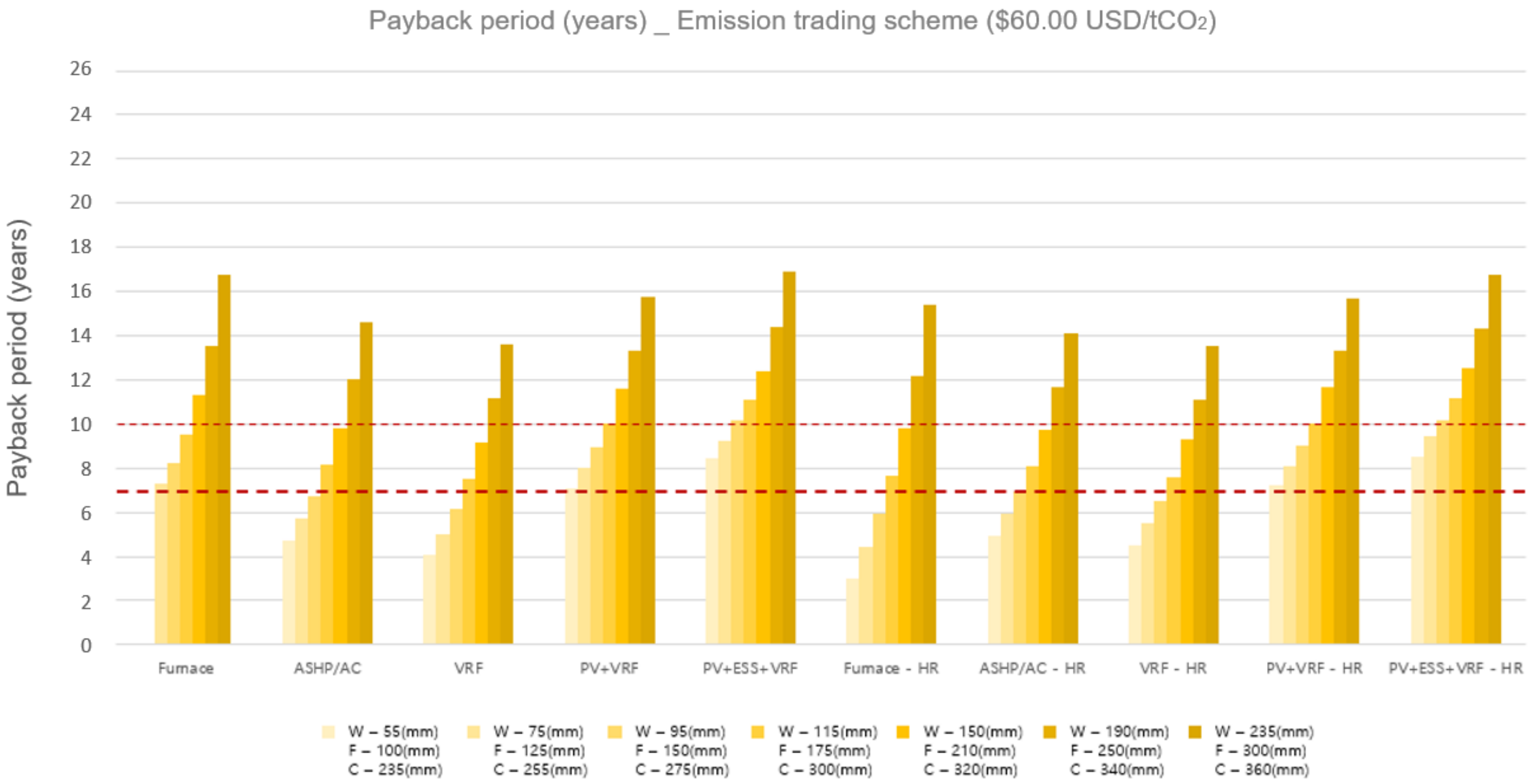


Figure B.6 Payback periods of the various building HVAC systems by applying the ETS (years) ($60.00 USD/tCO$_2$)

Table B.6
Payback periods of the various building HVAC systems by applying the ETS (years) ($60.00 USD/tCO$_2$)

	System	55(mm)	75(mm)	95(mm)	115(mm)	150(mm)	190(mm)	235(mm)
HR (N/A)	Furnace / window cooling unit	0.00	7.33	8.25	9.50	11.33	13.50	16.75
	ASHP / AC	4.75	5.75	6.75	8.17	9.83	12.00	14.58
	GSHP	6.83	7.83	8.92	10.00	11.67	13.75	16.25
	VRF	4.08	5.00	6.17	7.50	9.17	11.17	13.58
	PV+VRF	7.08	8.00	8.92	10.00	11.58	13.33	15.75
	PV+ESS+VRF	8.42	9.25	10.17	11.08	12.42	14.42	16.92
HR	Furnace / window cooling unit	3.00	4.42	5.92	7.67	9.83	12.17	15.42
	ASHP / AC	4.92	5.92	6.92	8.08	9.75	11.67	14.08
	GSHP	7.17	8.17	9.17	10.25	11.92	13.83	16.25
	VRF	4.50	5.50	6.50	7.58	9.33	11.08	13.50
	PV+VRF	7.25	8.08	9.00	10.00	11.67	13.33	15.67
	PV+ESS+VRF	8.50	9.42	10.17	11.17	12.50	14.33	16.75

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