A COMPARATIVE CASE STUDY OF SUSTAINABLE HEAT NETWORKS INCLUDING THREE HEAT COLLECTOR TYPES AND TWO DIFFERENT HEAT STORAGE SYSTEMS

Master thesis

SOURCE: AARDGASVRIJEWIJKEN.NL

SIMONE VAN DER VEEN

UTRECHT UNIVERSITY
MSC SUSTAINABLE DEVELOPMENT - TRACK: ENERGY AND MATERIALS
SUPERVISOR UTRECHT UNIVERSITY: ROBERT HARMSEN

COMMISSIONED BY DWA
SUPERVISORS DWA: MARTIJN KOOP AND PETER HEIJBOER

20-02-2022

Foreword and acknowledgement

This master thesis is my final step to graduation of the master Sustainable Development, track: Energy and Materials. Before conducting this research, I was already very interested in sustainability in the built environment. This thesis has even reinforced my enthusiasm to contribute to a more sustainable way of living. Although my thesis period took a different path than expected, I am grateful for the confirmation in choosing the right master's program that is totally in line with my interests. I look forward to contributing even more to a healthier and more sustainable society.

This thesis was conducted in collaboration with DWA and I would like to thank Martijn and Peter for their patience during my recovery process and sharing their knowledge in favor of this research. I really enjoyed being a part of DWA and meeting colleagues with the same interests. Also, I would like to thank Robert for his guidance throughout this year and his valuable feedback and tips to ease the process and improve my research. I always really enjoyed our talks and I am really pleased with you as my supervisor while accomplishing the final step towards graduation. In addition, I would like to thank Dan for his unexpected, really valuable, addition to the last week to enhance my thesis to its final level. Lastly, I would like to thank my family and friends for their support in the past year. It hasn't been easy but I'm really glad to be totally back on track again and being able to achieve the completion of my master with this result.

I wish you all a very pleasant reading experience.

Simone van der Veen

February, 2022

Summary

As a result of signing the Paris Agreement in 2015, The Dutch government has decided to reduce the Dutch emissions by 90 to 95% in 2050 (Klimaatakkoord, 2019b). Because the built environment is responsible for more than 30% of the total amount of emissions, multiple sub-goals have been set including the exclusion of natural gas from seven million of the total of eight million households and one million non-residential buildings by 2050 (Klimaatakkoord, 2019a). Because solar energy is one of the most distinguished renewable energy types, the aim is to investigate the potential of this resource in district heating. This was done by comparing different concepts on costs, CO_2 savings and the capability of meeting the heat demand of Dutch households.

Based on similar projects and strategies from Planbureau voor de Leefomgeving (2020b), five heating concepts are developed. These concepts consist of a solar thermal energy collector for the generation of heat, a heat storage system and a heat grid. Two types of PVT panels (from Triple Solar and Solarus) and one Flat Plate collector type (from G2energy) are incorporated. A Warm and Cold Storage (WCS) system and a High Temperature Storage (HTS) system are considered as the heat storage systems and two temperatures (12-15°C and 70°C) of heat grids are included. An overview and the numbering of the five concepts can be found in Figure 1 provided in 1.3. These concepts are all applied on a terraced house and an apartment. For the low temperature concepts (1, 3 and 5), in the dwelling, additional insulation and the appliance of an individual heat pump is considered. For the high temperature concepts (2 and 4), the appliance of a delivery set in the dwelling and a collective heat pump at site of the heat storage is considered.

To obtain the desired data to answer the research question, multiple calculations are made. Climate data is used to calculate the heat production by the solar collectors, and the amount of m^2 panels needed to cover the heat demand of the two included dwelling types including the heat losses occurring in the storage system and heat grid. With the amount of m^2 panels, the electricity production of the Triple Solar and Solarus panels is determined and the costs of applying each concept is calculated. Lastly, the CO_2 emissions savings are estimated based on the natural gas and electricity savings.

After obtaining the results and comparing the concepts on the three criteria (costs, CO_2 savings and coverage of the heat demand), Concept 2, 4 and 5 show the best score considering a terraced house. This is mostly due to good performances on the requirement of a low amount of m^2 to cover the heat demand and heat losses and comparatively low investment costs. For Concept 2, also high CO_2 savings are determined due to additional electricity production by the panel. For an apartment, Concept 3, 4 and 5 are the best performing concepts. This is also due to the same findings as for the concepts applied on a terraced house.

When looking at the total picture, it can be concluded that solar thermal energy is a good option considering a more sustainable heating system. However, additional insulation measures should be considered first before applying one of the concepts.

Samenvatting

Naar aanleiding van de ondertekening van het Overeenkomst van Parijs in 2015 heeft de Nederlandse overheid besloten de Nederlandse uitstoot te verminderen met 90 tot 95% in 20250 (Klimaatakkoord, 2019b). Omdat de gebouwde omgeving verantwoordelijk is voor meer dan 30% van de totale uitstoot, zijn er meerdere subdoelen gesteld waaronder het uitsluiten van aardgas van zeven miljoen van de in totaal acht miljoen huishoudens en één miljoen utiliteitsbouwen in 2050 (Klimaatakkoord, 2019a). Omdat zonne-energie een van de meest onderscheidende vormen van hernieuwbare energie is, is het doel van dit onderzoek om de potentie van deze bron in stadsverwarming te onderzoeken. Dit is gedaan door verschillende concepten te vergelijken op het gebied van kosten, CO_2-besparing en het kunnen voldoen aan de warmtevraag van Nederlandse huishoudens.

Op basis van vergelijkbare projecten en strategieën van Planbureau voor de Leefomgeving (2020b) zijn er vijf concepten ontwikkeld. Deze concepten bestaan uit een zonnecollector voor warmteopwekking, een warmteopslagsysteem en een warmtenet. Er zijn twee typen PVT-panelen (van Triple Solar en Solarus) en één type vakke plaat collector (van G2energy) meegenomen. Als warmteopslagsysteem is er een Warm Koude Opslag (WKO) systeem en een Hoge Temperatuur Opslag (HTO) systeem beschouwd en zijn er twee temperaturen (12-15°C en 70°C) warmtenetten meegenomen. Een overzicht en de nummering van de vijf concepten is te vinden in Figuur 1 in 1.3. Deze concepten worden zowel toegepast op een rijtjeswoning als op een appartement. Bij de lage temperatuurconcepten (1, 3 en 5) is extra isolatie toegepast op de woning en de inbouw van een individuele warmtepomp. Voor de hoge temperatuurconcepten (2 en 4), een aflever set is meegenomen in de woning en een collectieve warmtepomp is toegepast op de plaats van de warmteopslag.

Om de gewenste gegevens te verkrijgen om de onderzoeksvraag te beantwoorden zijn er meerdere berekeningen gemaakt. Met klimaatgegevens is de warmteproductie door de zonnecollectoren berekend en de hoeveelheid paneeloppervlak dat nodig is om de warmtevraag van de twee opgenomen woningtypen te dekken, inclusief de optredende warmteverliezen in het opslagsysteem en het warmtenet. Met het benodigde paneeloppervlak is de elektriciteitsproductie van de Triple Solar en Solarus panelen bepaald en zijn de kosten voor het toepassen van elk concept berekend. Ten slotte is de besparing van CO_2-emissies berekend op basis van de besparingen op aardgas en elektriciteit.

Na het verkrijgen van de resultaten en het vergelijken van de concepten volgens de drie criteria (kosten, CO_2 reductie en het voldoen aan het warmtevraag) scoren Concept 2, 4 en 5 het beste voor een rijtjeshuis. Dit is vooral te danken aan een laag aantal m^2 benodigd om de warmtevraag en -verliezen te dekken en relatief lage investeringskosten. Voor Concept 2 werd ook een hoge CO_2-besparing vastgesteld door extra elektriciteitsproductie door het paneel. Voor een appartement zijn Concept 3, 4 en 5 de best presterende concepten. Dit komt ook grotendeels door dezelfde bevindingen als bij de drie concepten toegepast op een rijtjeshuis.

Op grond van de verkregen resultaten kan worden geconcludeerd dat thermische zonne-energie een goede optie is voor een duurzamer verwarmingssysteem. Er moeten echter eerst aanvullende isolatiemaatregelen worden overwogen voordat een van de concepten wordt toegepast.

Table of Contents

1 Introduction

1.1 Background

To contribute to the goal of limiting global warming to 2 and preferably 1.5 degrees Celsius, The Netherlands has committed itself to reduce their impact by signing the Paris Agreement in 2015 (UNFCCC, 2015). Large commitments and strong goals need to be set by the 195 participating countries to reduce their emissions. The Dutch government has set its own goals to reduce the Dutch emissions by 90 to 95% in 2050 compared to the measurements in 1990 (Klimaatakkoord, 2019b). The total amount of emissions in 1990 was approximately 221 megaton CO_2 equivalent which must be lowered to a maximum of 11-23 megatons in 2050 to achieve this goal (CBS, 2021b).

Multiple sub-goals have been set to reduce the Dutch emissions within the coming thirty years (Klimaatakkoord, 2019b). This includes decreasing the impact of the built environment which is responsible for more than 30% of the total energy use in The Netherlands (Rijksoverheid, 2017). Reducing this amount could have a significant decreasing effect in the total amount of greenhouse gasses emitted. Currently, one third of the total amount of primary energy in The Netherlands is used for heating purposes of which 80% is covered by natural gas (Coenen et al., 2018). The Dutch climate agreement includes agreements to exclude natural gas from seven million of the total of eight million households and one million non-residential buildings by 2050 (Klimaatakkoord, 2019b). Although the natural gas extraction has greatly contributed to the Dutch welfare through international trade, it also caused some adverse effects (Koopman, 2012). Besides the impact on the environment caused by the gasses emitted during combustion, it also caused social and economic concerns. Due to the extraction of natural gas in, mainly, the province of Groningen, multiple earthquakes have occurred in the past years (OnsAardgas.nl, n.d.). Furthermore, the extraction of this gas could cause subsidence which could have negative consequences for water management and buildings on top of these gas fields.

The Dutch government plans to exclude the use of natural gas from heating systems per district. Each municipality must develop a strategy for each district before the end of 2021 (Klimaatakkoord, 2019b). Such strategy could include the use of residual heat from industry, the production of heat using biomass, biogas, geothermal energy and/or other ways to extract heat from the air, water or the earth (Coenen et al., 2018). In most cases, a heat network is one of the main elements in these strategies (Planbureau voor de Leefomgeving, 2020b). A heat network exists of a grid of insulated pipes from a centralized location to households and buildings to supply heat for space and water heating (Department for Business Energy & Industrial Strategy, 2017). Coenen et al. (2018) investigated the potential of heat grids in The Netherlands and found that half of the required heat, which is a quarter of the total energy demand, could be covered by heat networks. The construction of a heat network supplied by heat generated from sustainable energy resources could thus have a meaningful contribution to the energy transition towards a more climate neutral energy system (Coenen et al., 2018). The most common sustainable energy resources for heating consist of geothermal energy, residual heat from industry and energy from renewable resources (Hoogervorst, 2017).

1.2 Problem definition

One of the most distinguished renewable energy types is solar energy which is environmentally friendly, free and applications to generate solar energy are generally easy to apply (Herez, El Hage, Lemenand, Ramadan, & Khaled, 2020). However, different from individual solar boilers, central solar thermal energy production is still not commonly applied in The Netherlands on large scale. The only application of solar thermal energy on larger scale in The Netherlands can be found in Almere where 2700 households are supplied (Bezemer, 2010). In addition, four out of the 46 pilot projects initiated in 2018 and 2020 to gather experience with the phasing out of natural gas included solar thermal energy applications (Programma Aardgasvrije wijken, n.d.). These projects are further discussed in section 2.2.

Solar thermal energy is, so far, not covered by the five main strategies (nor sub-strategies) identified by the 'Planbureau voor de Leefomgeving' (PBL) to help municipalities to develop their heat transition plan for replacing natural gas by a renewable heating source (Planbureau voor de Leefomgeving, 2020a).

To obtain a better overview of the possible advantages and/or drawback of large-scale use of solar thermal applications in the Dutch context, more research is needed into the annual heat production and the economic feasibility (Dullemen, 2020). This will eventually help decision makers include these applications into consideration when developing a more sustainable heating system.

Shafieian, Khiadani, and Nosrati (2018) reviewed the latest developments of heat pipe solar collectors and found that limited research was done on the economic feasibility of these type of collectors, especially focusing on specific neighborhoods. Taking consumption patterns of a specific location into account would enable a more comprehensive outcome which is also supported by Andersen et al. (2019). Moreover, previous research only reported performances in the short-term where annual performance values would be more significant (Shafieian et al., 2018). They only considered simplified assumptions. Furthermore, Herrando, Pantaleo, Wang, and Markides (2019) addressed the higher investment costs of Photo Voltaic Thermal (PVT) panels and other solar collectors compared to alternatives like commercial Photo Voltaic (PV) panels whose energy could be used to generate heat using e.g. a heat pump. They state that additional research is required to enhance the efficiency of a PVT panel. Mohammadi, Khanmohammadi, Khorasanizadeh, and Powell (2020) propose that more research should be done on developing forecasting models, control strategies and more efficient operation strategies. More research to full solar driven energy systems is required to derive more knowledge about the real potential of such systems in different cases. Andersen et al. (2019) also states that more research would be beneficial to the importance of district heating in a local systems context. It is important to know what district heating could contribute related to future practice and policy.

Although the combination of solar thermal energy, heat storage and a heat network has already been under investigation in the past few years, a detailed comparison and overview of different strategies for one specific case is still lacking.

1.3 Aim and research questions

Based on the knowledge gap defined in 1.2, the aim of this research is to collect data of different heating systems to compare these results on costs, CO_2 emission savings and the ability to cover the heat demand of two dwelling types. In this way, the drawbacks and advantages of each system will be investigated. Details about the total design of the five heating systems is provided in section 2.6.

To eventually obtain the desired results, the following main research question is formulated:

How do different sustainable heating systems based on solar-thermal technologies compare regarding costs, CO_2 savings and the capability of meeting the heat demand of Dutch households?

For this research, two initial analyses developed by Planbureau voor de Leefomgeving (2020b) are used as baseline for the development of five heating system concepts to analyze the prospect of solar thermal energy generation in a more sustainable future. The two analyses considered in this research include a heat network and a heat storage system. This concept is used for the development of five concepts which also include a heat network, two different heat storage systems, and two types of solar collectors to supply the heat. A comparison of the data obtained after calculations will indicate, firstly, if this concept could be a possible contribution to the transition to a more sustainable heating system, and secondly, which concept would be most beneficial. The different concepts will be compared on costs of the total system, CO_2 savings compared to the current situation where natural gas is still in use, and the capability to meet the current heat demand. These concepts will be compared after calculations using detailed information about the different technologies. More detail about the different integrated technologies and parameters will be provided in Chapter 2. First the motive and guidelines behind this research will be further discussed followed by the integrated technologies and parameters. Finally, a synthesis will be provided in which the connection between the different aspects (Figure 1) will be indicated.

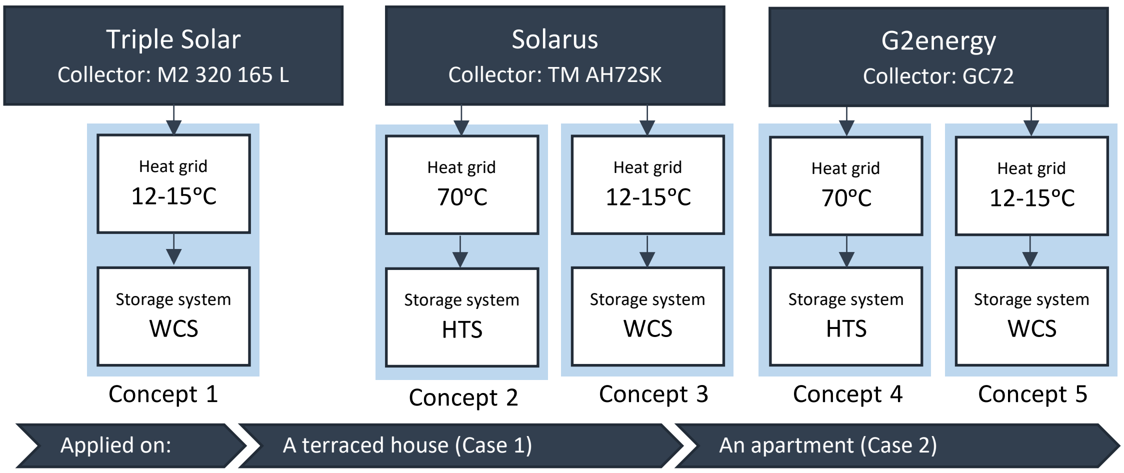

FIGURE 1 OVERVIEW OF THE FIVE CONCEPTS INCLUDED IN THIS RESEARCH WHICH WILL BE APPLIED ON TWO CASES.

This study will be executed using two forms of existing dwelling types to guarantee full inclusion of different valuable options. The five concepts will be applied on both a terraced house and an apartment, this is further elaborated in section 2.6.

1.4 Commissioner

This research is developed in collaboration with DWA, an engineering and consultancy company, which expressed its interests in the possible contribution of solar collectors and different heat storage systems to a sustainable heating system. This company is specialized in sustainable options within the energy transition for the built environment. Their expertise and valuable information will be used in favor of this research to finally obtain a reliable and useful outcome for future practices in this field.

2 Theoretical background

In this chapter, the theory behind the research is elaborated upon. First a small research project was conducted in the current situation regarding the Dutch Climate agreements and options within solar thermal energy generation (2.1 and 2.2). After gaining a wide overview of the possibilities within the natural-gas free transition, the scope was created and the system boundaries were set (2.3). The focus per parameter was set (2.4, 2.5) and the different strategies were formed which can be found in 2.6.

2.1 Dutch Climate agreement: built environment

In 2018, the first step towards a Dutch Climate Agreement was taken. The Dutch parliament assigned five sector groups (electricity, built environment, industry, agriculture and land-use, and mobility) together with the Dutch Climate Council to develop a strategy to reduce the amount of greenhouse gasses emitted. Moreover, this document of more than six hundred commitments is a step-by-step plan to eventually reach the goals set in the Paris Agreement. Because this report is only focused on the built environment, only a short summary of the approach for this sector will be discussed.

As mentioned in Chapter 1, the main challenge for the built environment is to exclude the use of natural gas from seven million houses and one million non-residential buildings before 2050. This means many more natural-gas-free neighborhoods including heat networks, the need for far-reaching insulation in combination with electric heating (Van Vuuren, Boot, Ros, Hof, & den Elzen, 2017). Municipalities get high responsibilities to find the best solution for each neighborhood (Klimaatakkoord, 2019b). This will be realized in cooperation with residents and building owners whose investment costs will repay itself through a reduction in energy costs over the years. In 2021, each municipality had to develop a plan in which the different steps towards fulfillment of the agreements was set. This plan can be adjusted every five years. Through an increase in demand for sustainable applications, standardization and innovation in the coming years, a reduction of costs is expected. This will make it more affordable for building owners and residents.

2.2 Solar thermal pilot projects in the Dutch built environment

Various projects have been launched to investigate the potential of heat grids including four incorporated solar thermal energy technologies to generate heat for households (Programma Aardgasvrije wijken, n.d.). Multiple projects are supported by 'Programma Aardgasvrije wijken' (PAW) which is a partnership between several governmental units which includes a knowledge and learning program for municipalities to stimulate the natural-gas free transition. The board of the PAW consists of: the ministry of the interior and kingdom relations, the ministry of economic affairs and climate policy, the interprovincial consultative body, the union of water boards and the association of Dutch municipalities. Two different rounds of natural-gas free pilot projects have already been launched in the past years. Because this research is only focused on solar thermal energy, a heat grid and two specific heat storage systems, only cases including these technologies will be discussed. In the first round (2018), the project in the Noordoostpolder and Vlieland used solar collectors and a Warm Cold water Storage system (WCS) (Hoogers, Go, Drok, & Bergboer, 2018). The details behind this heat storage system will be discussed further in 2.4.3. The neighborhood called Duinwijck, which is located on Vlieland, will heat around 38 houses with a sustainable heating system (Gemeente Vlieland, 2019) and the project planned for the neighborhood Nagele, in the Noordoostpolder, covers around 500 dwellings and other buildings (Hoogers et al., 2018). These pilot projects created the first realizations in early 2021 where the fundamentals of the total systems are put into place. In the second round (2020), 's Hertogenbosch started a pilot project using PVT panels, a heat pump and a WCS for the heating system (Gemeente 's-Hertogenbosch, 2020). And in Lingewaard a pilot project was started using a combination of wood fired heat production and water- and solar thermal energy (Gemeente Lingewaard, 2020). Both projects are still in the conceptual phase and not put into practice yet.

Although PAW provides an easy way for the neighborhood to transition a neighborhood from natural gas, other projects, not connected to PAW, are often initiated. One of these projects is Spaargas Ramplaankwartier which is totally initiated by inhabitants (Ramplaankwartier, n.d.). The project is based in the neighborhood Ramplaankwartier (1200 dwellings) in Haarlem which aims to be natural gas free in 2040. Solar thermal energy will be used to provide the residents with their heat demand which will be generated by PVT panels. These panels, and the dwellings, are all connected to a heat grid and the surplus of heat is stored in a WCS.

Even though most of these projects are still in the designing or realization phase, the composition of these projects is used as inspiration to finally obtain five realistic concepts for this research which can be found in paragraph 2.6. The integration of a heat grid and storage system is essential to eventually be able to fully cover the heat demand by solar heat only.

2.3 The five PBL strategies as a guideline

To identify the drawbacks and advantages of different technologies and applications, this research will compare five different concepts which all contribute to the goal of excluding the use of natural gas from households by 2050 (Klimaatakkoord, 2019b). These strategies are related to the initial analyses (referred to as S1-S5) developed by Planbureau voor de Leefomgeving (2020a). The first four PBL strategies (S1-S4) include combinations with currently used technologies and sources, and the fifth strategy (S5) includes the use of hydrogen which is still in the developing stage leading to the application on large scale. Every strategy includes sub-strategies which all have the same layout and main concept but differ on technical level. For this research, strategy S3-C and S3-D are of main interest because these strategies are the most adjustable to solar thermal heat inclusion. These strategies are used as baseline for the five concepts used for this research and explained in 2.3.1 and 2.3.2. At the end of each section, the concepts for which the described strategy is used is indicated.

2.3.1 Strategy 3-C:

The design of strategy 3-C is displayed in Figure 2 (Planbureau voor de Leefomgeving, 2020b).

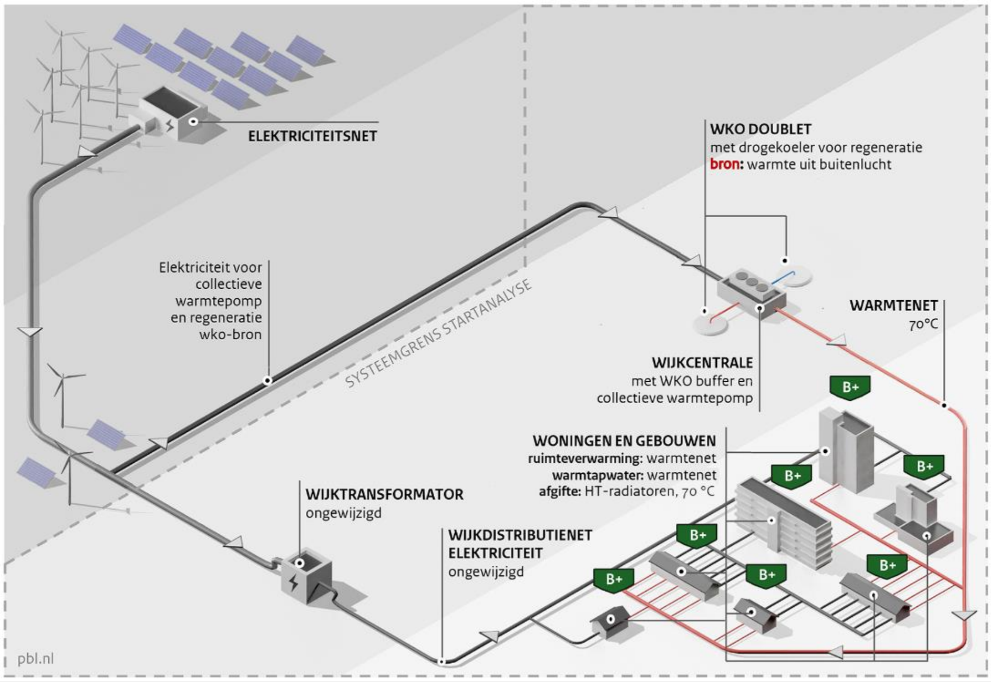

FIGURE 2 SIMPLIFIED REPRESENTATION OF STRATEGY 3 C (PLANBUREAU VOOR DE LEEFOMGEVING, 2020B).

On the bottom right side of Figure 2 are the consuming buildings and houses displayed which are connected to a heat grid. The initial 70°C received from the heat grid can directly be used for space heating, with high temperature radiators, and tap water. After usage of the heat, it is going back to the WCS which extracts heat from the air and uses residual heat from the dry cooling coil to keep the temperature in the heat buffer at 50°C. The dry cooling coil adds cold air to the ground to reduce the energetic imbalance between the buffers with a high and low temperature (VHGM, n.d.).

This strategy is used as a guideline for the 70°C concepts (Concept 2 and 4) displayed in Figure 1. Further elaboration is provided in 2.6.

2.3.2 Strategy 3-D

Figure 3 shows the second strategy (3-D) which will be used as baseline for this research.

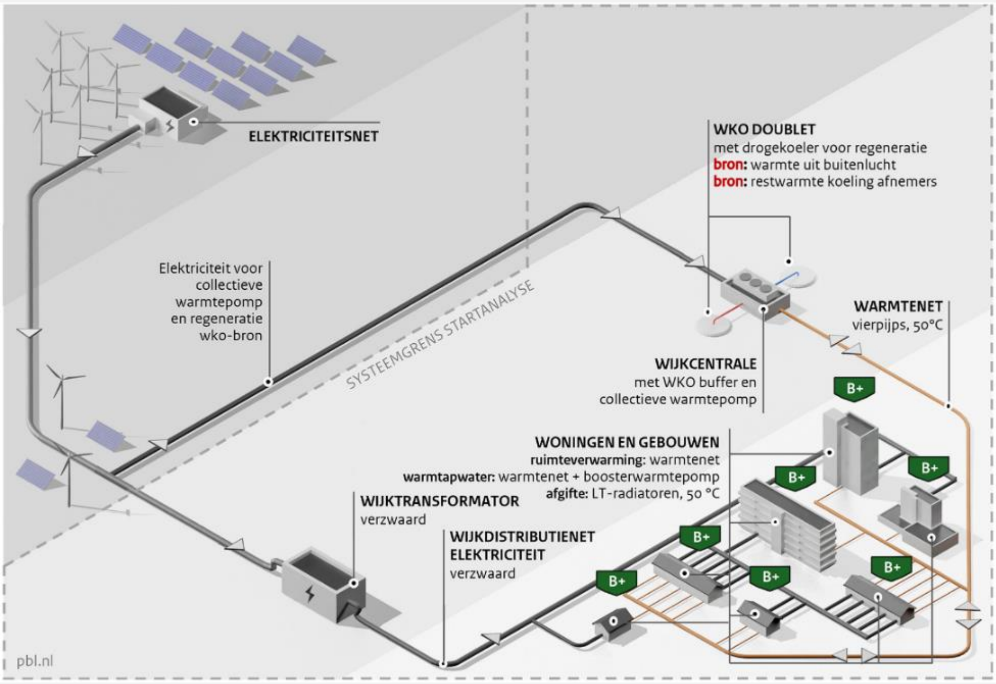

FIGURE 3 SIMPLIFIED REPRESENTATION OF STRATEGY 3 D (PLANBUREAU VOOR DE LEEFOMGEVING, 2020B).

The strategy shown in Figure 3 has the same layout as the previous strategy but here a 50°C heat grid temperature is considered (Planbureau voor de Leefomgeving, 2020b). Because a lower temperature heat grid is considered, low-temperature radiators are used for space heating and the temperature is increased to the preferred temperature for tap water using a booster heat pump.

This strategy is used as a guideline for the 12-15°C concepts (Concept 1, 3 and 5) displayed in Figure 1. Further elaboration is provided in 2.6.

2.4 Technologies integrated in the five heating concepts

In this paragraph, the different technologies which are included in this research are further elaborated. First detailed information about the included solar collectors is provided (2.4.1). Next, the concept of a heat grid is introduced and developments within this field are discussed (2.4.2) followed by an introduction about different types of thermal energy storage systems (2.4.3). In 2.4.4, the concept of a heat pump is discussed which will also be included in some of the concepts in this research. Lastly, the effect of additional insulation applied in residential buildings will be elaborated upon.

2.4.1 Solar collectors

In this report, only the implementation of Photo Voltaic Thermal (PVT) hybrid solar collectors and Flat Plate collectors (FPC) are considered. The choice for PVT panels is made based on the ability to generate both electricity and heat at the same time which makes it versatile in usage. Also, focused on the future, it is more likely that this technology will be applied than collectors which are focused on thermal energy generation only (Heijboer, 2021). However, to obtain a reliable and valid outcome, also Flat Plate collectors will be taken into account. These collectors are currently still one of the most diffused type of solar collectors worldwide (Greco, Gundabattini, Gnanaraj, & Masselli, 2020). First, the specifics of a PVT panel will be discussed in section 2.4.1.1 and the two panel types which are included in this research will be introduced. In the second section (2.4.1.2) information about the Flat Plate collector is provided and the type of FPC which is included in this research is further introduced.

2.4.1.1 PVT panels

PVT panels are a combination of commonly used photovoltaic (PV) panels and solar thermal collectors in a single device. PVT panels are typically manufactured by applying a suitable PV layer to the absorber of a conventional thermal collector (Buonomano, Calise, & Vicidomini, 2016). In that way, both electricity and heat can be generated by distributing the thermal energy to a fluid, typically water or air. Also, absorbing the heat from the PV modules has a beneficial effect on the electricity production due to a reduction of efficiency losses (Buonomano et al., 2016). Following a study by Brottier and Bennacer (2020) to the thermal performance of PVT panels in western Europe, this panel could generate a temperature over 45°C during five months of the year. Moreover, because this technology is in rapid development, Solarus (2021a) even claims to be able to produce a maximum temperature of 70°C with their PVT modules. To obtain a better understanding of the various types of PVT panels, an overview is given in Figure 4.

Part	Variety	
Front face	Overglazed	Non-overglazed
	Under vacuum	
PV emitters	Crystalline	Semi-transparent
	Thin film	Diverse
Fluid types	Air	Heat pipes
	Glycol water	Refrigerant
Material of the heat exchanger	Nano fluid	Bi-fluid
	Copper	Stainless steel
	Aluminium	Polymers
Shape of the heat exchanger	Sheet-and-tube	Channels
	Serpentine	With fins
	Roll bond	Free
Type of contact	Below	Multiple passes
	Above	Direct (no MCP)
	Below and above	Indirect (MCP)
Fixation of the heat exchanger	Glue	Mechanical
	Encapsulation	
Backside	With insulation	Without insulation

FIGURE 4 THE VARIETY OF OPTIONS FOR PVT MODULES (BROTTIER & BENNACER, 2020)

As shown in Figure 4 a wide variety in the composition of PVT modules exist. Following a market investigation into PVT collectors on the European market by A. de Keizer, Bottse, and de Jong (2018), the current most commonly applied PVT panels are uncovered Flat Plate PVT collectors. Because an enormous variety of uncovered Flat Plate collectors exist, the expertise and experience in this field in The Netherlands from Heijboer (2021) is used to make the choice of which one to include in this investigation. For this research a currently often applied PVT module, Triple Solar PVT panel, and a new type of PVT panel, PowerCollector™ aH72SK, is considered. Following Figure 4, both panels can be classified as follows discussing only the most essential parameters. As front face, an overglazed layer is used which exists of an additional glass plate on top of the panel which increases the thermal efficiency (Kim & Kim, 2012; Solarus, 2021c; Triple Solar, 2021). However, because heat gets trapped underneath this layer due to a decreased PV cooling effect, the photovoltaic efficiency is usually a bit lower compared to a regular PV panel. As most commonly used, both panels use crystalline as PV emitter and the heat exchanger exists of copper. As fluid type, both panels use glycol water which is an antifreeze solution and has better heat transfer parameters compared to water only which increases its thermal efficiency (Ebaid, Ghrair, & Al-Busoul, 2018).

More details about each of the panels is provided below.

TRIPLE SOLAR PVT PANEL

The Triple Solar PVT panel is a well-known and often applied PVT panel for this kind of project (Heijboer, 2021). Also compared to an analysis of C. de Keizer et al. (2016), its performance data suits the average values of three other well-known types of PVT panels currently on the market (Triple Solar, 2021). Although the technical information resembles the average PVT panel, the composition of this panel is different. A combination of a regular PVT and a heat pump is put in one device to extract heat from both open air as daylight (Triple Solar, n.d.). Average PVT panels generally extract from sunlight only. Furthermore, this panel can only generate temperatures around 10ºC which is in comparison with the other included collectors very low. Therefore, the inclusion of a heat pump is always required when applying this type of panel. For this research, the panel M2 320 165 L is included which is based on data availability.

More detailed data about this panel is provided in Table 1.

TABLE 1 DETAILED INFORMATION TRIPLE SOLAR COLLECTOR M2 320 165 L (TRIPLE SOLAR, 2021).

General	Value	Unit
Measurements	1667 x 995 x 65	mm
Total surface	1.65	m2
Functional surface	1.63	m2
Weight	27	kg
Photovoltaic data		
Cell type	Mono-crystalline Si	
Rated power	320	W + 3%
Max power voltage (Vmpp)	35	V
Max power current (Impp)	9.15	A
Voc	42.6	V
Isc	9.8	A
Module photovoltaic efficiency	19.6	%
Temp. Coefficient Pmpp	-0.37	%/°C
Temp. Coefficient Voc	-0.3	%/°C
Temp. Coefficient Isc	0.06	%/°C
Thermal data		
Thermal power	450	W_p
Optical efficiency	47	%
Thermal heat loss coefficient (a_1)	45.71	W/m2*K
Thermal heat loss coefficient (a_2)	0	W/m2*K
Stagnation temperature	62	°C
Max pressure	6	bar
Max operational temperature	85	°C
Costs*	1062.86	€/panel
* Costs are inclusive installation, all the necessary materials and BTW	644.16	€/m2

POWERCOLLECTOR™ AH72SK

For this research, also another type of PVT module is taken into account. This panel is currently one of the newest PVT panels on the Dutch market and claims to have the highest renewable energy production and the highest CO_2 emission savings compared to other PVT panels (Solarus, 2021a). Up to 89% of the radiation can be converted into electricity (19.4%) and thermal energy (70%). Following Solarus (2021c), these panels are able to generate a maximum temperature of 70°C which can directly be used for space heating and hot tapwater.

Figure 5 shows the estimated energy production throughout the year in Dutch climate conditions.

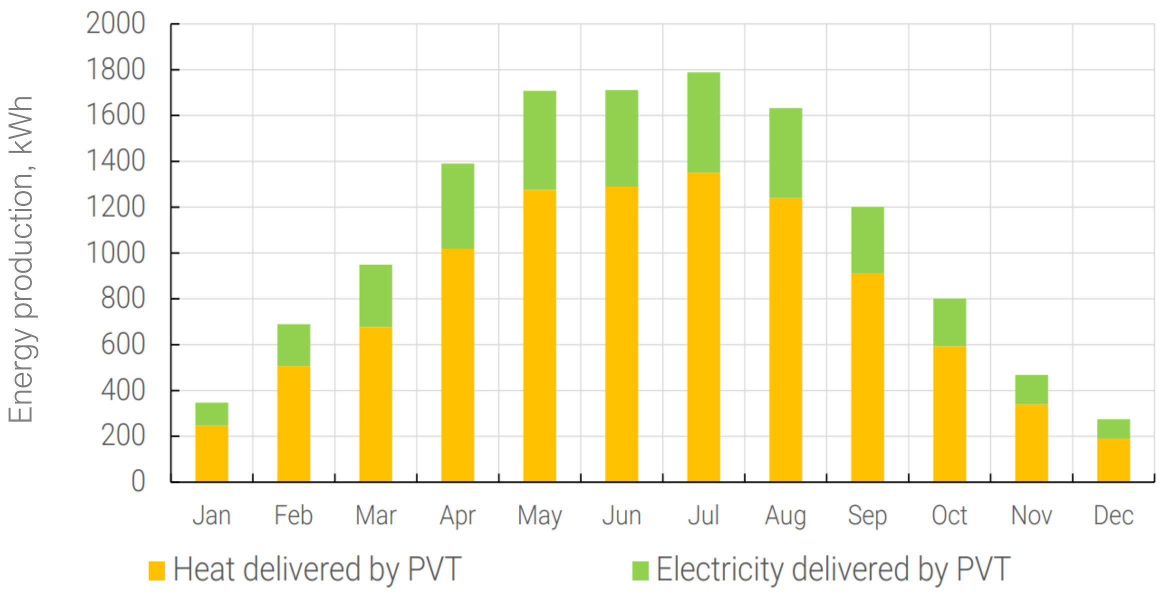

FIGURE 5 SIMULATED MONTHLY HEAT AND ELECTRICITY GENERATION BY 10 POWERCOLLECTOR™ AH72SK PANELS IN THE NETHERLANDS (SOLARUS, 2021A)

As shown in Figure 5, ten of these panels could generate 9,636 kWh of heat a year which is equal to ~986.4 m³ of natural gas worth around €890 (€0.90/m³ gas). This eventually leads to an CO_2 emissions savings estimation of 1,864 kg of CO_2 a year. Focused on electricity, yearly these panels could generate 3,325 kWh of electricity worth around €830 (€0.25/kWh). This leads to a CO_2 emissions savings estimation of 1,849 kg of CO_2 a year. In total, these panels could save up to 3,714 kg of CO_2 a year.

More qualitative data is provided in Table 2.

TABLE 2 DETAILED INFORMATION POWERCOLLECTOR™ AH72SK PANEL (SOLARUS, 2021B)

General	Value	Unit
Measurements	1970 x 995 x (85+22)	mm
Total surface	1.96	m2
Functional surface	1.88	m2
Weight	50	kg
Photovoltaic data		
Cell type	Mono-crystalline Si	
Rated power	380	W + 3%
Max power voltage (Vmpp)	40.19	V
Max power current (Impp)	9.46	A
Voc	48.11	V
Isc	10.36	A
Module photovoltaic efficiency	19.4	%
Temp. Coefficient Pmpp	-0.41	%/°C
Temp. Coefficient Voc	-0.33	%/°C
Temp. Coefficient Isc	0.6	%/°C
Thermal data		
Thermal power	1375	W
Optical efficiency	70	%
Thermal heat loss coefficient (a_1)	5.98	W/m2*K
Thermal heat loss coefficient (a_2)	0	W/m2*K
Stagnation temperature	126	°C
Max pressure	10	bar
Max operational temperature	85	°C
Costs*	1646.4	€/panel
* Costs are inclusive installation, all the necessary materials and BTW	840	€/m2

2.4.1.2 Flat Plate collectors

The Flat Plate collector acts like a black body with a transparent cover to avoid dispersion of solar radiation (Greco, Gundabattini, Gnanaraj, & Masselli, 2020). This causes a greenhouse effect in the collector that forces heat to remain trapped and causes an increase in temperature of the collector. This leads to a very high absorbing temperature, some systems are even able to absorb up to 95% of the incoming solar radiation. Like a PVT panel, the core of the collector is the capturing part and a fluid, typically liquid or air, is used as transfer medium. This fluid circulates through a bundle of pipes in the collector to absorb as much heat as possible. For this research, a heat collector of G2energy will be considered. This company is one of the biggest suppliers of Flat Plate collectors in The Netherlands (Heijboer, 2021). After correspondence with G2energy (Molenaar, 2021), its decided to include the GC72 collector. This type of collector has already been applied in multiple larger projects in the horticulture sector and has, additionally, great potential to contribute to the heat transition on district level.

The only difference in classification (Figure 4) between the PVT panels (Triple Solar panel and PowerCollector™ aH72SK) and this type of panel is that this type of FPC typically uses water instead of glycol water as fluid type in the collector. Because this panel operates following a return system, stagnation and frost damage is prevented and the addition of glycol is not required.

The panel data is displayed in Table 3 below.

TABLE 3 DETAILED INFORMATION FLAT PLATE COLLECTOR GC72 (G2ENERGY, 2021; MOLENAAR, 2021).

General	Value	Unit
Measurements	6250 x 1220 x 110	mm
Total surface	7.625	m2
Functional surface	6.9	m2
Weight	130	kg
Thermal data		
Thermal power	-	W
Optical efficiency	77.3	%
Thermal heat loss coefficient (a1)	2.934	W/m2*K
Thermal heat loss coefficient (a2)	0.0206	W/m2*K
Stagnation temperature	185	ºC
Max pressure	3	bar
Max operational temperature	-	ºC
Costs*	1906.25	€/panel
* Costs are inclusive installation, all the necessary materials and BTW	250	€/m2

2.4.2 Heat grids: generations and temperature levels

To deliver the stored heat to the households, a heat network is used. To get a clear overview of the different types of heat networks, the networks are distinguished in generations and temperature levels (Papa, Wijnant-Timmerman, & van Leeuwen, 2019). First the generations are explained followed by the temperature levels.

Due to new innovations and developments in the past years, various generations can be distinguished (Papa et al., 2019). For each generation, a short summary is given.

Heat distributed by a first generation heat network is delivered in the form of steam which has a high energy content. The steam was transported through pipes in underground concrete tunnels or highly insulated overground pipes (Papa et al., 2019). This kind of heat distribution was mostly used between 1880 and 1930 to supply heat for industrial processes which required additional heat of around 300ºC. Due to low efficiency (25%), high investment costs due to corrosion of the pipes by discharge of condensate and pressure losses, a second generation was developed.

The second generation of heat networks is similar to the first generation but distributes hot water instead of steam (Papa et al., 2019). The water is overheated to a temperature over 100ºC and kept under pressure which causes a higher efficiency and 50% reduction of fuel use compared to the first generation. Also, comparatively less material was used. This type of heat works was mostly applied between 1930 and 1980.

Due to the increasing urge to reduce the use of energy, a third generation heat network was developed (Papa et al., 2019). The pipes included in this kind of network are better insulated and directly put into the ground without any concrete protection cover. This improved its efficiency and less energy was lost in the system. Still, water is the main heat distributer in these networks but now lower temperatures can be considered which also improves the overall efficiency of the system. Currently, these types of heat grids are the most applied.

The fourth and the fifth generation are still in development. The prospect is that the fourth generation of heat networks will mostly be applied between 2020 and 2050 (Papa et al., 2019). This kind of network is dominated by low temperature heat, both the inflow and outflow have a lower temperature compared to third generation which reduces energy and heat loss. This type of grid can easily be modified to smart energy systems in which (seasonal) heat storage is considered and the in- and outflow is precisely monitored and coordinated. Although the fourth generation heat network is still in development and just being implemented, a fifth generation is already on its way. This network is operating at near ground temperatures and exchanges both heat and cold in a bidirectional way between the connected dwellings (Lund et al., 2021). This heat and cold is facilitated by a seasonal heat storage and requires a heat pump to obtain the desired temperature for space heating and hot tap water.

In this research, the heat grids included in the concepts are based on the third and fourth generation grids. The first and second generation heat grids are outdated and low in efficiency compared to the last three generation networks. However, because the fifth generation heat grid is still in development and no cold temperatures will be included in this research, the third and fourth generation are considered most suitable.

As mentioned in 2.4.2, the heat grids can also be subdivided in temperature levels. Four temperatures levels for heat networks are defined in Table 4.

TABLE 4 CURRENTLY USED HEAT NETWORKS DIVIDED IN FOUR TEMPERATURE CATEGORIES (KIRCH, DEN DEKKER, & DUIJFF, 2020; PAPA ET AL., 2019).

Type of heat network	Characteristics
High temperature	
Primary	- Maximum temperature: 120°C Minimum temperature: 90°C - Mostly used for distribution of residual heat from waste incineration or power plants. - Water can directly be used for hot tapwater and space heating.
Secondary	- Maximum temperature: 100°C Minimum temperature: 70°C - Water can directly be used for hot tapwater and space heating.
Medium temperature	- Maximum temperature: 90°C Minimum temperature: 50/55°C - Currently mostly used. - Water can directly be used for hot tapwater and space heating.
Low temperature	- Maximum temperature: 55°C Minimum temperature: 30°C - Water can directly be used for space heating. - A additional application is needed to increase the temperature for hot tapwater.
Very low temperature	- Maximum temperature: 25°C Minimum temperature: 10°C - Water requires additional heating for usage for hot tapwater and space heating.

As shown is Table 4, different heat grid temperatures can be distinguished. From a high temperature of 120°C to a very low temperature of around 10°C. The high temperatures can generally directly be used for space heating and/or hot tap water, for the lower temperatures the intervention of a heat pump is essential to increase the temperature to its desired degree.

2.4.3 Storage systems

As shown in Figure 6, almost two third of the yearly irradiation of the sun is delivered between May and September although the heat demand is mainly appearing from October to April (Mangold & Deschaintre, 2015).

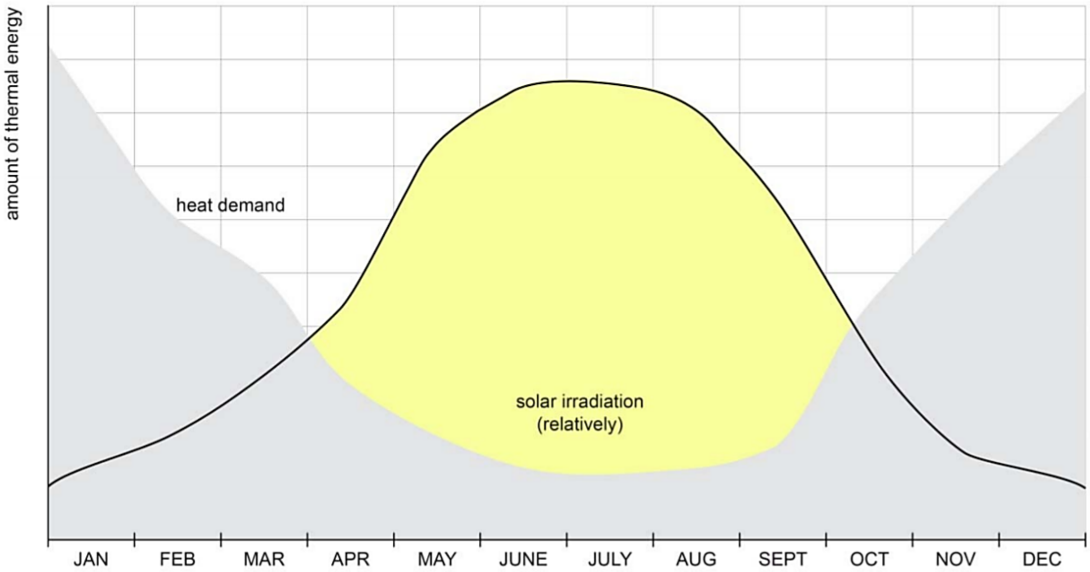

FIGURE 6 HEAT DEMAND AND SOLAR RADIATION OVER A YEAR (SOURCE: SOLITES).

To guarantee sufficient heat supply throughout the year, every concept includes a heat storage system. This bridges the seasonal mismatch between high demand for heat in colder times and the large amount of heat generation in summer times. Thermal storage systems can be classified in three different mechanisms: sensible, latent, and thermochemical (Yang, Liu, Kramer, & Sun, 2021). Figure 7 shows a clear overview of the different techniques.

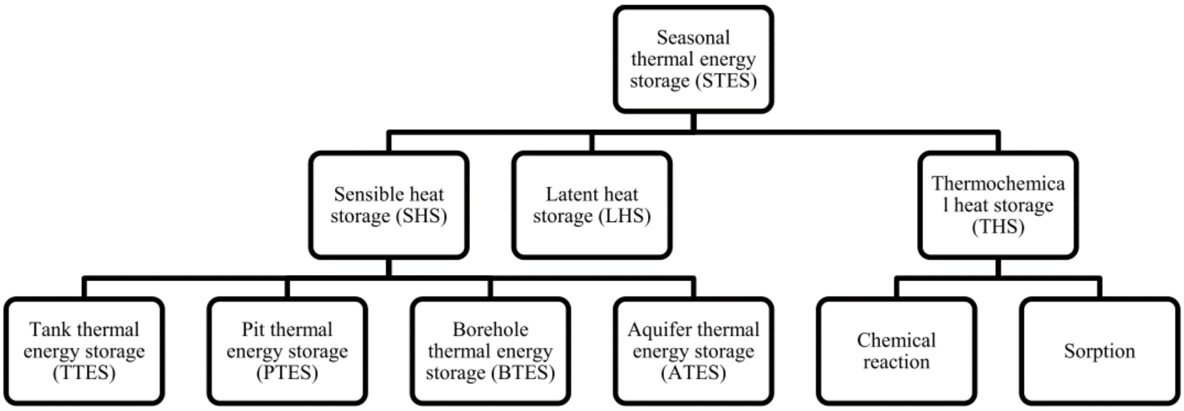

FIGURE 7 SUMMARY AND CATEGORIZATION OF CURRENTLY USED THERMAL ENERGY STORAGE SYSTEMS (YANG ET AL., 2021).

Because sensible heat storage is currently the most reliable and mature in seasonal heat storage systems (Xu, Wang, & Li, 2014), latent heat storage and thermochemical heat storage will not be discussed in this report. Latent and thermochemical heat storage systems still present too many difficulties and more research is needed to optimize their efficiency (Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011). This research will only focus on directly applicable systems to ensure an outcome for direct use within this field.

Sensible heat storage includes tanks and underground thermal energy storage in aquifers or soil (Xu et al., 2014). Collected heat, by e.g. solar thermal collectors, is converted into sensible heat in material that is able to efficiently absorb the heat and release it when required. This type of heat storage can be subdivided in four categories:

TANK

In most cases, a thermal energy storage tank is made out of stainless steel or concrete with highly insulated thick walls (Xu et al., 2014) where two different arrangements can be distinguished: A tank in which the insulation is attached to the outer wall or a double-wall vacuum envelope in which powder particles are stored (Yang et al., 2021). Artificial tanks are usually buried underground or placed outside buildings. Besides artificial construction, this type of storage can also be geological cavities in which water is stored without a clearly constructed tank (Pinel et al., 2011). In both cases a flow of water transports heat to or from the tank or a fluid is used which in circulated in a inserted heat exchanger in the tank. Although these tanks are typically highly insulated, the efficiency is still a concern due to thermal buoyancy which causes hot water to be at the top of the tank and cold water in the bottom (Xu et al., 2014). The occurring mixing effect causes a degradation of temperature which could have a negative effect on the efficiency of the whole system. Although this system is still under investigation to guarantee a more stable thermal status inside the tank, this type of thermal energy storage has already been applied in small scale cases like residential and commercial buildings and in large scale cases connected to a district heating system (Yang et al., 2021).

PIT THERMAL ENERGY STORAGE

Water pit heat storage systems consist of a excavated basin in the form of a upside down pyramid in which water is stored and sealed by a highly insulated lid (Bai et al., 2020). Usually, polymer liners are used to cover the bottom and sides of the basin. Artificial pits, also called buried tanks, are typically constructed near the surface or below ground and made out of stainless steel or reinforced concrete. The pit can be totally filled with water or a water-gravel mixture in which the gravel fraction is around 60 - 70% (Mangold & Deschaintre, 2015). Although a water-gravel mixture pit needs to be bigger to guarantee a sufficient amount of water in the pit, the space above the pit can be easily used for e.g. a parking lot.

BOREHOLE

In this type of heat storage, the ground is used directly as storage material (Xu et al., 2014). Vertical or horizontal tubes are inserted into the ground to serve as a heat exchanger. The free soil surrounding these tubes act as storage medium and the water is used as transfer fluid. The most suitable soil type is clay in both water-saturated as stone form because of its high capacity of heat retention. Also, no or a low groundwater flow is preferred to guarantee a high efficiency (Mangold & Deschaintre, 2015). Depending on the capacity, the ground could be heated up to a temperature of 80ºC. Although Xu et al. (2014) specifically mentions this technology as a good option for seasonal storage system of solar heat, it requires a 3 - 5 times larger volume than other storage systems due to its low energy storage density. It requires a minimum volume of 20,000 m^3 of ground to be financially and energetically interesting (Mangold & Deschaintre, 2015). Also, because of its lower charging and discharging power, a buffer storage is often required to be integrated in the system.

AQUIFER

Another technique of heat storage includes naturally occurring groundwater layers in the ground (Mangold & Deschaintre, 2015). Two adjacent groundwater wells are used which are separately fed with cold or warm water. Because of the separated injection process, both wells require a pump and production- and injection pipes. The most suitable geological formation is a layer with a high level of porosity, a low groundwater flow rate, high hydraulic conductivity and a leakage proof layer up and down the wells. Because of the specific conditions for this technique, an extensive investigation should first be conducted to determine if the site is suitable for aquifer thermal energy storage. Also, Dutch policy includes strict regulations for this type of heat storage (Yang et al., 2021). The water temperature of the injected water is not allowed to be higher than 25 - 30°C, and occurrence of thermal imbalance is not allowed between the two individual wells.

2.4.4 Heat pump

In all five of the concepts (Figure 1), a heat pump is integrated to guarantee the temperature to be sufficient for usage for hot tapwater and space heating. However, the location of this heat pump differs per heat grid temperature. For the 70°C heat grids, the heat pump will be a collective application and located at the heat storage site. Because the temperature in the storage system decreases over time and a 70°C heat grid is considered, the temperature will be increased at the storage site. For the 12-15°C heat grids, the heat pump will be individually integrated at the location of the user.

A heat pump converts the low incoming temperature flow to a higher temperature by consuming energy (Sayegh et al., 2018). For space heating a temperature of 35-50°C could already be sufficient if additional insulation is applied (only applicable to existing dwellings). However, tap water requires a higher temperature. Following the NEN 1006 (2018), the Royal Netherlands Standardization Institute, the temperature of hot tapwater should be minimal 55°C to ensure safe use. In most cases, a temperature of 60°C is integrated to include a small buffer to guarantee a safe level for usage. For this research an electric water-water heat pump is integrated. To get a better understanding of the values used for the calculations for this application, a short explanation of the functioning of the heat pump is provided following Figure 8.

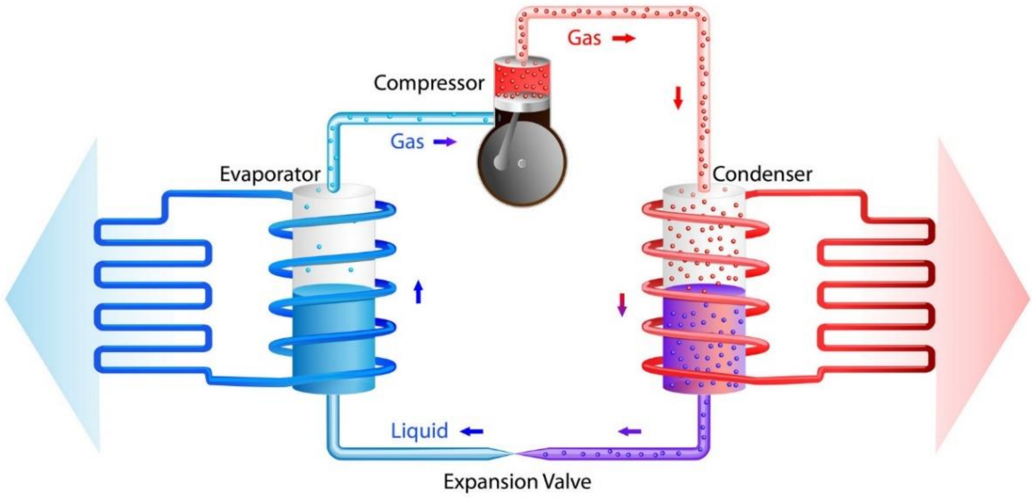

FIGURE 8 ILLUSTRATION OF THE WATER-WATER HEAT PUMP INCLUDED IN THIS RESEARCH (HOT WATER HEAT PUMPS, N.D.).

On the left side of Figure 8, in the evaporator part of the system, a fluid with a low boiling point is used (Hepbasli & Kalinci, 2009). The incoming water (blue pipe) discharges its heat to the liquid so the liquid starts to boil and evaporates. The created gas flows into the compressor part where it gets compressed to a preferred temperature (depends on the usage). In this part, most of the electricity is consumed. Finally, the high temperature gas discharges its heat to e.g. a central heating system of a dwelling (red pipe) and the condensate flows back to the evaporator part where the cycle can start over.

For this research, the following values will be used in the calculations (Table 5). This research will only include the calculations for the concepts including a 12-15°C heat grid, this is further elaborated in 3.1.7.

TABLE 5 HEAT PUMP CHARACTERISTIC VALUES FOR AND 12-15°C HEAT GRID (HEIJBOER, 2021).

Variables	Wp1	ΔT	Twork
T_{out} condenser (K)	331	3	334
T_{out} evaporator (K)	279	2	277
η	60%		

As shown in Table 5, the considered temperature for the condenser will be 331 K with an included 3 K loss (indicated with ΔT) (Heijboer, 2021). This results in an 334 K operation temperature. For the evaporator a final temperature of 277 K will be considered. The total efficiency is estimated at 60%.

Commonly an individual heat pump is connected to a reservoir (generally 50-100 liters) to guarantee sufficient hot water for direct use. Generally the efficiency of the total system lays around 50 – 70% (Heijboer, 2021). This is further discussed in 3.1.5.

2.5 Insulation

Following Heijboer (2021), only dwellings attached to a 12-15°C heat grid require additional insulation to guarantee efficient space heating. Commonly a lower temperature will be used in the central heating system of the dwellings connected to a 12-15°C heat grid compared to regular heating systems in which natural gas is still used as an energy resource. To obtain an overview of the current average gas demand per dwelling type, Figure 9 is provided.

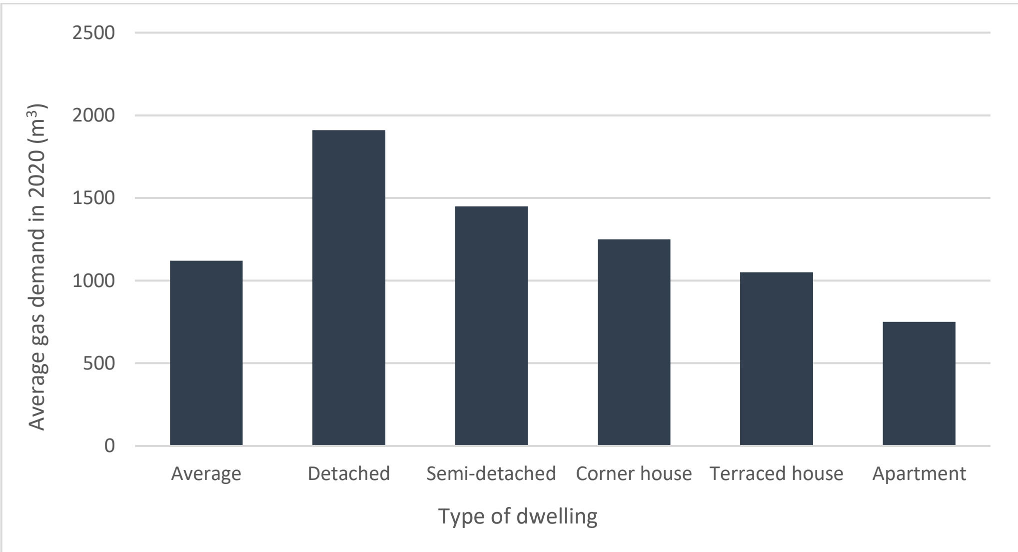

FIGURE 9 AVERAGE GAS USE PER DWELLING TYPE IN THE NETHERLANDS (CBS, 2020).

Figure 9 shows the average gas demand (without additional insulation) of dwellings in The Netherlands which was around 1120 cubic meters (m^3) in 2020. (Semi-)detached houses and corner houses show the biggest consumption with a demand of 1250 – 1910 m^3. While terraced houses and apartments show a lower demand of respectively 1050 and 750 m^3. Because the main goal of this research is to investigate the possible future of solar collectors, the two dwelling types with the lowest gas demand will be of main interest for this research. If this research eventually shows a possible future for this kind of heating system, more research could be conducted to the suitability for other type of dwellings.

Following a study by Thomsen et al. (2016), who investigated the heat demand for space heating and hot tap water after renovation of a residential building, a decrease of 32% was determined. In this investigation, comprehensive energy retrofitting was performed on a Danish apartment complex. This renovation included new facades, additional insulation, new windows, PV panels installed on the roof and mechanical ventilation including heat recovery. Also, Heijboer (2021) confirms this change in heat demand following earlier projects by DWA where a decrease of 20 – 30% was established. In addition, an investigation by Kolaitis et al. (2013) even found a decrease in heat demand of 21–47% in a comparative assessment study to the appliance of external and internal insulation measures to residential buildings in Oceanic climate regions. Although the external insulation measures resulted in approximately 8% higher energy savings, the appliance of internal insulation shows a large amount of energy savings over the year. Because no specific location is used in this research and different insulation measures can be applied, a lower value than the average value of the performances is assumed. This will avoid high performance values which may be unrealistic in a real case. Therefore a reduction of 25% in heat demand will be considered. This means that the gas demand of a terraced house and an apartment will be reduced to respectively 787.5 and 562.5 m^3/year for the low temperature concepts.

2.6 Synthesis

As shown in Figure 2 and Figure 3 both strategies do not include solar collectors yet but for this investigation these panels are added in the calculations to finally measure the total heat production and feasibility of this approach. Also, the suitability of different types of storage systems, dwelling types and heat grid temperatures will be investigated to get a more complete overview of the possibilities within this approach. After collection of the information provided in Chapter 2 and mainly 2.4, the concepts for this research were developed. The choices and connections between the different concepts are summarized below.

For the collectors, 3 types of collectors will be included: Triple Solar M2 320 165 L, Solarus PowerCollector™ aH72SK and G2energy Flat Plate collector GC72. All three of the collectors differ in functioning. The panel from Triple Solar and Solarus are both PVT panels which means that both electricity and heat are generated at the same time. However, unlike Triple Solar, the collector from Solarus can deliver both a low temperature of 12-15°C as a high temperature of 70°C. The panel from Triple Solar can only deliver a temperature from around 10°C because heat is extracted from both open air as daylight compared to radiation only (Solarus). The included collector from G2energy is a Flat Plate collector which is only able to generate heat at both low and high temperatures similarly to the collector from Solarus. An overview of the five concepts and the different included parameters is provided in Figure 10.

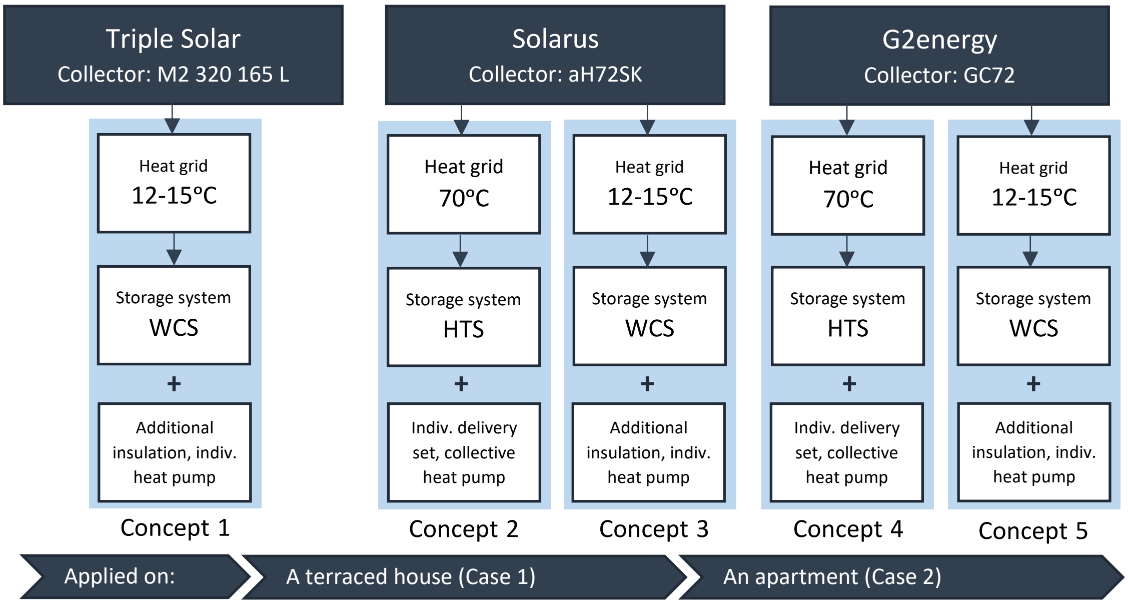

FIGURE 10 OVERVIEW OF THE DIFFERENT PARAMETERS INCLUDED IN THE FIVE CONCEPTS IN THIS RESEARCH.

After selecting the collectors, the heat grid temperatures were established. For this research, two most opposite types of concepts are chosen regarding the minimum and maximum operational temperature of the collectors. In this way, first the suitability of this approach can be investigated and future research can establish the suitability of other approaches in between these two extremes. Following the maximum and minimum performance values of the collectors, the integration of a 12-15°C and 70°C is established. This selection is also based on research by DWA (2021) which established that these two types of heat grids are currently the best choice regarding energetic value and heat loss. Because the collector from Triple Solar is only able to generate a temperature of around 10°C, only a low temperature heat grid is integrated for this type of collector.

The choice of a heat storage system is based on the integrated heat grid temperatures. For this research two types of sensible heat storage systems will be taken into account varying in temperature and construction. The focus will be on borehole and aquifer systems because these are currently the most widely used (Mangold & Deschaintre, 2015). The most common thermal energy system in The Netherlands is a Warm and Cold water Storage system (WCS) (Drijver, 2019). This storage system consists of two water buffers, one with cold water at around 8°C and one with warm water at around 15°C at a depth of 30 to 250 m (RVO, n.d.). This type of storage requires an additional heat pump on consumer level to increase the temperature from 15 to 35-60°C to use for space heating and hot tap water. Other types of relatable storage systems are a High Temperature thermal energy Storage system (HTS) and a Medium High Temperature thermal energy Storage system (MHTS) (Drijver, 2019). These storage systems use the same concept as the WCS but differ in temperature. The MHTS consists of a warm water buffer of 15 to 30°C and a HTS uses a warm water buffer of 30 to 60°C.

Because the heat grids will be at a temperature of around 12-15°C and 70°C, only a WCS and an HTS system are included in this research. Although HTS systems are still under investigation and not often applied yet, this type of storage does have some important advantages compared to lower temperature heat storage systems (Zwamborn, 2021). Because heat, stored in an HTS, can directly be used for both hot tap water and space heating, more energy is saved as the interference of an individual heat pump is unnecessary. This could save up to 50% more CO_2 compared to a very low temperature heat storage system in which the inclusion of a heat pump is essential (Zwamborn, 2021). Also, the inclusion of both opposite types of storage systems (WCS and HTS) result in a wide outcome in which all intermediate concepts are included as well. If one of these concepts seem to be suitable regarding costs, heat production and coverage of the heat demand, more research could be conducted into other types of concepts in between these two extremes.

After selection of the main parameters for this research, additional applications are included to guarantee high efficiency of the total system. For each heat grid temperature, an outline of the requirements is given in Table 6.

TABLE 6 OVERVIEW HEAT GRIDS AND ADDITIONAL REQUIREMENTS (HEIJBOER, 2021).

Heating requirements for different type of dwellings	**Heat grid 70°C**	**Heat grid 12-15°C**
New construction	Space heating by radiators	Space heating through floor heating
Existing dwellings	Additional insulation is barely needed, radiators do not have to be replaced	Additional insulation + larger radiators required
Requirements for the two types of heating		
Space heating	Delivery set	Heat pump delivers 35-50°C
Tap water	Delivery set	Heat pump delivers to boiler >60°C
Requirements per system		
Individual system per dwelling	Delivery set	Individual heat pump
Collective system	Heat pump + HT-storage (or shallow geothermal energy storage or WCS) + collective collector system	Storage system (WCS) + collective collector system

As shown in Table 6, new construction dwellings only require adjustments in the design of the heating system by changing the way of heating from radiators to floor heating when applying a 12-15°C instead of a 70°C grid (Heijboer, 2021). Existing dwellings, however, require more adjustments to be able to meet the heat demand for both space heating and hot tapwater. Dwellings connected to a low temperature system (12-15°C) require additional insulation and an individual heat pump to increase the temperature for the use of space heating and hot tap water. Dwellings connected to a 70°C system only require a delivery set to guarantee a well-managed in and out flow of the water in the system. At the storage location, a heat pump is also integrated to ensure a steady temperature of 70°C in the heat grid.

The five different concepts (Figure 10) will be applied on two cases. Because the design of new construction can easily be adjusted to solar thermal energy use by adding insulation and direct installation of a heat grid, only existing dwellings are incorporated in this research (Heijboer, 2021). Moreover, following CBS (2021c) the housing stock in The Netherlands counts around eight million dwellings. If solar thermal energy would be found suitable for this type of housing, the transition towards a more sustainable heating system may accelerate in the coming years. Because the construction of a heat grid is costly and the length of pipes should be limited, (semi-)detached dwellings will be excluded for this research (Heijboer, 2021). This decision is also based on the average heat demand for these dwelling types (Figure 9). In this research, one case is focused on a neighborhood with terraced houses (Case 1) and one case is focused on several apartment buildings (Case 2). The size of the neighborhood and the amount of apartments is dependent on the results. The calculations will be executed following the demand of one household. In this way, the results can be applied on any size of neighborhood when considering applying one of the concepts.

3 Methods

This chapter comprises a detailed elaboration of the research method. For this research a framework is used to guarantee a stepwise approach to finally obtain the desired data to answer the research question. Figure 11 shows the main calculation steps, indicated with the white horizontal boxes, and the final comparison step, indicated with the yellow box.

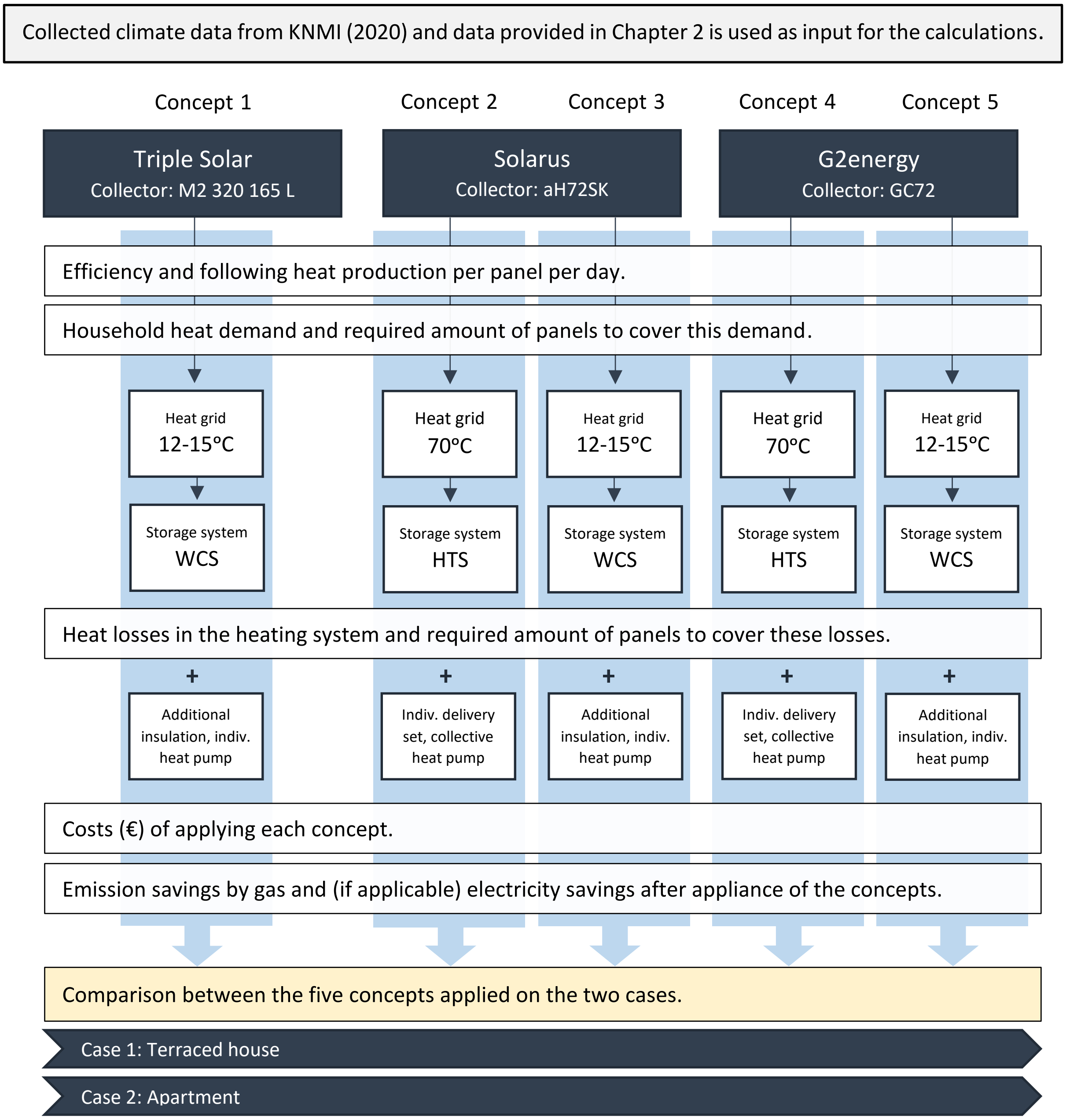

FIGURE 11 METHODOLOGICAL FRAMEWORK

The calculations and comparison steps indicated in Figure 11 are further elaborated in 3.1 and 3.2.

3.1 Calculations

3.1.1 Solar collector efficiency

The provided efficiency (η_0) of the collector producers is generally a value measured under fixed circumstances, also known as the standard test conditions (STC). These conditions include an air mass of 1.5, a solar radiation value of 1000 W/m^2, and the cell temperature is set at 25°C. Because these conditions are rarely occurring, and not realistic compared to data measured throughout the year (KNMI, 2020), an additional formula is used. This formula provides a more realistic efficiency value based on daily climate data including the ambient temperature and radiation. Because the energy source for the Triple Solar panel is not only focused on radiation, this panel is not included in these calculations and the provided efficiency by the producer is used to obtain the potential generated heat. The formula used for the panels from Solarus (Concept 2 and 3), and G2energy (Concept 4 and 5), a required supporting formula to calculate the average collector temperature (t_m), and the symbol clarifications can be found below (Equation 1 and Table 7).

EQUATION 1 COLLECTOR FORMULA (DU, HU, & KOLHE, 2013).

$$\eta = \eta_0 - a_1 \cdot (t_m - t_a) / G - a_2 \cdot (t_m - t_a)^2 / G$$

$$t_m = (t_{in} + t_e) / 2$$

TABLE 7 CLARIFICATION SYMBOLS PROVIDED IN EQUATION 1.

Symbol	Description	Unit
η	Calculated efficiency	%
η_0	Efficiency under STC	%
a_1	Thermal heat loss coefficient	W/m^2*K
a_2	Thermal heat loss coefficient	W/m^2*K
t_m	Average collector T	°C
t_a	Average ambient T	°C
t_{in}	Temperature of collector inflow	°C
t_e	Temperature of collector outflow	°C
G	Radiation per day	W/m^2

The specific values per collector (η_0, a_1 and a_2) can be found in Table 1, Table 2 and Table 3. The t_{in} and t_e are based on the heat grid temperatures. For the 12-15°C heat grid, a T_{in} of 6°C is assumed, and the T_{out} is set at 12°C (Heijboer, 2021). For the T_{in} an T_{out} for the 70°C concepts, respectively 50°C and 70°C is assumed.

The climate data (t_a and G) is collected through the 'Koninklijk Nederlands Meteorologisch Instituut' (KNMI) which is the national data and knowledge center for weather, climate, and seismology in The Netherlands. KNMI has around fifty weather stations located in The Netherlands to gather precise information about all kinds of climate parameters. For this research, the average radiation and ambient temperature of all weather stations is used, both values are provided as an average for 24 hours (KNMI, 2020). Because no specific data for the heat demand could be found, and only the course of the heat demand over the day is included, the climate data will also be based on daily averages. The radiation is provided in Joules per square centimeters (J/cm^2) which is converted to Watt per square meter (W/m^2). With this data, the formulas can be filled in and the efficiency per day is achieved.

3.1.2 Heat production by the solar collectors

After calculating the efficiency per day, the heat production can be calculated using the obtained efficiency value, and the radiation obtained from KNMI (2020). Because the radiation is provided in J/cm^2 and the heat production is calculated in joules per panel per day, first the radiation is converted to J/m^2. After that, the functional surface (m^2) of the concerning collector is used to obtain the radiation incidence per panel. Finally the efficiency is included to obtain the amount of heat production per panel including daily climate data.

Because these values are relatively large, the amount of heat production is converted from J to giga joules (GJ).

3.1.3 Heat demand per household and required panel surface area

Because the demand varies per dwelling type, two different demand values are used. This research includes the demand for a terraced house (Case 1), and an apartment (Case 2). The average demand of these dwellings is obtained in the amount of gas use per household. For a terraced house, a gas demand of 1050 m^3/year is included, for an apartment, a gas demand of 750 m^3/year is considered (CBS, 2020). Because additional insulation is required for the dwelling connected to a 12-15°C heat grid (Table 6), a decrease in heat demand will be implemented. A reduction of 25% will be included based on findings discussed in 2.5. The insulation measures will not be applied to the 70°C heat grid concepts (see Table 6).

To be able to compare the heat production of a collector with the demand of the dwelling, the gas demand should be converted to GJ/day. This is done using the calorific value of gas (35.17 J/m^3) and the efficiency of the central heating boiler (85%) (Heijboer, 2021). In this step, a 25% decrease in heat demand by insulation is added. After calculating the yearly heat demand, the amount of heat consumption per day is calculated. This is based on a measured demand curve of ~4500 households which includes the daily heat demand for the year 2018 (DWA, 2018). These values were converted to daily percentages to be able to apply them to the values obtained from CBS (2020). In this way a more realistic demand curve is created compared to only dividing the demand values of CBS (2020) by the number of days in 2020.

After obtaining the heat demand per day, the amount of required panels that is needed to cover this heat demand can be calculated. First the amount of two panels is assumed as a starting point. The amount of heat production (for these two panels) for each day was calculated by multiplying the heat production per panel (explained in 3.1.2) by the amount of panels (in this case 2). This value was then used to calculate the difference between the demand and production side. In colder days, this value is usually negative and on warmer days, this value is generally positive. This means that on colder days, the heat production by the collectors is not sufficient to cover the heat demand of the dwelling and heat will be extracted from the heat storage system. On warmer days, overproduction of heat takes place and the surplus will be added to the heat storage. To finally be able to calculate the amount of panels needed to fully cover the heat demand, the difference between production and demand is summed up and the analysis tool called Solver from Excel is used to solve this calculation. This solver tool is used to guarantee no difference between production and demand by changing the amount of panels in a way that the sum of the difference between production and demand is set to zero.

3.1.4 Seasonal heat storage

After calculating the amount of panels required to fully cover the heat demand, the stored heat can be calculated. First, the difference in production and demand is summed up per day. This means that e.g. if on the 1st of January a difference of -0.10 was calculated and on the 2nd of January a difference of -0.12 was determined, the total difference on the 2nd of January would be -0.22. This eventually delivers a minimum over the year of 2020. This minimum is converted to a positive number and used as starting point for the next column of calculations. This column includes the amount of heat that should be present in the storage to guarantee coverage of the heat demand throughout the year when the production of the collectors is not sufficient. Furthermore, the amount of heat that is added during overproduction was also calculated. During extraction, this value is set to zero and during overproduction, the difference between production and demand is calculated which will be assumed to be added to the heat storage.

3.1.5 Heat losses in the heating system

The losses occurring in a heating system are dependent on the temperature. A heating system operating at a temperature of 70°C will experience more heat loss compared to a heating system at 12°C. This is caused by the larger difference compared to the surrounding temperature. Because the ground generally has a constant temperature of around 12°C, the losses occurring during transportation and storage for a 12-15°C heating system are negligible (Heijboer, 2021). Therefore, the losses will be heat grid specific. For Concept 2 and 4, including a heat grid operating at 70°C, storage losses and losses occurring during the transportation of the heat will be taken into account. Because the 12-15°C includes an individual heat pump which is usually connected to a boiler vessel (Table 6), the losses in the heating system at dwelling level will be included for Concept 1, 3 and 5.

3.1.5.1 70°C concepts

Following a report from CE Delft (2020b), the efficiency of a high temperature heat storage system is dependent on the soil composition and commonly between 40 to 80%. This means that on average, the efficiency is around 60% and thus 40% of the heat is lost over the year. To be able to apply this value to the obtained values, the maximum amount of heat which would be present in the system at a certain moment in the year is calculated. This is done by using the MAX() function in excel. This function searches for the largest value occurring in a column or row. In this case, the overproduction values (explained at the end of 3.1.4) are used. The largest value is divided by 366 days (amount of days in 2020) and multiplied by the storage loss (40%).

For the heat grid, a previous investigation from DWA (2021) was used. In this investigation, the heat loss occurring in different temperature heat grids connected to various dwelling types was calculated. For stacked houses (apartments) and non-stacked houses (terraced houses), the loss per house was calculated at respectively 4.65 GJ/year and 9.58 GJ/year. These values are divided by 366 days to obtain the loss in GJ/day.

3.1.5.2 12-15°C concepts

For the low temperature heat grid, an estimation of the heat losses in the total heating system of the dwelling is included. These losses occur during transportation of heat, and heat storage to and in the reservoir. For this research, an average of 60% is incorporated (see 2.4.4). This is different from a 70°C heat grid because in that case the same temperature can be used for hot tapwater and space heating.

3.1.5.3 Number of panels required to cover the losses

Finally the amount of panels is calculated to cover the heat loss in the heating system. These calculations followed the same path as the calculations mentioned in 3.1.3 for calculating the amount of panels required to cover the heat demand. For these calculations, the Solver function from Excel is used to set the sum of the difference between production, and total loss to zero by changing the amount of panels.

With the amount of panels required to cover the heat demand and the heat losses, the total amount of panels required for the specific dwellings were calculated by taking the sum of these two values.

3.1.6 Electricity production by the solar collectors

Although heat production is of main interest in this research, the collectors from Triple Solar (Concept 1) and Solarus (Concept 2 and 3) are also able to generate electricity. To be able to calculate the production over the year 2020, the photovoltaic efficiency of the two panels is used (see Table 1 and Table 2). Because the orientation and angle of the panels is unknown but essential to guarantee optimal yield, an average value of 85% is usually used to cover the potential loss due to deviation from the optimal position (SMARTcirculair, 2019). This average is based on the Hespel table provided in Figure 12.

East South West

Angle of inclination (°)

	-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	
0	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	0
5	88	88	89	89	89	90	90	90	91	91	91	91	91	91	91	91	91	92	92	92	91	91	91	91	91	91	91	91	90	90	90	91	91	91	90	89	89	5
10	89	90	91	91	91	92	92	93	94	94	94	95	95	95	95	95	95	96	96	96	95	95	95	95	95	95	94	94	94	93	93	93	92	91	91	90	90	10
15	88	89	90	91	92	93	93	94	95	95	95	96	96	96	97	97	97	97	97	97	97	97	97	96	96	96	95	95	95	94	94	93	92	91	91	90	89	15
20	87	88	89	90	91	92	93	94	95	96	96	97	97	97	98	98	98	98	98	98	98	98	98	97	97	97	96	96	96	95	94	93	92	91	90	89	88	20
25	87	88	89	90	91	92	93	94	95	96	97	98	98	99	99	99	99	99	99	99	99	99	99	98	97	97	97	96	96	95	94	93	92	91	89	88	87	25
30	86	87	88	89	90	92	93	94	95	96	97	98	98	98	99	99	99	100	100	100	100	100	100	99	98	98	97	96	96	95	94	93	91	90	89	87	86	30
35	84	85	87	88	89	91	92	93	95	96	97	98	98	98	99	99	99	100	100	100	100	100	100	99	98	98	97	96	95	94	93	92	90	89	88	86	85	35
40	82	83	85	86	87	89	90	92	94	95	96	97	97	98	99	99	99	100	100	100	99	99	99	98	98	98	97	96	95	93	92	91	89	88	87	85	84	40
45	80	82	84	85	86	88	89	91	93	94	95	96	96	97	98	98	98	99	99	99	98	98	98	97	97	96	95	95	93	92	91	89	88	87	85	84	82	45
50	78	80	82	84	85	87	88	89	91	92	93	94	95	95	96	96	96	97	97	97	97	97	97	96	96	95	94	93	92	90	89	88	86	85	84	82	80	50
55	76	78	80	82	83	85	86	87	89	90	91	92	93	94	94	94	95	95	95	95	95	95	94	94	93	92	91	90	89	88	86	85	83	82	80	78	78	55
60	74	76	78	79	81	83	84	85	86	87	88	89	90	90	91	91	92	93	93	93	93	93	93	92	92	91	90	89	88	87	86	85	83	81	80	78	76	60
65	72	74	76	77	78	80	81	82	84	85	86	87	88	88	89	89	89	90	90	90	90	90	90	89	89	88	87	87	85	84	83	82	80	79	77	75	73	65
70	69	71	73	74	75	77	78	79	81	82	83	84	85	85	86	86	86	87	87	87	87	87	87	86	86	86	85	84	83	81	80	79	77	76	74	72	70	70
75	66	68	70	71	72	74	75	76	78	79	80	81	81	82	83	83	83	84	84	84	84	84	84	83	83	82	81	81	79	78	77	76	74	73	71	69	68	75
80	63	65	67	68	69	71	72	73	74	75	76	77	77	78	79	79	79	80	80	80	80	80	80	79	79	79	78	77	76	75	74	73	71	69	68	66	65	80
85	60	61	63	64	65	67	68	69	70	71	72	73	73	74	75	75	75	76	76	76	76	76	76	75	75	75	74	73	72	71	70	68	67	66	64	63	62	85
90	56	57	59	60	61	63	64	65	66	67	68	69	69	70	71	71	71	71	71	71	71	71	71	71	71	71	70	69	68	66	65	64	63	62	61	59	58	90
	-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	

FIGURE 12 HESPEL TABLE; CALCULATED LOSS FACTORS FOLLOWING THE ORIENTATION AND ANGLE OF A PHOTOVOLTAIC PANEL (SMARTCIRCULAIR, 2019).

The potential electricity production over the year 2020 is calculated using Equation 2 below. The symbol clarification in provided in Table 8.

EQUATION 2 ELECTRIC YIELD PVT PANEL PER DAY (BAHAIDARAH, SUBHAN, GANDHIDASAN, & REHMAN, 2013).

$$P_{elec} = G * A_{func} * \eta_{elec}$$

TABLE 8 SYMBOL CLARIFICATION EQUATION 2

Symbol	Description	Unit
G	Radiation per day	W/m^2
$\mathbf{A_{func}}$	Area of the functional part of the panel	m^2
$\mathbf{\eta_{elec}}$	Electric efficiency	%

Before Equation 2 can be used, first the radiation is converted from J/cm^2 to J/m^2. After filling in the formula, the value is converted to GJ.

3.1.7 Heat pump: electricity demand

In all five of the concepts a heat pump is integrated (Figure 10). Because the calculations are only focused on the production and consumption of one household, the division of the electricity demand of the collective heat pump (integrated in concept 2 and 4) over the dwellings is hard to predict without the knowledge of the size of the neighborhood. Due to this lack of data, it is assumed that the electricity demand of the collective heat pump is negligible, and only the calculations for the individual heat pump, integrated in the 12-15°C concepts (Concept 1,3 and 5), will be discussed. Its electricity use is included to obtain a valuable final comparison of the different concepts included in this research. Generally the 'coefficient of performance' (COP) is used to express the performance and efficiency of the heat pump. This value can be calculated using the Carnot formula provided in Equation 3. The clarification of the symbols is provided in Table 9.

EQUATION 3 CARNOT FORMULA (ZHAO ET AL., 2017).

$$COP_{h.carnot} = T_{cond} \;/\; (T_{cond} \cdot T_{eva})$$

$$COP_{h} = \eta \cdot COP_{h.carnot}$$

TABLE 9 CLARIFICATION SYMBOLS PROVIDED IN EQUATION 2.

Symbol	Description	Unit
$COP_{h.carnot}$	Coefficient of performance	-
COP_{h}	Coefficient of performance	-
T_{cond}	Temperature of the condenser	K
T_{eva}	Temperature of the evaporator	K
η	Efficiency of the system (50-70%)	%

To guarantee a temperature high enough to be used for both space heating and hot tap water, a temperature of 60°C is considered. Most of the water will be saved in a boiler vessel for the use of hot water for e.g. showering or consumption. The other part will be used for space heating purposes. The output is estimated at around 8°C which will be pumped back into the cold well of the WCS. The considered values for Equation 3 can be found in Table 5 provided in 2.4.4.

The values (T_{cond}, T_{eva}, and η) are system dependent, and, as mentioned before, this research is focused on providing a reliable outcome with variables included. The feasibility of the system will be analyzed at maximum level (e.g. in another approach, a temperature level of 35°C can be considered for space heating and a temperature of 60°C can be considered for hot tap water). Following this approach, floor heating as well as heating through radiators is possible. If this approach appears to be applicable, other, lower energy intensive, systems will be applicable as well.

3.1.8 Costs of applying the five concepts

Because coverage of the heat demand is generally not the only important aspect that should be taken into consideration when applying a strategy of this size, also an estimation of the costs will also be provided. For this research only investment costs will be considered, subsidies are kept out of scope.

For each heat grid temperature, the costs are based on different aspects. The costs for the concepts including a 12-15°C heat grid (Concept 1, 3 and 5) will be based on: (1) the collectors, (2) the inclusion of an individual heat pump, (3) the construction and connection to a heat grid and (4) a WCS, and (5) additional insulation. The costs for the concepts including a 70°C heat grid (Concept 2 and 4) will also be based on: (1) the collector costs, (2) the construction and connection to a heat grid and (3) a seasonal heat storage system (in this case a HTS). However in this case a collective heat pump on the site of the heat storage location will be considered (4) where only a delivery set in the dwelling is required (5).

The collector costs can be found in Table 1, Table 2 and Table 3. The costs for the inclusion of an individual and collective heat pump, additional insulation and appliance of a delivery set are based on values used by DWA for similar projects for which realistic budget estimations are requested (Heijboer, 2021). The heat grid costs are based on a model created by DWA (2018) which is now also widely used by other companies. This model includes an estimation of the heat losses occurring in a heat grid for different temperatures, and the costs for construction and connection to multiple households is calculated. The heat storage costs are calculated using Equation 4. The clarification of the symbols and the included values are provided in Table 10.

EQUATION 4 COST ESTIMATION HEAT STORAGE SYSTEMS (HEIJBOER, 2021)

$$Costs_{storage} = P \times \Delta T \; X \; cp \; 4.2 * 3.6 * (1 - (1/COP)) * Q$$

TABLE 10 SYMBOL CLARIFICATION EQUATION 4 AND PRESENTATION OF THE INCLUDED VALUES.

Symbol	Description	Unit
P	Heating capacity dwelling Terraced = 6, Apartment = 4	kW
ΔT	Difference in temperature between in and outflow WKO = 6, HTS = 30	K
COP	Coefficient of performance, in this case a COP of 3.5 is considered	-
Q	Volumetric flow rate related to price WKO = 4000, HTS = 5000	€/m^3/h

After calculating the total costs of the different applications and requirements, the costs saved by the exclusion of natural gas and electricity production by the Triple Solar and Solarus panel (Concept 1, 2 and 3) will also be provided in a graph. It will provide a better perception of the costs and cost savings after appliance of such a system. In this way, the pay-back time will be illustrated. For the electricity savings, a tariff of 0.28 €/kWh$_e$ is considered (Heijboer, 2021), and because most of the values are focused on 2020, a natural gas price of 27.81 €/GJ gas used is used based on 2020 end-user cost data from CBS (2021a).

3.1.9 CO_2 reduction of the heating system

The reduction of CO_2 of the different concepts will be based on the gas savings and electricity savings, both over the period of one year. For the gas savings, a CO_2 emission factor of 56.4 kg CO_2/GJ is used (RVO, 2019). The emission factor of electricity is often fluctuating over time and dependent on the type of resource used to produce the electricity. Following a report from Planbureau voor de Leefomgeving (2021), a reduction of 44% of CO_2 emissions is predicted over the coming 10 years, although electricity use shows a more constant course. This is due to the use of more sustainable resources for electricity production in the coming years. Therefore, the CO_2 emission value for 2020 of 0.52 kg CO_2/kWh (CE Delft, 2020a) will be reduced to a predicted 0.29 kg CO_2/kWh. The two emission values for gas and electricity are applied on the gas demand of the concerning household (Figure 9), and the electricity generated by the amount of calculated collectors (explained in 3.1.6).

3.2 Comparison

This part will focus on three main criteria: amount of solar panels needed to cover the heat demand and heat losses, costs and CO_2 reduction. The comparison is made following Table 11.

TABLE 11 COMPARISON TABLE OF THE FIVE CONCEPTS APPLIED ON TWO CASES TO ANSWER THE RESEARCH QUESTION.

Criteria	Ranking	
Amount of panels needed to cover the heat demand and losses occurring in the heating system	Low > high	
Costs (€)	Low > high	
Co_2 reduction (kg)	High > low	+

Every concept is ranked (1 = most desired, 5 = least desired) based on the three criteria shown in Table 11. For the amount of panels and costs, a low value is preferred and for CO_2 reduction a high value is preferred. The sum of the rankings provide the best choice regarding these criteria. All five concepts will be analyzed per dwelling type, what results in two final conclusions to the research question of this research.

4 Results

In this chapter the results are presented. The method behind the calculations used to obtain these results is provided in Chapter 3. The same structure is followed in the method subsections. After discussing the results (4.1), the obtained values will be compared in 4.2. In the graphs, the collectors will be indicated with TS (Triple Solar panel M2 320 165 L), PC (Solarus PowerCollector^{tm} aH72SK) and FPC (G2energy Flat Plate collector GC72).

4.1 Calculations

4.1.1 Solar collector efficiency

After using Equation 1 (see 3.1.1), the following average efficiencies were established (Table 12). A figure is created to show the course of the efficiencies during the year 2020 for PC and FPC.

TABLE 12 AVERAGE ANNUAL EFFICIENCIES CALCULATED USING EQUATION 1 FOR THE FIVE CONCEPTS.

Solar collector	Heat grid 70°C	Heat grid 12-15°C
Triple Solar M2 320 165L	-	47.00%
Solarus PowerCollector^{TM} aH72sk	63.68%	69.93%
G2energy Flat Plate collector GC72	73.07%	77.26%

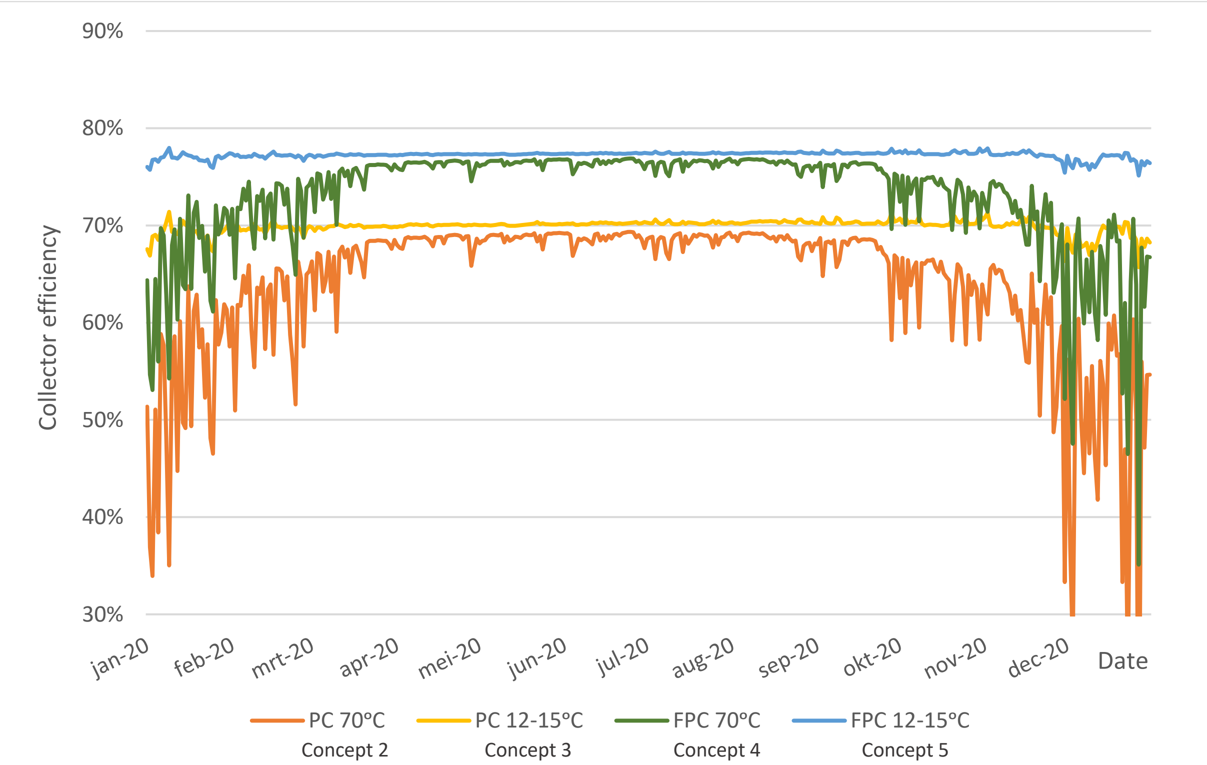

FIGURE 13 CALCULATED EFFICIENCIES OVER THE YEAR 2020 FOR FOUR CONCEPTS.

Because Equation 1 is not applicable to the Triple Solar collector (Concept 1), a fixed value of 47% is used (Table 12). However, the other two collectors show a more variable course (Figure 13). As expected, the efficiency shows the largest values in summer times, and the greatest fluctuation in winter times. This is due to less cloudiness, higher temperatures and higher radiation values in the months April to September compared with October through March (KNMI, 2020). The Flat Plate collector shows the highest efficiency during the year compared to the PowerCollector from Solarus.

This is explained by a higher initial efficiency (Table 3) compared to the initial efficiency from the collector from Solarus (Table 2). Also, less fluctuation in winter times is observed for the Flat Plate collector. This is probably due to its higher overall efficiency because all the other values included in Equation 1 are identical for all concepts with the same heat grid temperature. Furthermore, although these values show a predictable course, the efficiencies seem to be quite large. An average efficiency of around 60 to almost 80% in The Netherlands seems almost unrealistic. However, after comparing the production values (provided in 4.1.2) to measured data from Solarus (2021c) and the G2energy collector (TNO, 2021), relatively the same curve was observed. Because these production values are a direct result of the calculated efficiencies, the calculated values can be assumed to be realistic.

4.1.2 Heat production by the solar collectors

After calculating the efficiencies per panel type, climate data from KNMI (2020) is used to obtain the heat production over the year (see Figure 14 and Figure 15). The concepts are divided per heat grid temperature.

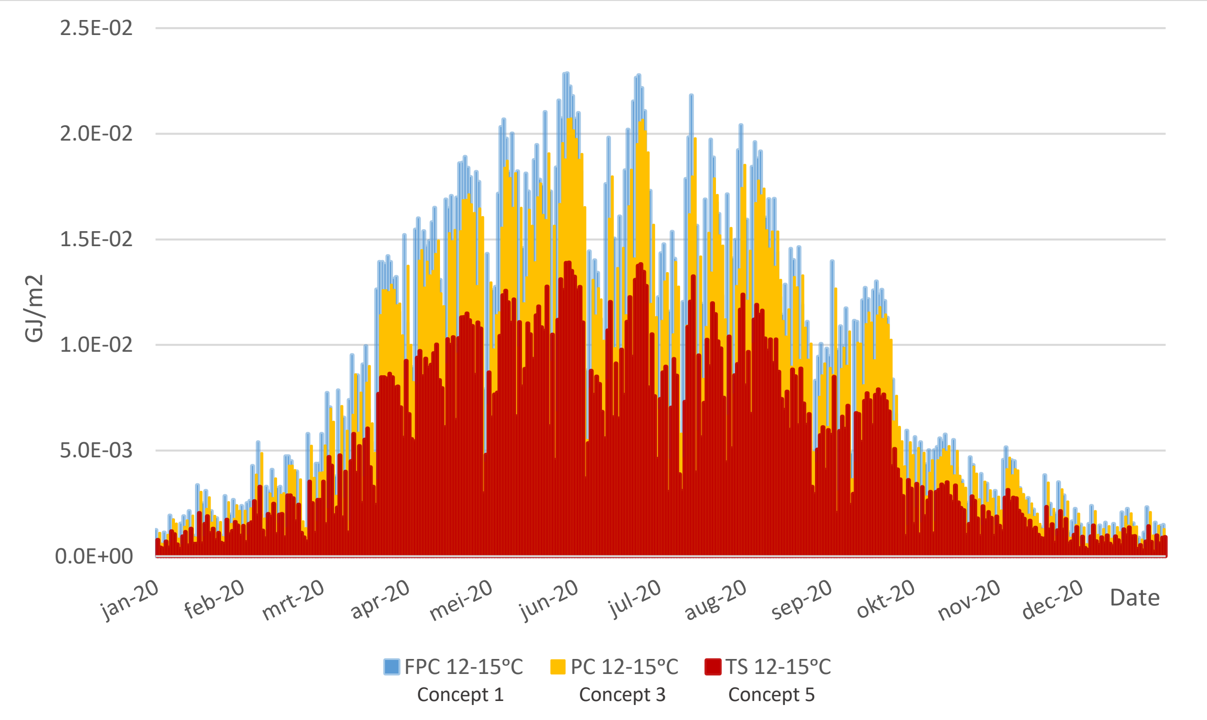

FIGURE 14 CALCULATED HEAT PRODUCTION FOR CONCEPTS 1,3 AND 5 OVER THE YEAR 2020.

Figure 14 shows the heat production of the three concepts including a 12-15°C heat grid. As expected following the average efficiencies shown in Table 12, the collector from Triple Solar shows the lowest production over the year compared to the other two panels from G2energy and Solarus. The Flat Plate collector from G2energy shows the highest production which is also in line with the efficiency values discussed in 4.1.1.

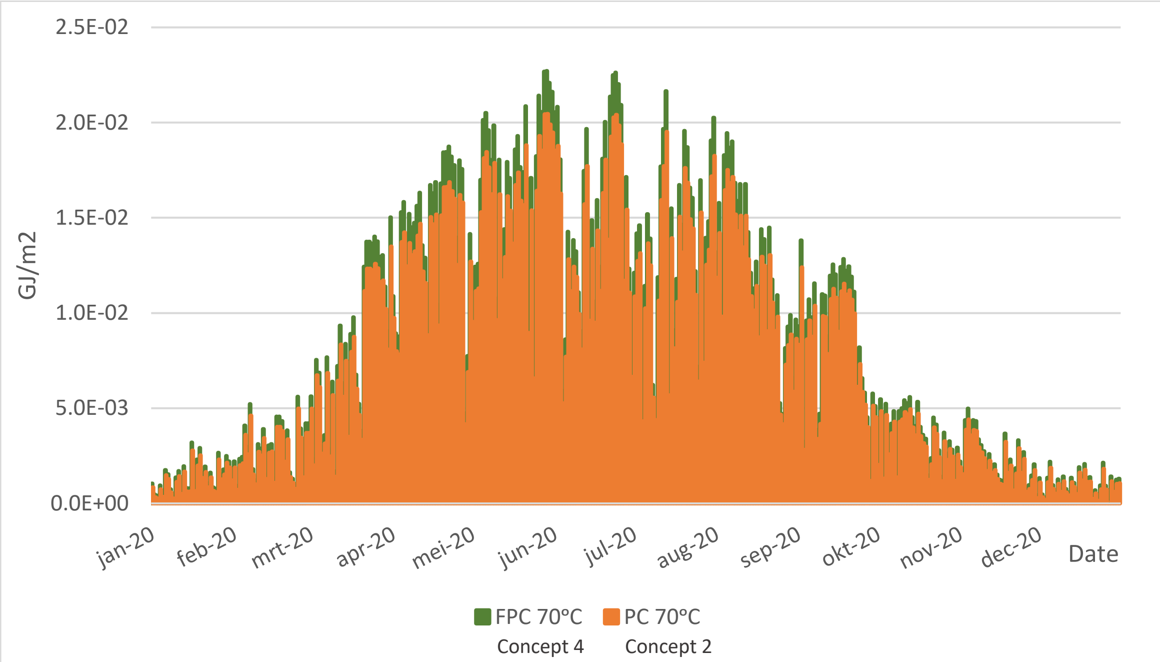

FIGURE 15 CALCULATED HEAT PRODUCTION FOR CONCEPT 2 AND 4 OVER THE YEAR 2020.

In Figure 15, the graph shows a curve totally in line with the values presented in Table 12. Again, the Flat Plat collector from G2energy shows greater heat production over the year compared to the PowerCollector from Solarus.

4.1.3 Heat demand per household and required panel surface area

To be able to determine the amount of panels needed to cover the heat demand of the two different dwellings (terraced house and apartment), first the heat demand per day was calculated. This is done using data from an investigation from DWA (2018) in which the heat demand of ~4500 households was measured. Figure 16 shows a percentage curve of this data in which the total amount of heat demanded over the year was set to a 100%.

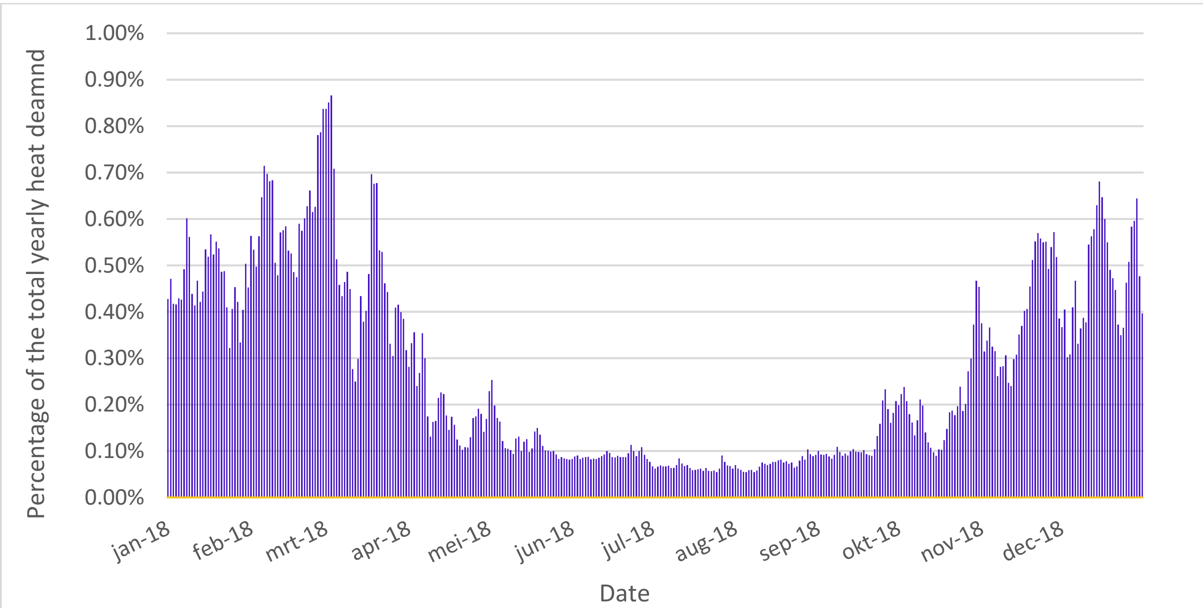

FIGURE 16 DAILY HEAT DEMAND OF ~4500 DUTCH HOUSEHOLDS COMPARED TO THE TOTAL HEAT DEMAND IN 2018 (DWA, 2018).

The curve (Figure 16) shows the highest demand around March which can be explained by a 1.5°C lower temperature compared to previous years (KNMI, n.d.). In winter times, a higher demand can be observed due to colder weather and more heat is used for space heating compared to summer times in which the heat demand shows lower values. These percentages were used to obtain a similar curve using the data provided from CBS (2020) (Figure 9).

Following the heat demand per day for each dwelling type and the amount of heat production per m^2 for each panel, the surface area of panels needed to cover the heat demand is calculated. The obtained values are provided in Table 13.

TABLE 13 REQUIRED M^2 TO COVER THE HEAT DEMAND OF THE DWELLINGS INCLUDED IN THE FIVE CONCEPTS. RANKED WITH COLOR PER DWELLING TYPE IN VERTICAL DIRECTION (RED=LEAST DESIRED, DARK GREEN= MOST DESIRED).

Concept	Solar collector	Heat grid T	Terraced house	Apartment
1	Triple Solar panel	12-15°C	13.75	9.82
2	Solarus PowerCollector™	70°C	13.04	9.35
3		12-15°C	9.49	6.78
4	G2energy Flat Plate collector	70°C	12.41	8.86
5		12-15°C	9.12	6.52

As shown in Table 13 the best performing panel is the Flat Plate collector from G2energy. Using a 12-15°C heat grid, for a terraced house and an apartment respectively 9.12 m^2 and 6.52 m^2 will be sufficient to cover the total heat demand. Using a 70°C heat grid, this panel seems to be the best choice regarding the lowest m^2 necessary to cover the total heat demand for both an apartment, and a terraced house. Also, in most cases, applying a 12-15°C heat grid seems to require a lower amount of m^2 to be able to cover the heat demand for both dwelling types. This is not the case for the Triple Solar panel. Using this panel, it requires the most m^2 to cover the total heat demand in all cases. This can directly be clarified by its lower efficiency explained in 4.1.1.

4.1.4 Seasonal heat storage

To be able to guarantee sufficient heat over the year, heat will be stored in seasonal storage systems. The total process of charging and discharging the storage with heat is displayed in Figure 17. Because this curve is calculated by setting the difference between demand and production values to zero (explained in 3.1.3), the graphs for the other panel types will show almost the exact same curve. For this reason, only the storage curve for Concept 2 (PowerCollector from Solarus) is provided as an example.

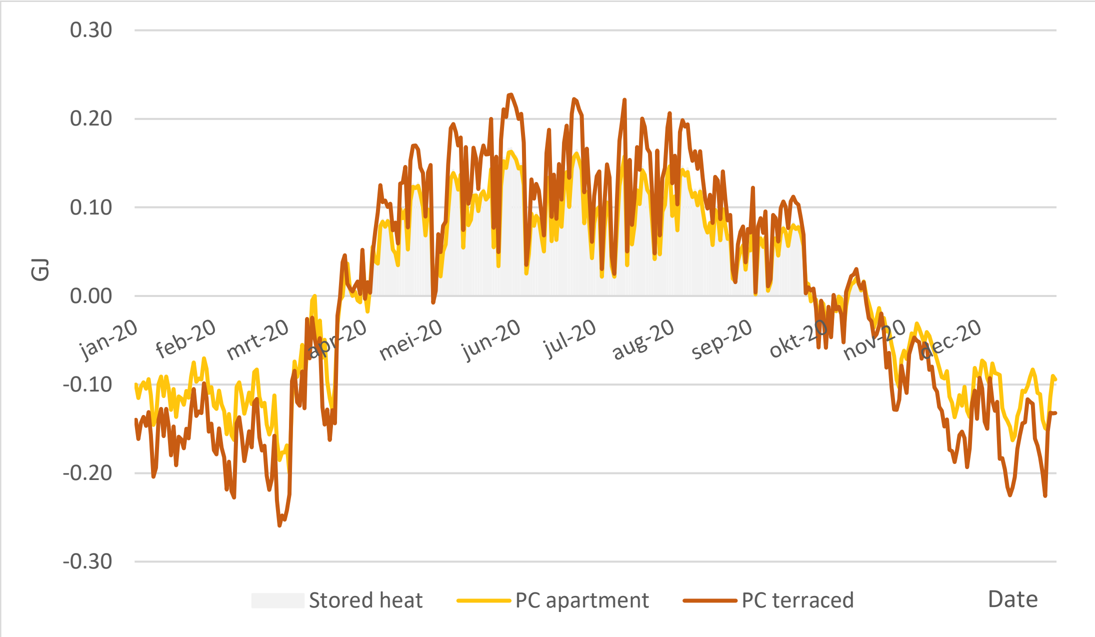

FIGURE 17 CHARGE AND DISCHARGE PROCESS OF THE SEASONAL HEAT STORAGE FOR CONCEPT 2 (12-15°C) OVER THE YEAR 2020.

As expected, also compared to Figure 6 provided in 2.4.3, Figure 17 shows discharge of heat around October to the end of March and charging of heat takes place in April to the end of September. The charge period is highlighted with a light grey area. Because the demand and production is equalized over the year, the heat storage values are comparatively in the same range. Table 14 shows the amount of heat that will be stored during the year. The values are equal to the grey surface underneath the lines provided in the example graph shown in Figure 17.

TABLE 14 TOTAL AMOUNT OF GJ STORED HEAT OVER THE YEAR 2020.

Concept	Solar collector	Heat grid T	Terraced house	Apartment
1	Triple Solar panel	12-15°C	16.07	11.48
2	Solarus PowerCollector™	70°C	21.76	15.58
3		12-15°C	16.08	11.49
4	G2energy Flat Plate collector	70°C	21.66	15.47
5		12-15°C	16.07	11.48

As shown in Table 14, the amount of GJ stored over the year are similar in each concept including the same dwelling type, and heat grid temperature. This is due to the same heat demand over the year. These values will be further discussed in 4.1.5.

4.1.5 Heat losses in the heating system

As mentioned in 3.1.5, the heat losses can be divided into heat losses for the concepts including a 70°C heat grid (Concept 2 and 4), and a 12-15°C heat grid (Concept 1, 3 and 5). Therefore, the results are divided into two sections based on their heat grid temperatures.

4.1.5.1 Heat grid 70°C

In the concepts including a 70°C heat grid, only the heat losses occurring during storage and transportation of heat through the heat grid are included. Because the calculated amount of stored heat over the year (Table 14) are in the same extent and in this step only divided by 366 days, the difference between the values is minimal. Because fixed numbers are used for the heat grid losses, the heat grid losses are identical for each concept. Because all these numbers show a huge similarity, Table 15 shows only the values per dwelling type.

TABLE 15 AMOUNT OF HEAT LOST PER DAY IN GJ PER DWELLING TYPE FOR THE 70°C HEAT GRID CONCEPTS (2 AND 4).

Dwelling type	Storage loss	Heat grid loss	Total
Terraced house	~0.0235	0.03	~0.0535
Apartment	~0.0169	0.01	~0.0169

To get a better understanding of these values in an overall perspective, Figure 18 is created. This curve is only created using the PowerCollector (Concept 2) as an example.

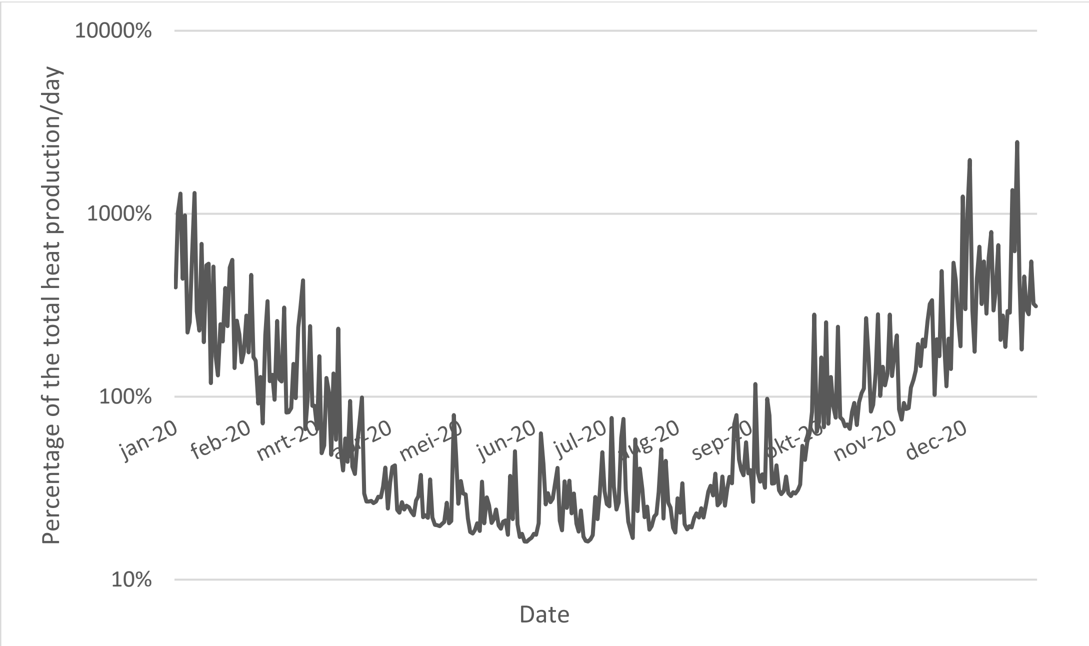

FIGURE 18 PERCENTAGE OF LOST HEAT COMPARED TO THE TOTAL HEAT PRODUCED PER DAY FOR THE POWERCOLLECTOR FROM SOLARUS IN THE 70°C CONCEPT (2) FOR AN APARTMENT.

Figure 18 shows a logarithmic curve in which the amount of loss is compared to the production of heat over the year (see 4.1.3). As shown, the amount of heat loss in the months October through March are at some days even ten times higher than the heat production. This confirms the assumption that more panels are required compared to only taking the heat demand into account. The amount of panels are calculated following the method explained in 3.1.5. These numbers are provided in Table 16 and will be further discussed in 4.1.5.3.

4.1.5.2 Heat grid 12-15°C

For the lower temperature concepts, only an estimation of losses in the heating system in the dwelling are taken into account. For this research an efficiency of 60% is considered. Again, the PowerCollector from Solarus (Concept 3) is taken as an example to show the loss curve over the year.

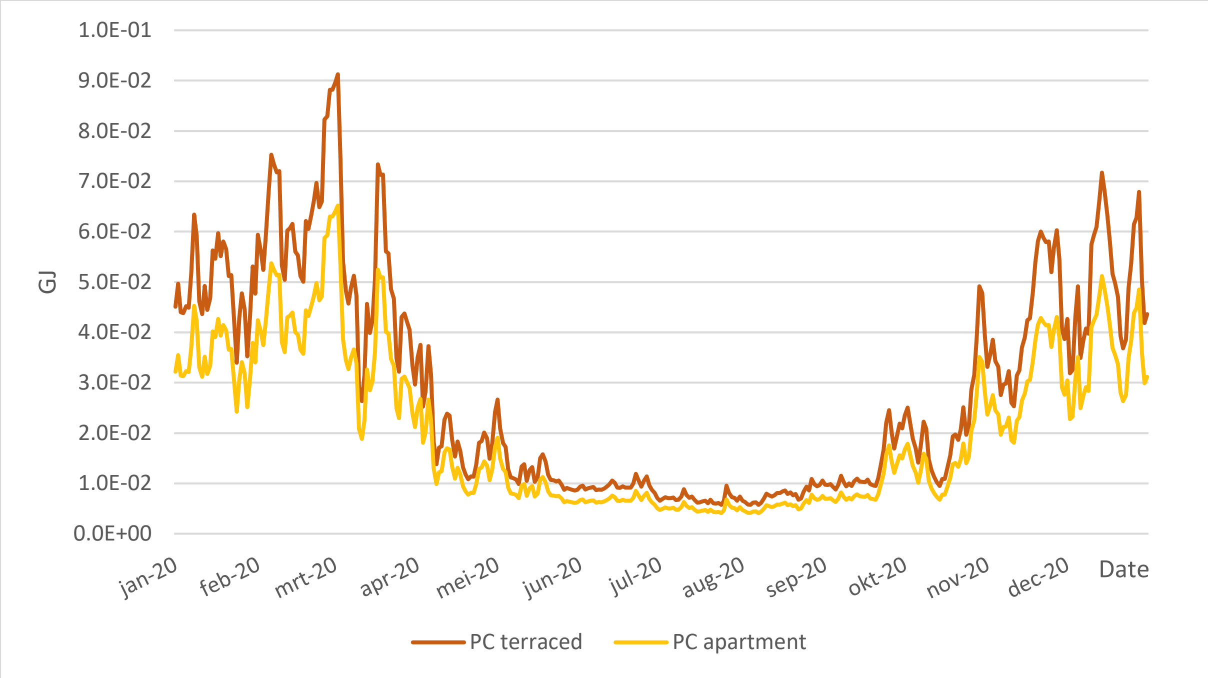

FIGURE 19 HEAT PUMP LOSSES OF THE POWERCOLLECTOR 12-15°C CONCEPT (3) FOR THE TWO DWELLING TYPES.

As shown in Figure 19, the graph follows the same curve as the demand curve provided in Figure 16. The losses are totally dependent on the heat demand which causes larger heat losses during periods with a higher demand for heat.

4.1.5.3 Number of panels required to cover the losses

After calculating the heat losses, the required amount of panels to cover these heat losses are determined and displayed in Table 16.

TABLE 16 REQUIRED M^2 TO COVER THE HEAT LOSSES OCCURRING IN THE FIVE CONCEPTS. RANKED WITH COLOR PER DWELLING TYPE IN VERTICAL DIRECTION (RED=LEAST DESIRED, DARK GREEN= MOST DESIRED).

Concept	Solar collector	Heat grid T	Terraced houses	Apartment
1	Triple Solar panel	12-15°C	5.27	3.93
2	Solarus PowerCollector™	70°C	6.80	4.04
3		12-15°C	3.93	2.81
4	G2energy Flat Plate collector	70°C	6.42	3.81
5		12-15°C	3.72	2.66

As shown in Table 16, a different ranking is established compared to Table 13. Again, the 12-15°C concept including the Flat Plate collector is the most desired option due to its high collector efficiency, low amount of heat loss, and a lower energy demand of the dwellings due to additional insulation. Interestingly, the Triple Solar shows a better score in this case. This is also due to more occurring losses, and a higher heat demand for the concepts including a 70°C heat grid. The PowerCollector connected to a 70°C heat grid seems for both dwelling types the least desired option.

4.1.6 Total amount of panels required for the whole system

After calculating the losses occurring in the five concepts, the required panels can be calculated to cover both the heat losses and heat demand (Table 17).

TABLE 17 REQUIRED M² TO COVER BOTH THE HEAT DEMAND AND HEAT LOSSES OF THE FIVE CONCEPTS. RANKED WITH COLOR PER DWELLING TYPE IN VERTICAL DIRECTION (RED=LEAST DESIRED, DARK GREEN= MOST DESIRED).

Concept	Solar collector	Heat grid T	Terraced houses	Apartment
1	Triple Solar panel	12-15°C	19.02	13.75
2	Solarus PowerCollector™	70°C	19.84	13.40
3		12-15°C	13.42	9.59
4	G2energy Flat Plate collector	70°C	18.83	12.67
5		12-15°C	12.84	9.17

Because only in the 12-15°C concepts additional insulation is incorporated, most of these concepts show the most desired option following Table 17. As expected, following the ranking in Table 13 and Table 16, the 12-15°C concept including the Flat Plat collector is the most desired. Although the Triple Solar collector has a lower efficiency compared to the other panels (Figure 13). The fact that insulation is added to the dwellings results in better performance for a terraced house compared to the 70°C concept including the PowerCollector (Concept 2).

4.1.7 Electricity production

As mentioned in 3.1.6, the panels from Triple Solar and Solarus are also able to generate electricity. Figure 20 shows the potential electricity production over the year 2020.

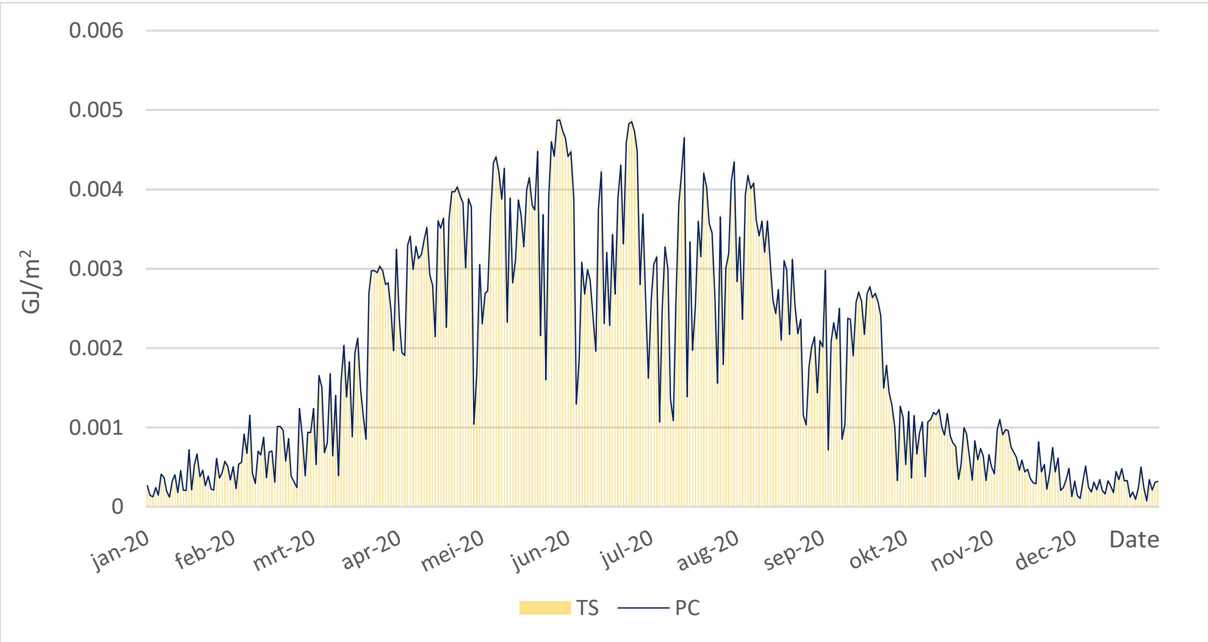

FIGURE 20 ELECTRICITY PRODUCTION OF THE TRIPLE SOLAR AND SOLARUS PANEL OVER THE YEAR 2020.

Because both solar panels have a similar efficiency value (Table 1 and Table 2), Figure 20 shows an almost identical curve. The Triple Solar is displayed with columns, and the PowerCollector only with a line to obtain a better overview of the almost overlapping curve. When looking closely, the slightly higher electricity production of the Triple Solar panel can be established which is totally in line with the higher efficiency value provided in Table 1. For the Triple Solar panel, a total of 190.91 GJ/m² was found and for the PowerCollector a total of 188.97 GJ/m² was determined.

4.1.8 Heat pump electricity demand

For this research, the electricity production is compared to the electricity use of the included heat pump (if applicable) to determine if the production can cover the demand. In the case of the 70ºC concept for the Solarus panel, a collective heat pump is integrated and its electricity demand can be covered by the electricity generation of the whole neighborhood. This demand per household is assumed to benegligible (see 3.1.7). To determine the electricity demand of the heat pump included in the 12-15ºC concepts, Equation 3 is used. Using the values displayed in Table 5, a COP of 3.52 was established. This means that per used GJ of electricity, 3.52 GJ of heat can be generated. With this value, the energy use for the 12-15ºC concepts were calculated. For the Triple Solar collector and PowerCollector from Solarus, it is assumed that the electricity generated by the collectors (see 4.1.7) is used for the heat pump. As an example, the difference in production and demand for the Triple Solar concept (Concept 1) for a terraced house is displayed in Figure 21. The amount of panels required for the concept (Table 17) is taken into account to obtain a realistic overview of the potential.

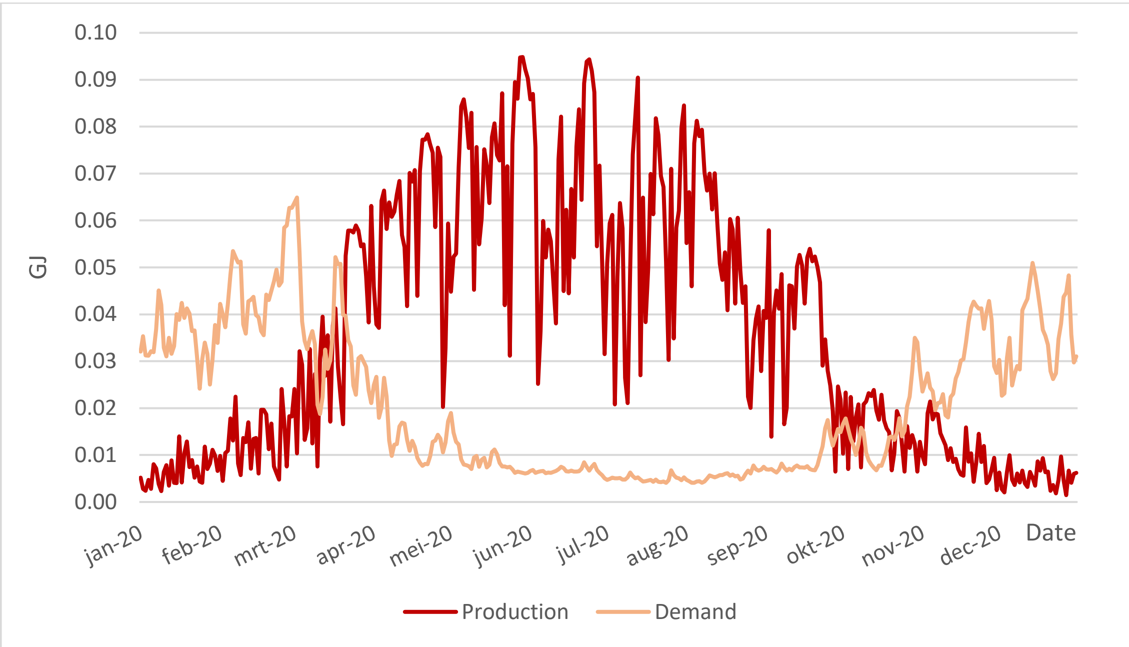

FIGURE 21 COMPARISON BETWEEN PRODUCTION OF ELECTRICITY BY THE TRIPLE SOLAR PANEL AND THE ELECTRICITY DEMAND OF THE INCLUDED HEAT PUMP FOR A TERRACED HOUSE (CONCEPT 1).

As shown in Figure 21, the production is more than sufficient to cover the electricity demand of the heat pump over the year. As mentioned before, and also observed in this graph, the electricity production shows a clear increase during summer times compared to a decrease in electricity demand for the heat pump in the same period. The calculated amount of GJ electricity production, the electricity demand of the heat pump, and the final surplus of energy is provided in Table 18.

TABLE 18 ELECTRICITY SURPLUS (GJ) RESULTS TRIPLE SOLAR COLLECTOR AND POWERCOLLECTOR FROM SOLARUS.

Heat grid T	Description	Concept 1 Triple solar		Concept 3 Solarus	
		Terraced	Apartment	Terraced	Apartment
12-15°C	Electricity production	13.23	9.45	9.13	6.52
	Heat pump demand	7.49	5.35	7.49	5.35
	Surplus	5.74	4.10	1.64	1.17

As shown in Table 18, in all cases a surplus of electricity is determined after subtraction of the electricity demand of the heat pump. This means that the amount of panels required to cover the heat demand and heat losses is also sufficient to cover the electricity demand of the heat pump.

4.1.9 Costs of applying the five concepts

Because the coverage of the heat demand is not the only important aspect to take into account when considering applying one of the five concepts, therefore the costs are calculated as well. Because no specific location is used for this research, and thus no detailed information of the two dwelling types being used, the costs are based on an estimation provided by DWA and the producers of the solar panels (Triple Solar, Solarus and G2energy). An overview of the costs is provided in Table 19 and Table 20.

TABLE 19 ESTIMATED COSTS FOR THE 12-15°C CONCEPTS. RANKED WITH COLOR PER DWELLING TYPE (RED=LEAST DESIRED, GREEN= MOST DESIRED).

Costs for	Concept 1 Triple solar		Concept 3 Solarus		Concept 5 G2energy	
	Terraced	Apartment	Terraced	Apartment	Terraced	Apartment
Collectors	€ 12,252	€ 8,859	€ 11,276	€ 8,054	€ 3,211	€ 2,294
Heat grid	€ 3,500	€ 2,500	€ 3,500	€ 2,500	€ 3,500	€ 2,500
WSC	€ 2,449	€ 1,633	€ 2,449	€ 1,633	€ 2,449	€ 1,633
Add. insulation	€ 25,000	€ 20,000	€ 25,000	€ 20,000	€ 25,000	€ 20,000
Heat pump	€ 7,000	€ 7,000	€ 7,000	€ 7,000	€ 7,000	€ 7,000
Total costs	€ 50,201	€ 39,992	€ 49,224	€ 39,187	€ 41,160	€ 33,426

As shown in Table 19, the total amount of costs for the 12-15°C concepts is for this research based on: (1) the costs for the collectors, (2) the construction and connection to the heat grid, (3) a seasonal heat storage system (WCS), (4) the inclusion of an individual heat pump, and (5) additional insulation. Based on the total amount of costs, the concepts including the collector from G2energy is the most desired option for both dwelling types. The Triple Solar panel seems to be the least desired option in both cases. This is due to higher costs for the collectors compared to the other two types of panels (see 2.4.1).

TABLE 20 ESTIMATED COSTS FOR THE 70°C CONCEPTS. RANKED WITH COLOR PER DWELLING TYPE (RED=LEAST DESIRED, GREEN= MOST DESIRED).

Costs for	Concept 2 **Solarus** Terraced	Concept 2 **Solarus** Apartment	Concept 4 **G2energy** Terraced	Concept 4 **G2energy** Apartment
Collectors	€ 16,668	€ 11,252	€ 4,707	€ 3,169
Heat grid	€ 1,100	€ 4,500	€ 1,100	€ 4,500
HTO	€ 612	€ 408	€ 612	€ 408
Coll. heat pump	€ 6,000	€ 2,400	€ 6,000	€ 2,400
Delivery set	€ 2,400	€ 1,100	€ 2,400	€ 1,100
Total	€ 26,780	€ 19,660	€ 14,819	€ 10,477

For the concepts including a 70°C heat grid, the costs are based on: (1) the costs for the collectors, (2) the construction and connection to the heat grid, (3) a seasonal heat storage system (HTS), (4) a collective heat pump located on site of the heat storage, and (5) the appliance of a delivery set in the dwelling (Table 20). As explained in 2.6, the Triple Solar panel is not included in this cost estimation. Looking at the total amount of costs, the Flat Plate collector shows a lower cost compared to the PowerCollector from Solarus for both dwelling types. This means that comparing these two concepts exclusively on costs, the concept including the collector from G2energy is the most desired.

To obtain a better visualization of the costs in an overall perspective, Figure 22 is created.

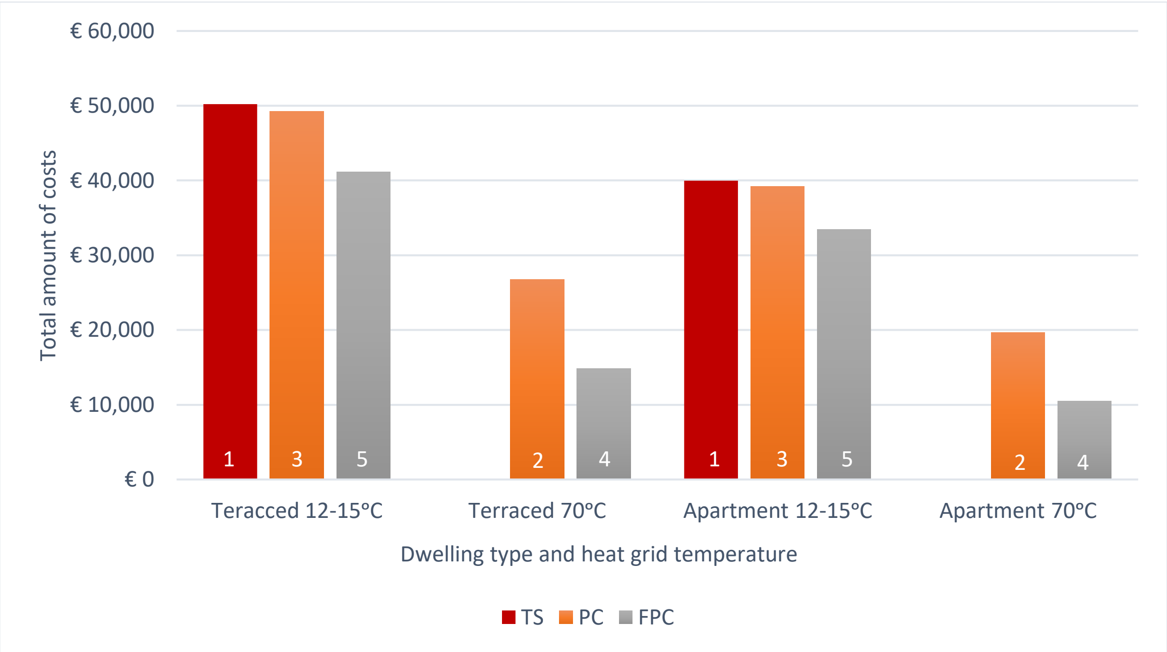

FIGURE 22 OVERVIEW OF THE COSTS OF THE FIVE CONCEPTS (INDICATED WITH A NUMBER) FOR TWO DWELLINGS TYPES.

As shown in Figure 22, for both a terraced house and an apartment, the 70°C concepts including Flat Plate collectors from G2energy would be the most desired concept based on investment costs. The Flat Plate collector is also the most desired for the 12-15°C concepts. The big difference in costs between the two heat grid temperature concepts is mostly caused by the inclusion of costs for additional insulation in the dwellings connected to a 12-15°C heat grid, and the higher costs for storage (Table 19 and Table 20). Although the costs for a WSC are much higher compared to the costs of an HTS, an HTS is probably more costly in long term due to more effort to maintain its thermal energy potential, usually at a greater depth (Vermooten & Lijzen, 2015). This difference is due to the price inclusion of one dwelling. The WCS needs to be bigger, compared to the HTS, in order to provide the same amount of thermal energy due to its lower ΔT (Table 10). Increasing the amount of connected dwellings would eventually result in lower costs for a WCS (Heijboer, 2021).

To obtain a more inclusive overview of the costs, and cost savings through gas savings and electricity production of both PVT panels, an indication of the payback time is provided. This comparison can be found in Figure 23 for Case 1 and Figure 24 for Case 2. The cost savings are indicated with a linear line and the investment costs are indicated with a vertical column.

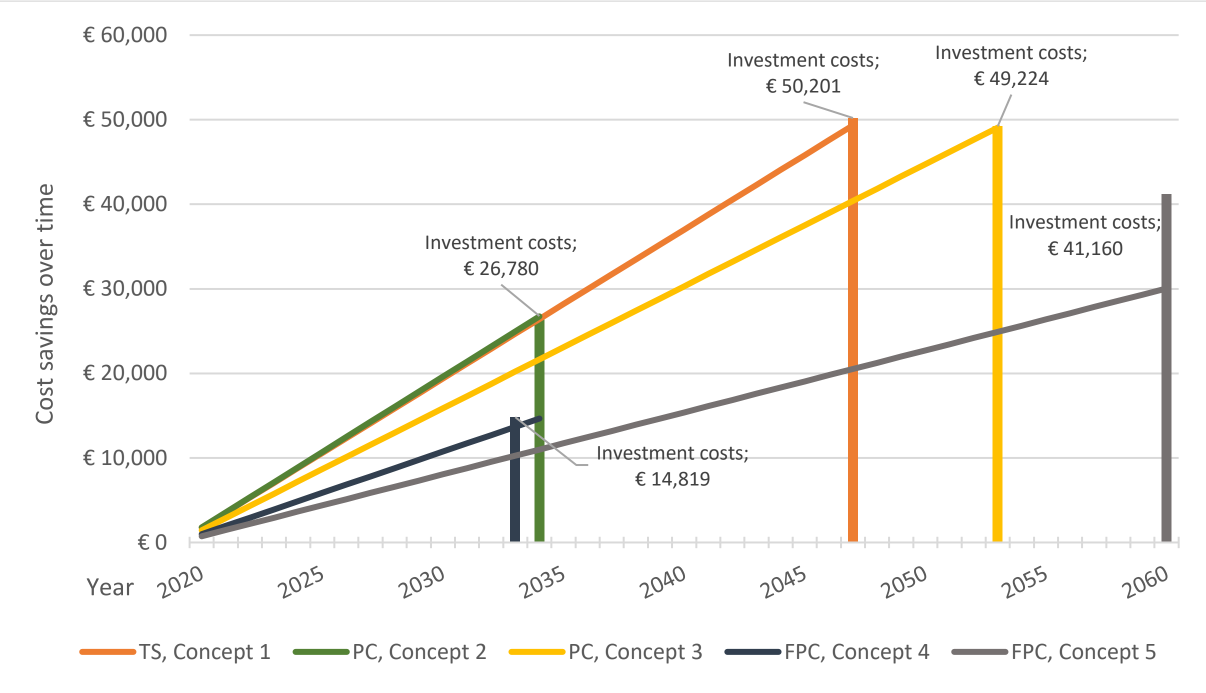

FIGURE 23 PAYBACK TIME OF THE FIVE CONCEPTS APPLIED ON A TERRACED HOUSE OVER THE PERIOD OF 2020-2060.

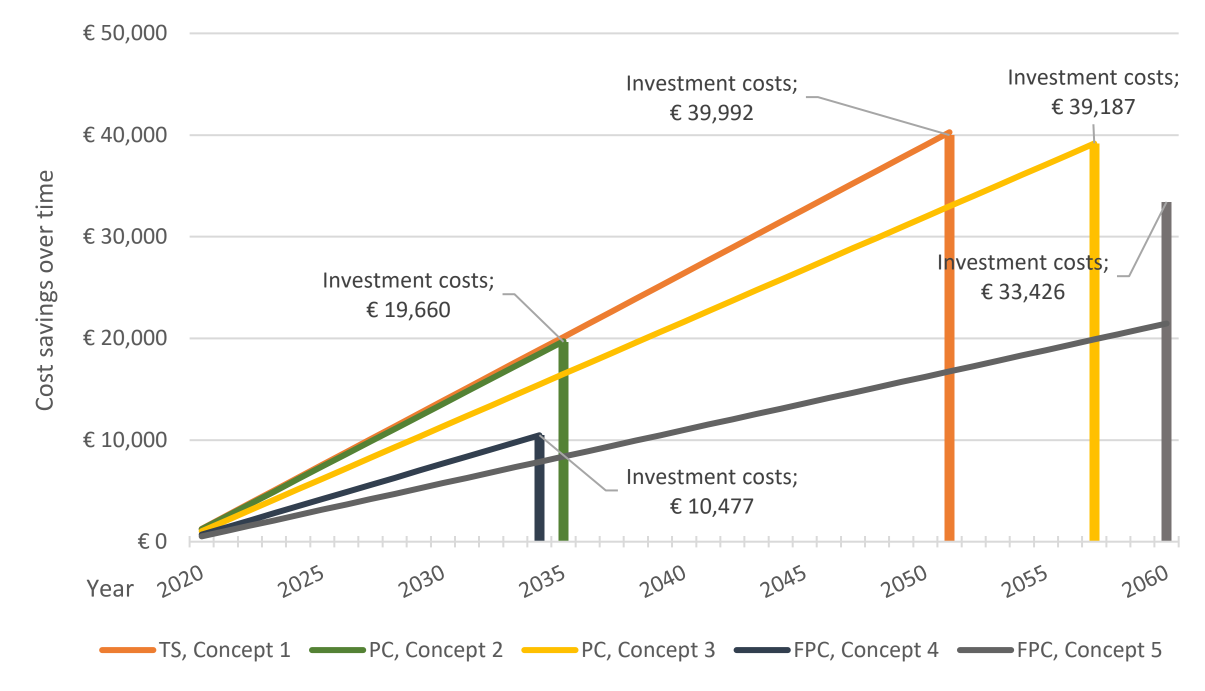

FIGURE 24 PAYBACK TIME OF THE FIVE CONCEPTS APPLIED ON AN APARTMENT OVER THE PERIOD OF 2020-2060.

As shown in Figure 23 and Figure 24, Concept 4 is the first concept that is able to cover the total costs of implementation for both dwelling types. The payback time of this concept is ~14 years for both dwelling types. This is due to its low collector costs (Table 3), and high overall efficiency (Figure 13). Also Concept 2 shows a comparatively short pay-back time of ~15 years for both dwelling types. For the other concepts, more time is required. The Triple Solar concept has a payback time of 28 years for a terraced house and 31 years for an apartment. For the PowerCollector concept (3), respectively 34 and 38 years is needed to cover the investment costs for a terraced house and an apartment. Lastly, for both dwelling types, Concept 5 shows the longest payback time. For a terraced house and an apartment, respectively 55 and 63 years is needed to cover the investment costs. This is due to no inclusion of electricity generation, and high integrated investment costs for additional insulation. What should be noted is that this payback estimation is only focused on the costs savings by energy savings over the year, no maintenance costs or other additional costs are included. These numbers are not included in the comparison part of this research (4.2) but further discussion is provided in Chapter 5.

4.1.10 CO_2 savings

In this research, the CO_2 savings is one of three criteria on which the final analyses is made. These savings are based on the natural gas and electricity savings over the year 2020. Because the Flat Plate collector is the only collector without a PV part, the CO_2 savings only include the emission savings regarding natural gas savings. Table 21 shows the calculated emission values for all concepts.

TABLE 21 AMOUNT OF KG CO_2 SAVED OVER THE YEAR 2020 PER CONCEPT AND DWELLING TYPE.

Dwelling type and heat grid T	Energy type	Triple solar	Solarus	G2energy
Terraced 12-15°C	Gas	1980.97	1980.97	1980.97
(Concept 1, 3 and 5)	Electricity	1066.01	735.62	
	Total	3046.97	2716.58	1980.97
Terraced 70°C	Gas		1980.97	1980.97
(Concept 2 and 4)	Electricity		1087.43	
	Total		3068.40	1980.97
Apartment 12-15°C	Gas	1414.98	1414.98	1414.98
(Concept 1, 3 and 5)	Electricity	761.43	525.44	
	Total	2176.41	1940.42	1414.98
Apartment 70°C	Gas		1414.98	1414.98
(Concept 2 and 4)	Electricity		734.10	
	Total		2149.08	1414.98

Following the data presented in Table 21, Triple Solar concept shows most CO_2 savings compared with the lower temperature concepts. This is totally relatable to the amount of m^2 panels needed to cover the heat demand discussed in 4.1.3 and its higher photovoltaic efficiency (2.4.1.1). For the higher temperature concepts, the Solarus concept (2) shows the highest emission saving values. The concepts (4 and 5) including the Flat Plate collector from G2energy show the lowest CO_2 savings. This is due to no addition of a PV part in the panel, and thus no electricity is produced.

4.2 Comparison

After calculating all the necessary values to obtain a well substantiated outcome following the three criteria mentioned in 3.2, the different concepts can be analyzed. This analyses is performed per dwelling type. The analyses for the two dwelling types will be collectively discussed following the ranking provided in Table 22 and Table 23. The reasons behind the rankings per criteria can be found in 4.1.6, 4.1.9 and 4.1.10.

TABLE 22 COMPARISON OF THE CONCEPT APPLIED ON A TERRACED HOUSE (1 = MOST DESIRED, 5 = LEAST DESIRED).

Concept	Collector type	Heat grid T	m^2 needed	Costs	CO_2 savings	Total
1	Triple solar	12-15°C	4	5	2	11
2	Solarus	70°C	5	2	1	8
3		12-15°C	2	4	3	9
4	G2energy	70°C	3	1	4	8
5		12-15°C	1	3	4	8

TABLE 23 COMPARISON OF THE CONCEPT APPLIED ON AN APARTMENT (1 = MOST DESIRED, 5 = LEAST DESIRED).

Concept	Collector type	Heat grid T	m^2 needed	Costs	CO_2 savings	Total
1	Triple solar	12-15°C	5	5	1	11
2	Solarus	70°C	4	2	3	9
3		12-15°C	2	4	2	8
4	G2energy	70°C	3	1	4	8
5		12-15°C	1	3	4	8

To obtain the substantiated overall comparison, the outcomes of the three criteria will first be summarized, followed by an overall comparison based on the total scorings provided in the last column of Table 22 and Table 23.

The first criterium is the amount of m^2 needed to cover the total heat demand of the dwelling, and the heat losses occurring in the system. On average, the lower temperature concepts show a lower required amount of m^2 mostly due to the higher efficiency over the year when there is demand for a lower thermal energy yield (Figure 13). Also, additional insulation shows more effect on the total outcome than the consideration of a specific dwelling type. Although the Triple Solar collector (Concept 1) is connected to a 12-15°C heat grid, the decrease in heat demand by additional insulation, and a lower amount of heat loss in the system is not enough to compete with Concept 4 and Concept 2 (when considering an apartment). This is due to its comparatively low efficiency.

For the second criterium, an identical ranking is established for both dwelling types. This is mostly due to additional costs for insulation. This investment is high but in the long term it will save more money compared to the 70°C heat grid concepts, due to lower heat demand. In both tables, Concept 4 shows the best scores. Also, when considering applying a 12-15°C heat grid, this panel seems to be the most desired option (Concept 5).

For the last criterium, a totally different ranking is determined. For a terraced house, Concept 2 is the most desired option. This is closely followed by the Triple Solar concept (Concept 1). This is due to a larger amount of m^2 required to cover the heat demand (see ranking first column) which leads to high emission savings caused by the large amount of electricity production. For an apartment, the Triple Solar concept shows the best score. This is mostly due to the high m^2 required for this concept. Because the collector from G2energy is not able to generate electricity, the outcomes were only based on the natural gas savings and thus the same scores were established for both concepts (4 and 5).

As shown in last column of Table 22, for a terraced house, the concepts including the Flat Plate collector from G2energy and Concept 2 (PC) show the best score. This ranking is for the G2energy concepts (4 and 5) mainly based on the best performance of heat generation and costs. For Concept 2, an overall good performance was determined. Also for an apartment, the G2energy concepts show a good ranking. The Solarus concept switches to a better performance for Concept 3, with a lower heat grid temperature. For both dwelling types, the Triple Solar concept (1) shows the highest score (and thus the least desired option).

When looking at the total picture of this table, neither of the dwelling types show a particular preference for a heat grid temperature. The four concepts including the Flat Plate collector, and the PowerCollector are evenly matched when compared to the three criteria.

Further interpretation of the values is provided in 5.1.

5 Discussion

After collection of the results presented in Chapter 3, the results can be evaluated. The relevance and consequences of the results will be discussed and implications of the findings are specified. After that, the limitations of this research are addressed. Potential weaknesses in the method are identified and the reliability of the obtained values is analyzed and further elaborated. Finally, a recommendation is provided focusing on practical actions and future research.

5.1 Contribution to research

After obtaining the final results it can be stated that solar thermal energy can have a significant contribution to the goal of limiting global warming by saving up to 3 tons of CO_2 every year. Also, comparing the results with other projects mentioned in 2.2, solar thermal energy can play an important role in the natural gas free transition. Through this research, an estimation of the costs is provided focusing on two different cases. These values can be used for future research when more detailed information about the heat demand for a specific neighborhood is considered. This will provide a more long-term performance assessment of solar thermal energy systems. The results show that a neighborhood is able to fully run on solar thermal energy only.

When comparing the concepts on their most important criterium for residents in a neighborhood, the coverage of their heat demand, a large amount of surface area is required. For a terraced house and an apartment respectively 13-19 m^2 and 9-13 m^2 is needed (Table 17). Because the roof area of both dwelling types is generally not very large, the chance of having enough suitable space for the installation of these panels is relatively low. This means that external space should be included to guarantee sufficient heat over the year. This is also often seen in similar projects like Gemeente Vlieland (2019) where 21 solar collectors will be placed on a group accommodation. Using a nearby building or open field lowers the investment costs of construction and pipe length. Both a totally collective solar thermal energy field or a partly collective system with individual collectors, and an additional collective solar field can be considered to guarantee sufficient heat over the years. This shows that solar thermal energy systems have a great potential to contribute to a more sustainable heating system in the built environment.

5.2 Research limitations

Because this research is conducted in a limited period of time, a narrow scope was considered and multiple assumption are made. The limitations in the method will be discussed followed by the assumption in the calculations.

To obtain the most efficient and realistic composition, the developed concepts (Figure 10) are based on other projects and strategies (see 2.2 and 2.3). Although the collectors are selected following high performance criteria and the appliance of certain panels in similar projects, one type of solar collector is kept out of scope. The Evacuated Tube Solar Collectors (ETSCs) is a very efficiency solar collector and can, even in colder climates, generate a temperature output over 100°C (Greco et al., 2020). It consists of a series of vacuum tubes which are arranged in parallel to each other (Greco et al., 2020). The vacuum within the tubes acts as a thermal insulator which limits the dispersion of heat. This device can easily be applied to a 70°C heat grid which may increase its performance. Considering the heat grid temperatures (Table 4), the appliance of a 50°C heat grid can be interesting as well. This temperature can directly be used for space heating and a heat pump is only needed to increase the temperature for safe usage of hot tap water. This would decrease the electricity demand for the generation of heat of a dwelling by 80% compared to a 12-15°C heat grid (Beurskens, de Keizer, Tigchelaar, & Solar, 2020). For the storage systems, other types of storage systems, like a pit or a tank, are worth considering. A pit is the most often applied heat storage system in Denmark, where the use of solar thermal energy is increasing (Beurskens et al., 2020). For the tank, the Ecovat is more often the applied technology (Beurskens et al., 2020). The Ecovat consists of a highly insulated concrete tank where a storage efficiency over 90% can be reached (van den Heuvel, 2020). Although this type of tank is still in the developing phase, the inclusion of more storage system types can result in a better overview of the possibilities.

If a specific neighborhood is to be considered, more parameters can be specified following the layout of the neighborhood, and the design of the dwellings. The selection of a specific neighborhood can provide a better overview of the possibilities for construction of the heat storage systems, and a heat grid. Applying an aquifer or borehole storage system requires suitable underground sand layers to efficiently store the generated heat. If these layers are not present or insufficient for this type or storage system, a different kind of heat storage or even a different way of heat supply can be considered. This is also the case for locations where other heat storage systems are already present. The interaction between two storage systems should be avoided to prevent a reduction of the efficiency of the systems (Hoegaerts & Energy, 2015). Furthermore, the inclusion of a specific location can provide a better overview of the possibilities regarding the appliance of solar collectors. For this research, an average value for the potential losses of electricity production due to deviation from the optimal position is included. If an optimal angle and orientation can be accomplished, the collectors can operate at their highest efficiency level.

The calculated costs are also very location dependent. In this research the costs for the construction and connection to a heat grid, seasonal heat storage system, and additional insulation are rough estimations. For some dwellings it may not even be worth it to invest in additional insulation due to very high costs or the demand for total renovation. However, the costs for a specific neighborhood with better insulated dwellings can on the other hand result in better cost performance of the 12-15°C heat grid.

The size of the neighborhood is also of importance, especially regarding the costs indicated for the heat storage systems. In the case of a large amount of connected dwellings to the heating system, another ranking can be argued. A larger WCS can result in a lower price, and thus a better score for the lower temperature concepts. This can eventually result in the 12-15°C concepts to be the most suitable. This means that Concept 5 would be the best choice for both dwelling types. On the other hand, as mentioned in 2.4.1, the appliance of PVT panels will be more beneficial regarding its ability to generate both heat and electricity at the same time. The cost savings through electricity production is not incorporated in the criteria. Although the exclusion of this criterium seems fair regarding the Flat Plate collector, the only collector which is not able to generate electricity, this additional criteria is of importance regarding the costs of the total system. As shown in Figure 23, these cost savings can cover the investment costs within 15 - 40 years. The incorporation of this can be an interesting addition for the residents or municipalities who are considering applying one of these concepts.

The costs are not only location dependent, but the inclusion of subsidies can have an effect on the final results. Subsidies can be claimed for the appliance of a solar water heater, a heat pump, the connection to a heat grid, or energy savings through the incorporation of different insulation measures (RVO, 2022). For this research, only the subsidies for additional insulation, the collectors and heat pump are of interest because of possible effects on the results. In this research, for additional insulation, an average investment price of €25,000 is included. This could be reduced by the inclusion of up to €101 per m^2 applied insulation, and additional subsidies can be requested for the appliance of insulated windows, and window-frames (Rijksoverheid, 2021). The inclusion of a specific neighborhood would result in a better cost estimation, and cost savings through subsidies. Because the subsidies will only be provided for either a heat pump or solar collectors, this will have a significant effect on the cost results (Rijksoverheid, 2021). Because the Triple Solar collector is dependent on the inclusion of a heat pump, the cost savings for this concept (1) will be comparatively lower compared to the concepts (2 and 4) where the inclusion of a heat pump is unnecessary. For a heat pump, a minimal amount of around € 3.750 can be provided (Rijksoverheid, 2021). The exact price is dependent on the type of heat pump installed. For the collectors, the amount of subsidies is dependent on the type of solar panel and the amount of m^2. For the Solarus collector, a subsidy of 155 €/m^2 is applicable (van der Schelling, 2022). For Concept 2, this would result in a reduction of €3,075 for a terraced house and €2,077 for an apartment. Applying the discussed subsidies on Concept 1 and 2 resulted in a reduction of respectively 9.4% and 15.6% for a terraced house, and 7.5% to 7.8% for an apartment. This example shows that the inclusion of these subsidies can have a significant effect on the final cost results. In addition, in the lower temperature concepts only the inclusion of an individual heat pump is considered which is relatively expensive compared to a collective heat pump per street or apartment building. A collective heat pump lowers the price per resident due to lower electricity demand through bulk production of heat (Heijboer, 2021). This can result in lower costs for the Concept 1, 3 and 5, and the subsidies per resident can be focused on the collectors to increase the cost savings. The construction of a heat grid, and heat storage system is also often funded by an energy supply company so costs can be charged for the usage of the system. This would lower the investment costs per household but adds additional yearly costs for the user. Furthermore, in some cases it is possible to claim back BTW of up to 80-90% for the collectors (van der Schelling, 2022). Although this can be applicable to all concepts, the concepts with high investment costs can be more in balance with the concept including less expensive collectors.

Considering the heat supply by the heat storage systems, only a minimal amount of heat that can be present in the storage system is considered. This can result in a shortage during unexpected cold weather in winter months. To avoid this deficiency, a buffer should be incorporated to guarantee sufficient heat during shortage or peak moments. The inclusion of this buffer can result in more overall heat losses, and thus an increase in collectors to cover these heat losses.

Lastly, for the final comparison a relatively simple method is used. In this way the ratio between the obtained results is not provided. Although this would have no effect on the final conclusion, this ratio can be meaningful when considering applying one or more concepts.

5.3 Recommendation for further research

Following the limitations addressed in 5.2, recommendation for future research can be indicated.

More research can be conducted on the suitability of more concepts. For the collectors, also the inclusion of ETCs can be of interest to obtain a more inclusive outcome towards the different possibilities within solar thermal energy production technologies. Different heat grid temperatures can be considered and a bigger variety of storage systems can broaden the perspective on solar thermal district heating. In this way, an overview of different concepts divided per dwelling type can be created to facilitate an easier, and more accessible database of options. This will help interested parties in applying such concepts on neighborhoods or a complex of different buildings.

The addition of a specific location can further indicate the suitability of certain heating concepts and a better estimation of the heat generation, costs, and energy savings can be provided. Future research can focus more on applying insulation measures before applying other sustainability measures to reduce emissions and costs on heating. More research into different kinds of areas, neighborhoods and dwelling types can provide a better overview of the best options for certain locations. The amount of criteria can be extended to obtain a well substantiated choice regarding the implementation of different sustainable heating systems. This would make it easier for interested parties to select the most suitable concepts to incorporate in further research, including the specifics of a location.

More research can be conducted on the economic feasibility of these concepts for residents, energy companies, and municipalities. Subsidies can be included to obtain a better estimation of the final costs for residents and to investigate the advantages of investment in this way of heating. The inclusion of inconsistencies in the total system should be further investigated. Back-up storage should be included, and more research should be conducted into the total efficiency of the system. Lastly, legislation around the construction of heat storage systems could be a valuable addition to this kind of research to investigate the suitability of specific locations. Storage systems up to 500 m in depth require a license based on the water law (Agentschap NL, 2013). Storage systems deeper than 500 m, commonly only applicable to an HTS, require a license following the Mining Act (IF Technology, 2012). Suitable sand layers and other types of undergrounds can be identified to ease the search for suitable locations.

6 Conclusion

The aim of this research is to compare five different heating system concepts, including three types of solar collectors, two heat grid temperatures and two types of seasonal heat storage, based on the capability of meeting the heat demand, costs and CO_2 savings. The development and a final overview of these concepts is provided in Figure 10 (2.6). The heat demand was assumed to be covered by the solar collectors only where the losses of the total system were incorporated. Because a surplus of heat production occurs in summer times, and a mismatch between demand and production occurs in winter times, a seasonal heat storage system was included to bridge this gap. This research was conducted for two dwelling types, a terraced house and an apartment. A heat grid was assumed to be the connection between all three aspects (dwelling, seasonal heat storage and solar collectors).

After obtaining the preferred data, the three main criteria (coverage of the heat demand, costs and CO_2 savings) are reviewed. For the coverage of the heat demand and the amount of investment costs, both dwelling types show a big preference for the concept including the Flat Plate collector from G2energy and a 12-15°C heat grid temperature. This is explained by a higher overall efficiency of the collector (Figure 13) which is also affected by the temperature demand (the lower, the more efficient). For the last criterium, the CO_2 savings, another most desired concept was established. The Triple Solar panel showed the largest savings for a terraced house and the PowerCollector 70°C concept (Concept 2) showed the largest savings over the year for an apartment. This is a direct result of the electricity production by the high amount of m^2 needed to cover the heat demand and losses occurring in the system.

In conclusion, the concepts including the Flat Plate collector and PowerCollector are the best scoring concepts. For a terraced house, both heat grid temperature concepts including the Flat Plate collector (Concept 4 and 5) and the 70°C PowerCollector concept (Concept 2) are the most desired. For an apartment, the same ranking was established but here the lower temperature PowerCollector concept (Concept 3) showed a better performance compared to the 70°C concept (Concept 2).

The most important motive behind this research was the question if it is even possible to generate and store enough heat to be able to cover the heat demand of an entire neighborhood. Although this research is only focused on the demand of one household, it is demonstrated that one household could run totally on solar thermal energy, however, the investment is high and lots of inconsistencies need to be incorporated.

7 Reference list

Agentschap NL. (2013). *Beheer Warmte Koude Opslag*.

Andersen, P. V. K., Georg, S., Gram-Hanssen, K., Heiselberg, P., Horsbøl, A., Johansen, K., . . . Møller, E. S. (2019). *Using residential buildings to manage flexibility in the district heating network: perspectives and future visions from sector professionals.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Bahaidarah, H., Subhan, A., Gandhidasan, P., & Rehman, S. (2013). Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. *Energy, 59*, 445-453.

Bai, Y., Wang, Z., Fan, J., Yang, M., Li, X., Chen, L., . . . Yang, J. (2020). Numerical and experimental study of an underground water pit for seasonal heat storage. *Renewable Energy, 150*, 487-508.

Beurskens, L., de Keizer, C., Tigchelaar, C., & Solar, H. (2020). *Aanzet tot Routekaart Zonnewarmte*.

Bezemer, R. (2010). Comfortable district heating by ingenious PLC-control. Solar heat for district heating and hot water; Comfortabele stadswarmte dankzij ingenieuze PLC-regeling. Zonnewarmte voor stadverwarming en warm tapwater. *Verwarming en Ventilatie, 67*.

Brottier, L., & Bennacer, R. (2020). Thermal performance analysis of 28 PVT solar domestic hot water installations in Western Europe. *Renewable Energy, 160*, 196-210.

CBS. (2020). Energieverbruik particuliere woningen; woningtype en regio's. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?fromstatweb

CBS. (2021a). *Aardgas en elektriciteit, gemiddelde prijzen van eindverbruikers*.

CBS. (2021b). Hoe groot is onze broeikasgasuitstoot? Retrieved from https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/hoofdcategorieen/hoe-groot-is-onze-broeikasgasuitstoot-wat-is-het-doel-

CBS. (2021c). Voorraad woningen; eigendom, type verhuurder, bewoning, regio. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82900NED/table?fromstatweb

CE Delft. (2020a). *Emissiekentallen elektriciteit*.

CE Delft. (2020b). *Verkennend onderzoek zonthermie Zuid-Holland*.

Coenen, P., van Zanten, M., Zijlema, P., Arets, E., Baas, K., van den Berghe, A., . . . te Molder, R. (2018). Greenhouse gas emissions in the Netherlands 1990-2016: National Inventory Report 2018.

de Keizer, A., Bottse, J., & de Jong, M. (2018). PVT Benchmark: An overview of PVT modules on the European market and the barriers and opportunities for the Dutch Market.

de Keizer, C., de Jong, M., Mendes, T., Katiyar, M., Folkerts, W., Rindt, C., & Zondag, H. (2016). Evaluating the thermal and electrical performance of several uncovered PVT collectors with a field test. *Energy Procedia, 91*, 20-26.

Department for Business Energy & Industrial Strategy. (2017). What is a heat network?

Drijver, B. (2019). Hoge Temperatuur Opslag (HTO). Retrieved from https://www.gebruikersplatformbodemenergie.nl/wp-content/uploads/2019/06/Benno-Drijver-IF-Technology.pdf

Du, B., Hu, E., & Kolhe, M. (2013). An experimental platform for heat pipe solar collector testing. *Renewable and Sustainable Energy Reviews, 17*, 119-125.

Dullemen, S. (2020). *A guide to large-scale solar thermal heat in the Netherlands.*

DWA. (2018). *JBDK warmtenet*.

DWA. (2021). *Berekening warmteverlies in warmtenet per gemiddelde woning*.

Ebaid, M. S., Ghrair, A. M., & Al-Busoul, M. (2018). Experimental investigation of cooling photovoltaic (PV) panels using (TiO2) nanofluid in water-polyethylene glycol mixture and (Al2O3) nanofluid in water-cetyltrimethylammonium bromide mixture. *Energy Conversion and Management, 155*, 324-343.

G2energy. (2021). *Thermische zonnecollector GC72*.

Gemeente 's-Hertogenbosch. (2020). 's-Hertogenbosch (Het Zand) - Aanvraag Proeftuin Aardgasvrij Wijk (2e ronde). In.
Gemeente Lingewaard. (2020). *Lingewaard (Zilverkamp) - Aanvraag Proeftuin Aardgasvrij Wijk (2e ronde)*.
Gemeente Vlieland. (2019). *AANVRAAG AARDGASVRIJE WIJKEN*.
Greco, A., Gundabattini, E., Gnanaraj, D. S., & Masselli, C. (2020). A Comparative Study on the Performances of Flat Plate and Evacuated Tube Collectors Deployable in Domestic Solar Water Heating Systems in Different Climate Areas. *Climate, 8*(6), 78.
Heijboer, P. (2021). [Personal communication].
Hepbasli, A., & Kalinci, Y. (2009). A review of heat pump water heating systems. *Renewable and Sustainable Energy Reviews, 13*(6-7), 1211-1229.
Herez, A., El Hage, H., Lemenand, T., Ramadan, M., & Khaled, M. (2020). Retrived on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. *Solar Energy, 207*, 1321-1347.
Herrando, M., Pantaleo, A. M., Wang, K., & Markides, C. N. (2019). Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. *Renewable Energy, 143*, 637-647.
Hoegaerts, C., & Energy, P. T. E. S. S. (2015). *TESSEL-openbaar eindrapport*: Delft: TNO.
Hoogers, A., Go, K., Drok, M., & Bergboer, R. (2018). *Aanvraag aardgasvrije wijken "Nagele in Balans"*.
Hoogervorst, N. (2017). *Toekomstbeeld klimaatneutrale warmtenetten in Nederland*: Planbureau voor de Leefomgeving.
Hot water heat pumps. (n.d.). How heat pumps work. Retrieved from https://hotwaterheatpumps.com.au/howheatpumpswork/
IF Technology. (2012). *Juridisch kader Hogetemperatuuropslag.*
Kim, J.-H., & Kim, J.-T. (2012). The experimental performance of an unglazed PVT collector with two different absorber types. *International Journal of Photoenergy, 2012*.
Kirch, M., den Dekker, L., & Duijff, R. (2020). Warmtenetten ontrafeld - Een praktische handleiding.
Klimaatakkoord. (2019a). *C Afspraken in sectoren C1 Gebouwde omgeving*. Retrieved from
Klimaatakkoord. (2019b). *Klimaatakkoord*.
KNMI. (2020). *Klimaatdata 2020*.
KNMI. (n.d.). Maart 2018. Retrieved from https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2018/maart
Kolaitis, D. I., Malliotakis, E., Kontogeorgos, D. A., Mandilaras, I., Katsourinis, D. I., & Founti, M. A. (2013). Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings. *Energy and Buildings, 64*, 123-131.
Koopman, A. (2012). *Duurzame Ontwikkeling met de Ondergrond.*
Lund, H., Østergaard, P. A., Nielsen, T. B., Werner, S., Thorsen, J. E., Gudmundsson, O., . . . Mathiesen, B. V. (2021). Perspectives on fourth and fifth generation district heating. *Energy, 227*, 120520.
Mangold, D., & Deschaintre, L. (2015). Seasonal thermal energy storage.
Mohammadi, K., Khanmohammadi, S., Khorasanizadeh, H., & Powell, K. (2020). A comprehensive review of solar only and hybrid solar driven multigeneration systems: Classifications, benefits, design and prospective. *Applied Energy, 268*, 114940.
Molenaar, K. (2021, 8-12-2021). [personal communication]
NEN 1006. (2018). *General requirements for water supply installations*.
OnsAardgas.nl. (n.d.). Alles over aardgas. Retrieved from https://www.onsaardgas.nl/alles-over-aardgas/
Papa, T. J. G., Wijnant-Timmerman, S. I., & van Leeuwen, R. P. (2019). Warmtenetten: Technische karakterisering.

Pinel, P., Cruickshank, C. A., Beausoleil-Morrison, I., & Wills, A. (2011). A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renewable and Sustainable Energy Reviews, 15*(7), 3341-3359.
Planbureau voor de Leefomgeving. (2020a). Startanalyse aardgasvrije buurten. Retrieved from https://themasites.pbl.nl/leidraad-warmte/2020/#
Planbureau voor de Leefomgeving. (2020b). Strategieën en varianten. Retrieved from https://themasites.pbl.nl/leidraad-warmte/2020/#
Planbureau voor de Leefomgeving. (2021). *Klimaat- en Energieverkenning 2021*.
Programma Aardgasvrije wijken. (n.d.). Proeftuinen op de kaart. Retrieved from https://www.aardgasvrijewijken.nl/proeftuinen/huidigeproeftuinen/default.aspx
Ramplaankwartier. (n.d.). Ramplaankwartier - project Spaargas. Retrieved from https://ramplaankwartier.nl/
Rijksoverheid. (2017). C-212 Green Deal Aardgasvrije Wijken.
Rijksoverheid. (2021). Subsidie voor duurzame energie en energiebesparing koopwoning aanvragen. Retrieved from https://www.rijksoverheid.nl/wetten-en-regelingen/productbeschrijvingen/subsidie-voor-zonneboiler-warmtepomp-pelletkachel-of-biomassaketel
RVO. (2019). *Berekening van de standaard CO2-emissiefactor aardgas t.b.v. nationale monitoring 2020 en emissiehandel 2020*.
RVO. (2022). Investeringssubsidie duurzame energie en energiebesparing voor woningeigenaren (ISDE). Retrieved from https://www.rvo.nl/subsidie-en-financieringswijzer/isde/woningeigenaren
RVO. (n.d.). Factsheet: WKO en warmtepompen. Retrieved from https://www.rvo.nl/sites/default/files/2017/07/RVO.nl%20-%20Factsheet%20WKO%20en%20warmtepompen.pdf
Sayegh, M. A., Jadwiszczak, P., Axcell, B., Niemierka, E., Bryś, K., & Jouhara, H. (2018). Heat pump placement, connection and operational modes in European district heating. *Energy and Buildings, 166*, 122-144.
Shafieian, A., Khiadani, M., & Nosrati, A. (2018). A review of latest developments, progress, and applications of heat pipe solar collectors. *Renewable and Sustainable Energy Reviews, 95*, 273-304.
SMARTcirculair. (2019). *Zonnepanelen berekeningen voorbeeld en uitleg.*
Solarus. (2021a). 100% Hernieuwbare Warm Water oplossingen. In.
Solarus. (2021b). *PowerCollectorTM aH72SK Productblad*.
Solarus. (2021c). Solarus hybride HT-PVT, Regeneratie van WKO-systemen. In.
Thomsen, K. E., Rose, J., Mørck, O., Jensen, S. Ø., Østergaard, I., Knudsen, H. N., & Bergsøe, N. C. (2016). Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. *Energy and Buildings, 123*, 8-16.
TNO. (2021). *Evaluatie van de energieprestatie van collectorveld 3 bij freesiateler Tesselaar.*
Triple Solar. (2021). *Technische documentatie warmtepomppanelen*.
Triple Solar. (n.d.). Hoe werkt het en veelgestelde vragen (FAQ). Rerieved from https://triplesolar.eu/introductie-pvt-warmtepomp-paneel/veelgestelde-vragen/
UNFCCC. (2015). Adoption of the Paris Agreement.
van den Heuvel, M. M. (2020). Peak Buffering by the Ecovat Thermal Energy Storage System.
van der Schelling, M. (2022).
Van Vuuren, D. P., Boot, P. A., Ros, J., Hof, A. F., & den Elzen, M. G. (2017). *The implications of the Paris climate agreement for the Dutch climate policy objectives*: PBL Netherlands Environmental Assessment Agency.
Vermooten, S., & Lijzen, J. (2015). Ecosysteemdiensten van grondwater en ondergrond: Beschrijvingen en relaties met activiteiten en maatregelen.
VHGM. (n.d.). REGENERATIESYSTEEM. Retrieved from https://vhgm.nl/werkgebieden/bodemenergie/technieken/regeneratiesysteem/

Xu, J., Wang, R., & Li, Y. (2014). A review of available technologies for seasonal thermal energy storage. *Solar energy, 103*, 610-638.
Yang, T., Liu, W., Kramer, G. J., & Sun, Q. (2021). Seasonal thermal energy storage: A techno-economic literature review. *Renewable and Sustainable Energy Reviews, 139*, 110732.
Zhao, X., Long, E., Zhang, Y., Liu, Q., Jin, Z., & Liang, F. (2017). Experimental study on heating performance of air-source heat pump with water tank for thermal energy storage. *Procedia Engineering, 205*, 2055-2062.
Zwamborn, M. (2021). High-temperature aquifer thermal energy storage. In.