Photovoltaic Thermal District Heating: A review of the current status, opportunities and prospects

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ABSTRACT

This work presents a first-of-its-kind review specifically on photovoltaic thermal district heating (PVT DH), compiling a wide range of sources information to view and analyse its current status. From this, interesting conclusions have been extrapolated that would otherwise be unreachable without this holistic view. Potential opportunities have also been identified in the use of PVT panels in conjunction with other heating technologies, such as heat pumps, for its application in DH. Sources used included academic literature, government reviews, environmental agencies, manufacturers, energy and finance news, industrial and a German installation report. The review starts with a discussion on the need for decarbonising heating in urban areas and introduces how PVT DH could be a potential solution. This is followed by a discussion on PVT technology in terms of efficiency, status and market. Due to the diurnal/seasonal nature of PVT, an overview of potential storage technologies was then provided. The review identified that it is evident there are various ’off the shelf’ storage technologies ready to be implemented in PVT DH systems. Following this, a discussion on PVT DH installations and studies investigates the advantages and disadvantages of this system. It is concluded that there is a need for future research to focus on the control strategies for PVT DH, taking into account the requirement to keep the PVT temperature low to optimise the electrical efficiency, and the integration of thermal storage and/or heat pumps. Finally, the review summarises how this investigation has led to the discovery of several external drivers which could put PVT DH ahead as a potential option when choosing clean heating strategies in the future. These include; progression towards 4th generation district heating, solar technology and storage technological advancement and cost reduction, mutual system performance improvement with heat pumps, and green legislation/policies. If knowledge and working experience of PVT DH systems can be expanded, particularly in control strategies, the system performance can be enhanced making it an attractive option for 4th generation district heating systems.

1. Introduction

As of January 2019, 197 countries signed or ratified the Paris agreement. The Grantham Research Institute found that all countries that acceded to the agreement, already had at least one law or policy on climate change [1]. While not to be used for making casual inferences, the “number of environmental laws” can be a useful proxy to gauge the importance ascribed on such aspects in policy. Figure 1 shows the global focus of new laws passed over the past 2 decades. In recent years, this metric has declined a seemingly counter-intuitive trend given the climate change emergency. This could be consistent with there previously being an increase in climate and environmental laws passed, which built up the stock of the existing legislature meaning the need for further laws fell since new policies were already covered by existing laws [2]. The new laws or policies defined have been pushing countries to reduce their CO_2 emissions, which has been a key driver for research and technological advancement in clean technology.

PV technology has particularly benefited from new government energy policies and subsidies resulting in a fast growing market. With a growing market, research efforts have increased leading to better materials and manufacturing processes with the efficiency for average commercial wafer-based silicon modules increasing from 12% to 17% (21% for monocrystalline) over the last decade, and a net price reduction of about 92% over the past 28 years [3]. The past few years has seen a remarkable increase in installed solar PV capacity reaching 773.2 GW by the end of 2020 [4].

Solar PV is now already competitive compared to all other fossil fuel generation. Economies of scale and further technological advancements are expected to further reduce the cost of solar PV technologies over the next few decades.

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Abbreviations

4GDH	4th Generation District Heating
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CSC	Concentrated Solar Collector
CSP	Concentrated Solar Plant
DH	District Heating
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GSHP	Ground Source Heat Pump
HP	Heat Pump
IEA	International Energy Agency
LCC	Life Cycle Cost
LTDH	Low Temperature District Heating
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic Thermal
SAHP	Solar Assisted Heat Pump
SDS	Sustainable Development Scenario
STC	Solar Thermal Collectors
ULTDH	Ultra Low Temperature District Heating
VPP	Virtual Power Plant

Globally, the levelized cost of electricity (LCOE) for solar PV is predicted to fall from an average cost of \$0.085/kWh in 2018 to between \$0.02-0.08/kWh by 2030 and between \$0.014-0.05/kWh by 2050 [5]. Solar power is expected to play a key role in driving the renewable energy growth in the next few decades, which makes a case for investigating innovation and opportunities in penetration of PV technologies.

Solar thermal collectors (STCs) have not kept up with the rising trends of the PV sector. The past several years have actually seen a reduction in additional capacity linked to low attention given to the heating sector energy policies, a decline in China's construction activities, market saturation and strong competition from PV and heat pump systems. Short term and quick changing subsidies without any long term policies have also hindered the product and market development of solar thermal collectors [6]. Despite the declining trend in recent years, global solar thermal

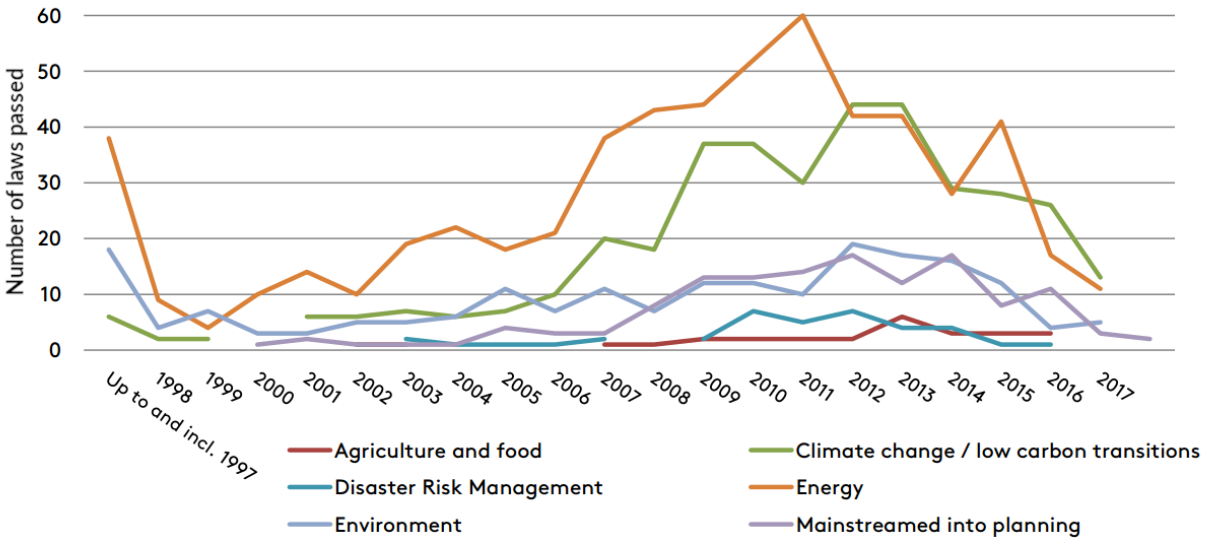

Figure 1: Global focus of new laws passed [1]

consumption is forecast to increase by 40% between 2021-2026, China is expected to be the greatest contributor to this growth, followed by the Middle East, the EU and the US [7].

Photovoltaic thermal (PVT) is a such a technology, essentially combining a PV panel with a STC. As a result, PVT can produce both heat and electricity, and simultaneously increase the electrical efficiency through cooling the PV panel. PVT has potentially a great role to play in the decarbonisation of energy, particularly in urban areas since this technology produces both heat and electricity which could be beneficial for scenarios with limited space.

1.1. The case for focusing on district heating in urban areas

In 2015 the buildings sector contributed to 28% of global emissions, with space heating accounting for almost 30% of building related carbon emissions [8]. This made a case for making buildings a focal point in the investigation on ways to decarbonise heating. Furthermore, it is predicted that 70% of the world's population will live in cities by 2060 [9], therefore, it is essential to explore the future of heating systems in urban areas. The energy technology mix in the decarbonisation of heating will vary from country to country. Various factors will influence technology, such as the climate, energy demand, budget, available space and heat density. In countries such as the UK where heating is currently heavily reliant on gas networks, there remains some uncertainty on the proper mix of low-carbon heating technologies that will replace gas heating. With a call for a global ban on gas boilers by 2025 [10], it is recognised that governments urgently need to develop heat decarbonisation strategies and commit to large scale trials of low carbon heating technologies to build evidence for long-term decision making [11]. In 2019 global heating equipment sales were dominated by fossil-fuel-based equipment and conventional electric heating technology (not heat pumps) making up almost 80% of new heating tech sales [6]. The Sustainable Development Scenario (SDS) forecasts that renewables, heat pump and district heating (DH) will need to make up about 50% of new sales by 2030. International Energy Agency (IEA)'s SDS is a pathway which meets the various global environmental goals and takes into account universal access [12]. It is also viewed by the Institute for Energy Economics and Financial Analysis (IEEFA) as the most likely scenario for the world's energy future [13]. However, it should be noted that the SDS gives just a 50% chance of keeping global warming below 2 °C and relies on the assumption of carbon capture and storage (CCS) being at a commercial scale by 2030, which is viewed by IEEFA as improbable given that current CCS trials are overly expensive. With an urgent need for uptake of non-fossil-fuel-based heating technology and no clear pathway of the makeup of the low carbon heating mix, research and development of alternative clean heating solutions will be vital to meet global emission reduction targets.

It has been found that DH, which utilises various heating sources to supply the demands of an area, remains competitive in heat-dense city areas whereas sparse urban areas with low heat density are more suited to alternative heating options to DH [14], such as single dwelling heating. Building structure and urban surroundings have been found to play an important role in the amount of energy consumed as a "more compact urban form tend to reduce consumption due to lower per capita floor areas, reduced building surface to volume ratio, increased shading, and more opportunities for district heating and cooling systems" [15].

Due to its profitability, one of the energy sources of DH can come from CHP schemes which have been installed in hundreds of DH schemes worldwide [16]. Due to the increased concern of fossil fuel emissions, the viability of combined heat and power (CHP) is reducing. Adopting new routes through biogas combustion or waste incineration, may have a more sustainable outlook [17]. Alternatively, the latest generations of DH have been increasingly integrating renewable energy systems. Various studies have highlighted how urban surroundings also strongly impact how renewable energy DH systems can be integrated into neighbourhoods using compactness and energy density as measures. Furthermore, with new homes now becoming more efficient, lower heating demands enable low temperature district heating (LTDH) to deliver lower thermal losses. This allows for the integration of lower temperature renewable sources such as geothermal or solar, further increasing the viability of the use of renewable resources in DH.

With the development of smart thermal networks the integration of multiple renewable sources, together with different energy storage systems, within DH networks becomes viable. A smart thermal network could be thought of as a parallel to smart electric grids, where the system feeds back real-time data from various parts of the network, which come together and form part of a remote intelligent control system [18]. Wireless metering, sensors and actuators can be used to achieve smart controls, smart heat regulation, optimisation and fault diagnosis which delivers a higher system efficiency and flexibility to integrate with multi-source networks, together with thermal storage. This is particularly important for integrating renewable energy systems to address the challenges that arise from the fluctuating and intermittent nature of some renewable technologies such as wind and solar. LTDH utilising renewable energy sources and smart networks is a concept of DH termed 4^{th} generation DH (4GDH) by Lund et al. [19].

1.2. Solar Photovoltaic-thermal panels with DH

Mohajeri et al. [20] found that compact neighbourhoods had a low energy yield potential for building facades and high potential for roofs of all analysed types of solar technologies. This was due to overshadowing from near neighbouring buildings which is a common feature in all compact neighbourhoods which reduce the PV and passive solar potential on building facades. In contrast, disperse suburban hoods had high solar potential for both roofs and facades for both STC and PV. The roof solar potential had little or no change when comparing compact and dispersed neighbourhoods due to their relatively uniform building height distributions. These findings could be applicable to other compact neighbourhoods with uniform building height distributions. Shubin et al. [21] found that within net zero energy communities, larger community scales cause a decrease in life cycle cost (LCC/m^2) up until a certain point. The greatest impact on LCC/m^2 was achieved at the scale at which the first feasible energy centre reached full possible capacity. It should be noted that due to the fluctuating and diurnal/seasonal nature of solar energy technologies, energy storage is required in order to provide energy when the demand is required. Since PVT panels produce both electricity and heat, electrical and/or thermal storage could be implemented in PVT systems.

1.3. Summary of review

There have been several solar, renewable or 4GDH DH reviews [22, 23, 24, 25] but none of these have included PVT, and no specific comprehensive reviews on PVT district heating have been found. Therefore, this review sets out to summarise, analyse and prospect the current situation of DH, PVT and storage, and the combined application of these technologies integrated within urban areas. Figure 2 shows a visual representation of how three core topics are interlinked together and come together to form the concept of PVT DH with storage in urban areas. Therefore, these three core topics are explored in this review with the following sections: Section 1 outlines the current photovoltaic thermal technology available, limitations, and the current market conditions. Section 2 details the different energy storage technologies available, their advantages and disadvantages and the current state of the market. Section 3 goes on to discuss 4GDH and where PVT DH fits in to this. Although PVT is the main focus of this review, it is important to understand the current situation of other solar technologies. This is because any technological, cost or market developments in PV and STC will also impact PVT, which has components from both technologies. PV and STC technologies are outside the scope of this review and were not exclusively included in this review, however the following papers and reports [26, 27, 28, 29, 30] contain updated technological and market information of both PV and STC technology which can be referred to for further context.

Using the systematic review principles of PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses), records were systematically reviewed in a three phase process. The first being a database search through various sources and identifying potential literature (n=840), the second a screening of the identified literature (n=185) where some records were excluded and the final stage an eligibility assessment where studies were further reviewed and either included or excluded based on the required criteria (n=108). Some keywords used in database searches were related to ’PVT DH’, ’solar energy and storage’, ’4GDH’, and ’PVT reviews’. Data were pulled together from academic literature, governmental reviews, environmental agencies, manufacturers, energy and finance news, and industrial reports to collate some otherwise unreachable interesting conclusions as to a potential future for DH, specifically PVT 4GDH.

2. Solar Photovoltaic Thermal Panels

PVT panels have become commercially available over the past decade. Being able to generate both thermal and electrical energy, PVT also has a greater combined thermal and electrical efficiency compared to conventional solar technologies [31]. This is beneficial when space is limited for heating technologies, such as in urban areas with many flats or terraced houses. With a means to integrate 4GDH in cities whilst taking advantage of the available solar potential and plummeting PV costs, the review has focused on PVT technology. An overview of the current status of PVT technology and the market is provided in this section, which builds up the discussion on the potential for PVT DH in urban areas.

2.1. Solar PVT types and efficiencies

There are flat plate collector (FPC), evacuated tube collector (ETC) and concentrated solar collector (CSC) types of PVT, however, uncovered FPC PVT systems dominated the PVT market with a 57% global share, air collectors follow with a 41% share whilst ETC and CSC types make up a small proportion. Glazed FPC PVT are also less popular making up just 2% of the PVT global capacity share [32]. The thermal efficiency of PVT collectors is slightly lower than STCs

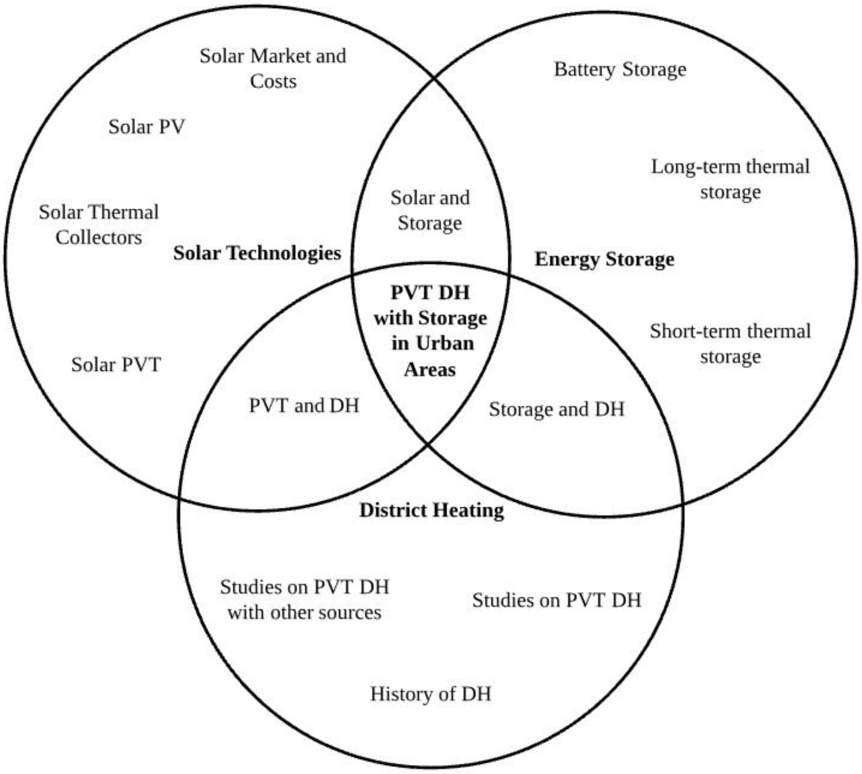

Figure 2: Venn diagram of review paper topics and how they all relate to PVT DH

due to the higher radiative losses incurred as solar cells typically have a higher emissivity. A popular water-based PVT panel's zero loss collector efficiency is 48.6% with a 12.9% PV module efficiency [33]. Zero loss collector efficiency is defined as the efficiency when the heat transfer fluid is at the same temperature as the ambient air. Recent experimental studies have found other thermal efficiencies ranging from 22-65.7% and electrical efficiencies between 10-15.5%. These studies looked at various water-based PVT designs [34, 35, 36]. Recently using nanofluids as the cooling fluid in a PVT system has been found to increase the thermal and electrical efficiency to 84.25% and 14.2% respectively [37, 38].

Solar air collectors use the ambient air to cool the PVT panel, the heated air can be used directly for applications such as space heating, ventilation and drying. Thermal efficiencies are generally lower than water-based PVT due to the lower specific heat capacities and heat transfer coefficients achieved in the cooling tubes and channels. Prabhakar et al. [39] found that the thermal and electrical efficiency for a wavy plate PVT air collector was 34% and 13.6%. Two other experimental studies investigated the efficiencies of a finned PVT air system. The first study found an average thermal and electrical efficiency of 49.5% and 13.98% could be achieved at 0.04533kg/s air flow rates [40]. The second study tested two different collector types, polycrystalline silicon and amorphous silicon, the latter being more thermally efficient by providing 46.8% efficiency with a 5.7% electrical efficiency [41]. Bi-facial PV have been found to generate 30 to 90% more electricity compared to mono-facial PV [42]. By integrating bi-facial PV into PVT by replacing the absorber with a reflector, air-based bi-facial PVT has been found to generate approximately 40% more electricity compared to conventional PVT systems with a similar thermal output to conventional PVT [43].

A recent experimental study of a flat plate water-based PVT found that the electrical output was 6% greater in comparison to a conventional PV panel under the same solar irradiation over three days in the Oman desert [44]. Although environmental factors were not considered such as humidity, wind and dust accumulation, the increased electrical output was in line with other literature [45] and the theory of PVT. The theory being that a standard PV module can reach 110 °C in direct sunlight [46], with a drop in efficiency of 0.452% for every degree Celsius above 25 °C [47], the cooling action in PVT thus minimises the PV performance drop at higher temperatures.

2.1.1. PVT Limitations

A review commissioned by the UK government in 2016 [48] observed that one of the main strengths of PVT technology is a more efficient use of area compared to other solar energy harvesting technologies. Another advantage and key selling point, is that with the removal of heat from the panel which is used for hot water/space heating, there is also a simultaneous increase in electricity production. Several obstacles to the growth of the PVT industry identified in the report were little industry involvement, lack of operational demonstrations, lack of awareness of the technology, and the complexity of installations compared to other solar technologies.

Whilst there are already several well established PVT manufacturers with products readily on the market, a lot of commercial PVT collectors still need some development coming in at technology readiness level (TRL) 8 on the NASA scale from level 1 (a concept) to level 9 (deployed in market) [49]. It is noted however, that a study commissioned by SwissEnergy, concluded that there are readily available uncovered, liquid-cooled PVT collectors which can be successfully implemented into operation; whilst generally covered or air cooled PVT collectors are not yet as widely available and some still require further development [50]. Typically PVT alone cannot supply all the winter space heating requirements, therefore there must be a drive to package it with another renewable energy system, such as heat pumps, to provide a system useful for the needs of domestic properties [51, 52]. Certainly, awareness and training could be raised amongst heat pump industries as to the benefits of using PVT as a heat source, this could be achieved through articles/reports and more presence at fairs and conferences to disseminate best practises and case studies [49]. Together with the progressive technological improvement of PVT, there is an opportunity to incorporate these systems in new builds as developers are encouraged to install renewable technologies, not only due to them on average increasing the property values [53] but also, as a result of the recasting of the Energy Performance of Buildings Directive (EPBD) to create zero energy buildings [48, 54]. This future uptake of PVT will have to be coordinated with improvements in the aesthetics together with optimisation of the configuration of the system [55] and the standardisation of PVT certification. When reviewing the PVT products in the market, there was a varying degree of maturity to different products with some showing minimal information and still undergoing certification. Solar heating and cooling (SHC) task 60 outlined the need for a combined all in one testing procedure for PVT, which also enables subsequent design changes to be covered at a lower cost. PVT certification development needs to be continued following on from work SHC Task 60 carried out with ISO and Solar Keymark [49]. Additionally, being new to the market, there is less experience in understanding synergies between the thermal and electrical generation in PVT, and how it may change throughout the products lifetime, an important area that will require further study and inclusion in the product data-sheets.

Work done under the SHC Task 60 has been hugely valuable to PVT progression; with deepened knowledge, standardisation and data outcomes it is anticipated that this will lead to positive progression observed in the market. Further collaborations, tasks and studies which widely share findings would create a further positive impact on the PVT market, ultimately increasing the building community/consumer confidence and awareness of the technology.

2.1.2. Solar PVT Market

The IEA SHC 60 assessed the viability of PVT technology. Being a new technology, Task 60 participants worked to accelerate market acceptance and commercial knowledge of PVT by developing best practice guidance. The task group observed an increase in PVT companies manufacturing high-quality systems. In spring 2020, 31 companies from 12 countries provided sales figures. Figure 3 shows how the PVT market has seen a steady global growth of an average 9% from 2018 to 2020. In 2020 Europe made up 57% of the total installed PVT collector area, with France accounting for 39% of capacity in Europe, with air-cooling PVT units dominating the single-family housing market [6, 30]. Historically, installers of residential PV have been more confident working with air cooling PVT instead of water or glycol. However, there has been an increase in the number of plumbers that have been trained to install PV, which has been leading to an increase in water-cooled PVT systems being installed. Although air-cooled PVT made up 37% of the global share of PVT at the end of 2020, a trend towards water-cooled PVT on multi-family/commercial properties is expected as experience increases and because water-based systems are more efficient than air-cooled PVT

[30, 56]. In Europe, Germany and France have been the only countries to have government policies and incentives in place specifically for PVT technology, which explains why they are the 2 leaders for PVT in Europe. Other countries have separate schemes for either PV or STC, though PVT is not always eligible for the funding, particularly in STC subsidy schemes that are not well prepared and are sometimes unfavourable for PVT. Task 60 recommended that the development of separate PVT subsidy schemes was required to simplify the situation rather than integrate PVT into existing STC and PV schemes [57]. Germany and France also have several well-established PVT manufacturers, no doubt local manufacturing, experience and marketing will play a part in PVT market growth in these countries.

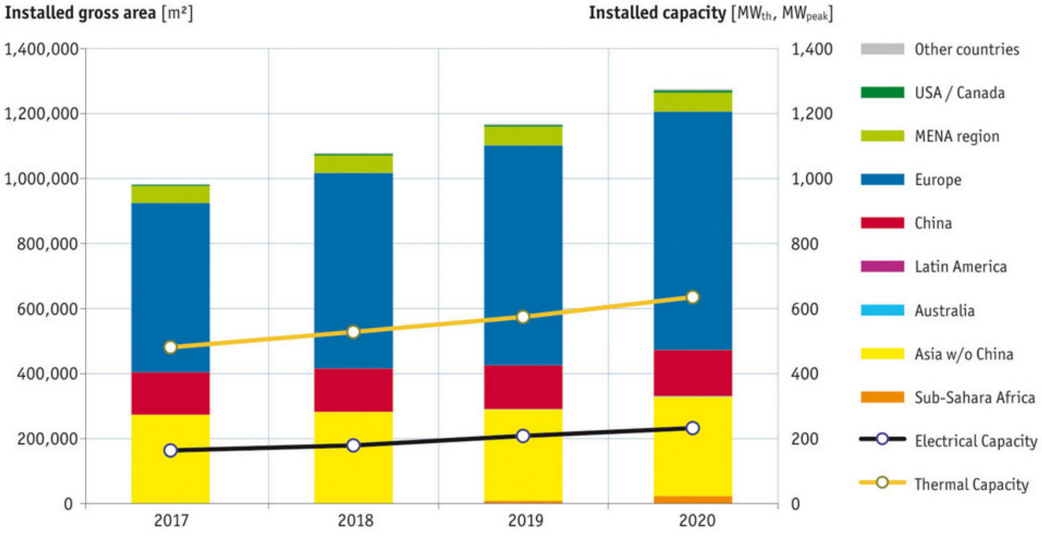

Figure 3: Global market development of PVT from 2017 to 2020 [30]: IEA SHC Task 60

In general the PVT industry has been slowly growing but currently facing strong competition from PV due to it being a more mature market with plummeting costs and more subsidy schemes in place. However, with opportunities such as the EU new green deal and the renovation wave strategy, which will improve building energy performance, PVT could become a prominent technology with the right support and interest. The PVT sector will need to be prepared to make a strong case and heard in order not to be excluded by policy as has previously happened. Renovation rates are currently low in Europe, with the weighted energy renovation rate at about 1% of the existing building stock each year [58]. As part of the renovation wave strategy for meeting a 55% emissions reduction target by 2030 based on 1990 levels, fresh investment over a sustained period will help overcome barriers for implementing energy efficiency renovations. The annual renovation rate target is set to double from the current 1% annual renovation rate by 2030. It should be noted that a quantitative analysis of the renovation wave by Buildings Performance Institute Europe found that a higher renovation rate and depth will be required to contribute to meeting the 2030 emissions reduction goal. It was concluded that the target should be corrected and quickly be increased from the annual deep renovation rate of 0.2% to 3% [59]. The European Commission state that one of the principles and benefits for increasing the building renovation rate is that it will also enable the integration of renewable energy sources to be implemented faster. This opens up exciting possibilities for 4GDH networks which could become another viable approach to consider when selecting heating strategies. The IEA task 60 group identified that with developments in 4GDH, where LTDH is being trialled and put forward as future options for expanding the decarbonisation of heating and cooling, PVT coupled with heat pumps could play a significant role in both distributed and centralised solutions [49]. Air source heat pumps are currently too noisy to be installed in certain dwellings, this could be overcome by using unglazed PVT collectors as the source for heat pump. It has also been identified that with the development of low energy buildings, building integrated PVT are a promising way to further reduce building energy consumption by reducing the heating or cooling loads of HVAC [60]. Another opportunity identified is in seasonal storage opportunities for PVT where otherwise wasted heat can be utilised during low solar heat output periods. Likewise, short term storage such as batteries could also be used with PVT to provide an uninterrupted electrical power supply.

3. Storage

Increased deployment of intermittent renewable energy has fuelled high cost and technological improvements in the energy storage industry. This has come about from increased manufacturing capacity, huge investments and increased R&D activities, which were largely focused on short-term storage such as battery technology [61]. Storage technologies have increasingly gained interest and research efforts since they can add numerous benefits to renewable energy systems; increased system flexibility, improved energy source utilisation, energy security and demand response flexibility. A study assessing the performance of a decentralised solar thermal system feeding into a DH network interestingly found that larger roof areas for the solar collectors did not always lead to greater cost savings due to the asynchronicity between the high solar energy conversion times and the occupant's energy demands [62]. The same conclusion can be assumed for PVT systems as they are solar collectors. This, therefore, supports the need for studying how thermal and electrical storage could support PVT systems by utilising energy storage and supplying on-demand, such systems could potentially decrease both the total heat generation capacity and overall costs [63]. The following sections outline the electrical and thermal storage technologies which could be used in conjunction with PVT. An overview of technology types is provided describing the pros and cons, how they are currently used in DH, and this leads to a discussion on the potential for PVT DH and storage in future systems.

3.1. Electrical

Since PV generation occurs during sunlight hours, which may not match demand hours, battery storage could help to improve the self-consumption of PV systems. In addition to increasing PV self-consumption, battery storage can also overcome grid overloading issues, which has become a problem in many countries, by charging them up with the excess electricity generated rather than sending it to the grid. When there are other PV systems in the area, if electricity is sent back to the local grid distribution, this could contribute to oversupply issues and lead to excessive voltages which can cause numerous issues such as equipment damage and the PV system tripping out.

3.1.1. Electrical Storage Market

Annual energy storage deployment increased from about 0.2 to 3.3 GW between 2013 and 2018. In 2018, Korea was accountable for almost one-third of energy storage deployment, however, installations fell by 80% in 2019 due to numerous fires at grid-scale storage plants in 2018 [64]. After a review, further fire and safety measures were implemented but five more fires occurred in 2019. A second enquiry discovered that the cause of fires were the batteries themselves. The controversy led to a loss in consumer confidence and a shrinking of the battery market in Korea. The decline of annual energy storage installations in 2019 demonstrated how batteries are still heavily reliant on policy intervention which creates direct support or marketing opportunities. The phase-out of solar feed-in tariffs in 2019 in Japan, pushed battery storage PV sales and installations with it reaching over 200 MW of annual installations in 2019. The removal of feed-in tariffs provided consumers with more incentive for self-consumption of electricity through battery storage, as opposed to previously exporting to the grid. Elsewhere in Asia, India approved a 1.2 GW large scale auction of a solar PV and storage system with a storage capacity for 50% of the electricity generated. Singapore set a target of 200 MW of storage post-2025. Concerns have grown over grid resilience due to wildfires in 2019 in California, this has encouraged a growth in storage and PV systems, with 10,000 systems sold in 2019. Other states in the US have committed to long-term storage targets. Similarly, the European Commission has demonstrated strong long-term support for energy storage, where storage has been made exempt from being double-taxed during both charging and discharging.

Some areas of Australia do not allow buildings to export surplus PV energy to the grid or require permission for PV connectivity where it may be denied if it could cause oversupply issues in the local area. For this reason, home energy system installations have grown in recent years, with 2020 seeing about 31,000 installations, gaining a 20% growth compared to 2019. Almost 10% of all new PV systems included a battery system in 2020, and it is predicted that 2021 will have a further 33,000 home energy storage installations [65]. Virtual power plants (VPPs) have been gaining interest in Australia since the successful demonstration of a prototype system that connected many PV and battery storage systems across 1000 residential and commercial buildings in Adelaide [66]. The project was announced in 2016, being the largest VPP at the time, which integrated residential battery storage globally. The system was all managed in a cloud-based control system. Using smart controls, the batteries could communicate to form a connected system that could operate as a 5 MW solar power plant. The VPP prototype proved its capability to create value for consumers, networks and wholesale market participants by reducing customer bills, managing and reducing grid network peak demands, wholesale cap trading and the ability to provide other grid diagnosis support services. The project in Adelaide has acted as a catalyst for the VPP market both in Australia and internationally.

With an increasing demand for battery storage, largely dominated by lithium-ion batteries, Figure 4 shows the low, mid and high cost projections developed by the National Renewable Energy Laboratory (NREL) to 2050 for the capital cost for utility scale battery systems. All projections have a predicted cost reduction to 2030. The IEA has stated that renewables will be vital in meeting global emissions reduction targets in the electricity generation sector. They have forecast that renewable energy (mostly wind and solar) will need to account for 88% of the global share of the electricity sector by 2050, a significant rise from the 29% share in 2020 [10]. Such a significant rise in intermittent renewable energy will help to drive the battery market sector, which will also naturally drive down costs due to the demand and research resources invested into the technology to become more competitive.

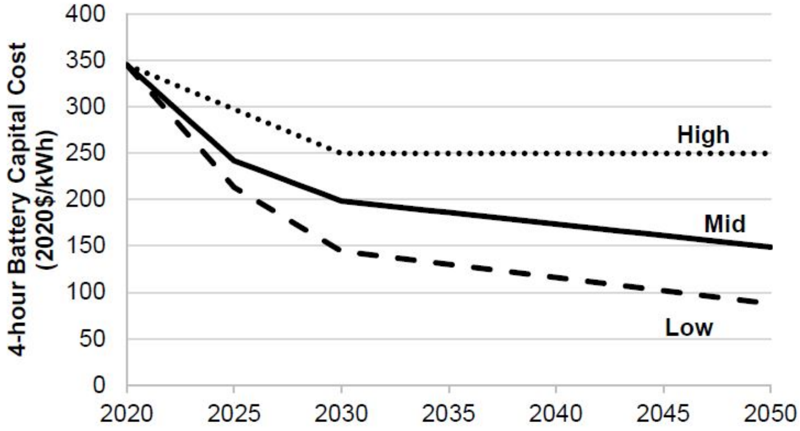

Figure 4: Battery storage cost projections per kWh from 2020 and forecasts to 2050 [67]

3.1.2. Electrical Storage Technologies

To date, lithium-ion (Li-ion) batteries still make up the majority of the new battery storage capacity installed. With the electric vehicle (EV) market being ten times greater than grid-scale batteries, Li-ion batteries have benefited indirectly in innovation and cost reduction [64]. Table 1 summarises the pros and cons of various other battery types in the market. Lead-acid batteries have been used in solar PV and storage systems because they have cheap upfront costs and are a mature and well-understood technology. However, the lifetime of lead-acid batteries is shorter than Li-ion, therefore Li-ion is considered a premium technology with higher efficiency, energy density and lifespan with lower long term costs. Despite the lower long term costs, Li-ion have higher upfront costs compared to lead-acid batteries, they also have issues with sustainable manufacturing and no solution for its recycling has been developed yet. With current large scale production, it is also forecast that essential metals for Li-ion batteries could be depleted in less than 30 years [68]. For this reason, there is much research into alternative promising battery types. Redox flow batteries are a promising upcoming technology and have recently acquired large sums of funding from the US and Saudi Arabia. Sodium sulfur batteries are another promising non-lithium based battery, which has a longer duration than Li-ion but currently has higher upfront costs.

3.1.3. Electrical Storage and PVT Integration

Several studies have assessed PV in conjunction with battery storage; these studies mainly analysed the system from an economics or life-cycle-analysis perspective [70, 71, 72, 73]. A techno-economic study by Parra et al. [70] compared the use of Li-ion batteries, lead-acid batteries, and hot water storage tanks for PV storage systems within an average UK dwelling. It was found that hot water tanks ranging between 100 l and 200 l were the most economic option in the UK, especially for properties that already had a storage tank that was previously heated using the grid. This was due to the higher life time costs of the battery storage systems coupled with the smaller ratio of PV power that they were able to capture compared to hot water tanks. However, the water tanks could only be used for DHW, whilst the

Table 1
Battery technology types [58, 69]

Technology	Pros	Cons
Sodium Sulfur (Na-S)	High energy density, charging and discharging efficiency and long cycle life.	Thermal management is required, thermal self-discharge, safety concerns from a sodium-sulfur reaction.
Lithium Ion (Li-ion)	Very high energy density, low maintenance, no priming required, relatively low self-discharge and high rated voltage.	Highly reactive and flammable, recycling programs and safety measures are required, natural degradation and ageing effect.
Redox Flow	Independent energy and power sizing, scalable for large applications, a longer lifetime with deep discharge and long cycle life.	More complex than conventional batteries, early development stage, high cost of vanadium and current membrane designs.
Lead-acid	Cheap, maintenance-free, mature technology, low self-discharge and high discharge rates.	Low energy density, a limited number of full discharge cycles, environmentally unfriendly, transportation restrictions and cannot be stored in a discharged condition.

battery systems could be used for electricity. The study concluded that battery storage may be more cost effective in other scenarios, such as if governments incentivise their use through legislature. With the removal of PV feed-in tariff subsidies and a shift towards the electrification of heating through heat pumps, the case for battery storage may now be stronger in certain scenarios. Urban areas with a high energy density could store excess PV power in batteries for later use when there is demand. In a heating scenario with PVT, electricity could be used to power additional heat pumps, auxiliary electric heating or even used directly as electricity. To make battery costs financially attractive in lower insolation regions, such as the UK, battery costs will need to continue to be rapidly reduced. Additionally, there needs to be subsidies that will create revenue from electricity generation [71].

Similarly to PV, battery storage can be used with PVT technology to improve system reliability and prevent energy supply intermittency. With promising advancement in both market and technology projected for battery storage, batteries could play an important role in future integrations of PVT systems. A study by Jafari et al. [74] analysed a system consisting of PVT modules, a fuel cell stack and battery storage to meet domestic hot water and electricity demands over the course or a year. Hydrogen was produced with any excess electricity and hot water from the PVT. The fuel cell used the generated hydrogen as required to meet the domestic hot water and electricity demands. It was found that a PVT/fuel cell (16kg of hydrogen)/battery storage system (80 kWh) operating under 8 consecutive days of cloudy weather had a 40% and 15% lower total net present cost and capital cost compared to an equivalent system with PVT and just battery storage (580 kWh). These 2 scenarios were found to be the optimal battery and hydrogen storage capacities for each system configuration. Therefore, battery storage with PVT was found to be more desirable for short-term storage such as during the night, with the generated compressed hydrogen being used for longer-term storage such as on consecutive cloudy days. Larger battery banks not only increase cost, but if stored over a longer period of time, the efficiency is reduced as the battery depletes its charge. It was not stated which battery technology was used in this study; different technologies could certainly produce varied results comparatively. Nevertheless, careful sizing and design of battery and PVT integration is always important. If the battery bank acts as the sole back up for electrical demand and it is met by an excessive demand, the battery life and performance will be depleted if the battery state of charge surpasses the recommended depth of discharge. Also in a DH scenario, Pakere et al. [75] found that there are economical benefits of converting excess electricity into heat, if the market price of electricity is lower than a DH heat tariff, therefore, battery storage may not be the most economical choice in certain PVT DH scenarios. This is further discussed in Section 4.

3.2. Thermal

It has been shown that DH system costs have been reduced with more use of fluctuating renewable energy sources for heat production and thermal storage [25]. There are various thermal storage technologies available, which would

Table 2
Thermal storage types [69, 76]

Technology	Pros	Cons
Molten Salt	Exceptional heat transfer capability, commercial and low cost, integration with CSP lower the levelised cost of electricity (LCoE).	Molten salts can be corrosive, must not be allowed to freeze, limited to CSP technology for power applications.
Hot Water Tank	Low cost and maintenance, simple installation.	High thermal losses over time, take up a large amount of space.
PCMs	High density of energy and can maintain a constant temperature.	Long pay-back period, repairs require damage to the system and low thermal conductivity.
Seasonal storage	Low thermal losses, long term storage	Can only be installed in sites with the available space

be selected based on the application, system size, location and budget. Table 2 shows a summary of the pros and cons for each technology.

3.2.1. Molten Salt

Molten salt storage is commonly used in large concentrated solar power (CSP) plants, it provides a continual on-demand supply of thermal power which removes the need for additional backup systems. Molten salt is typically used with CSP technology since the operating temperature ranges from 150 to 560°C, which is compatible with steam turbines used in the plant to produce electricity [77]. Gordon et al. [68] recently studied the novel unconventional use of molten salt conjunction with PV systems. When PV systems had excess electricity during peak sun hours, the power was used to resistively heat molten salt. The heat could be released to turn steam turbines when demand was needed later. A benefit of this method is that it utilised 2 mature relatively low-cost technologies, molten salt and PV, that are both ready for off-the-shelf implementation of the 2 technologies. Interestingly, this method of PV and storage allows for geographical separation of the PV and storage systems. Battery storage can also be separated from PV, however, it would require DC-AC-DC conversion, which would all incur some conversion losses. However, the conversion losses from using battery storage are minimal compared to the efficiency of steam turbines, which can be around 50% for electrical conversion. Note that CHP generator efficiencies can exceed 80% though [78]. Despite a lower overall system efficiency, this method presents itself as a viable solution for immediate implementation and expansion, not limited by material availability. The study also found that the solution has favourable economics, which could make a case for lower system efficiency compared to battery storage.

3.2.2. Hot water tanks

Thermal storage at a district capacity can have benefits over single dwelling storage. For instance, a larger hot water tank will have lower thermal losses and lower costs per unit of capacity compared to a smaller hot water tank for a single dwelling [79]. With DH systems typically using water as the heat carrier, water is often a suitable storage medium for DH storage systems. With a high heat capacity, availability, chemical stability, low cost and suitable temperature range for DH operations, water tanks can also have a wide range of capacities and charge/discharge rates [22]. Despite being a simple technology, well-designed integration of hot water tanks into DH systems is important. The capacity, configuration, number of tanks and control system can greatly affect the PVT and overall system functionality and performance.

3.2.3. Phase change materials

Organic compounds such as paraffin, alcohols, and fatty acids have been found to be promising low-temperature phase change materials (PCMs). This is due to their high thermal conductivity, chemical stablity, non-corrosiveness, non-toxicity and have melting points between minimum subcooling and the operational temperature of PV panels [80]. Phase change slurry (PCS) can also be used with solar energy, where both sensible and latent heat storage are produced and as a result more heat can be absorbed from the PV panel and transferred to the PCS [81]. Numerous analytical and experimental studies have demonstrated the potential for PCMs or PCS' being used with PVT or PV. Improvement of electrical efficiency was obtained by cooling the PV panels, whilst storage for the generated heat was used during non-sunlight hours [82, 83, 84, 85, 86, 80, 87, 88].

Atkin and Farid [83] performed an experimental and MATLAB-based simulation on the performance of RT40 (Paraffin) combined with graphite placed within an external heat sink for PV cooling. The heat sink reduced the PV surface temperature by 19 °C and raised the PV efficiency by 12%, the PCM-graphite combination improved it by 4% overall. Another study investigated the performance of vertical PVs found the electrical output increased by about 3% with the PCM [82]. However, the PCM effect of decreasing the PV module temperature was not as significant in winter due to the lower outdoor temperatures, despite high solar insolation. The study did not discuss or investigate how PCM-PV technology could be used in the context of PVT to produce both heat and electricity. Chen et al. [81] experimentally tested the performance of a PCS-based PVT system. Two systems were compared, one with water as the working fluid and the other with 30% alkyl hydrocarbon PCS. It was found that the daily average overall efficiency of the PCS-based system was 9.7% higher than the conventional water based PVT system. Another study experimentally investigated the performance of a palmitic acid PCM added underneath a PV panel, this was found to improve both the PV efficiency and increased the thermal extraction from the PV up to seven times when to a conventional PV Browne et al. [84]. There could be some interesting potential in the PCM-PVT integration into building facades [80]. Commercially, a company has patented a PCM based heat battery which is up to four times more compact that conventional hot water tanks and lower heat losses. The heat battery is compatible with a variety of energy sources such as PV and heat pumps [89].

3.2.4. Seasonal thermal storage

Seasonal thermal energy storage, such as ground source heat pumps (GSHP), can be useful for solar energy systems due to solar energy's seasonal nature, which has high solar insolation in summer and lower in winter. In addition to low solar insolation in winter, the ambient temperature is also lower, which reduces solar thermal systems efficiency. Having one larger centralised system installed, GSHP-PVT DH systems benefit from greater overall system efficiency and lower costs when compared to equivalent single dwelling installations of the same capacity. This was highlighted in the study by Canelli et al. [90] where a GSHP-PVT system supplying electricity and heating/DHW to a residential and office building in Napoli (South Italy) was modelled. The study highlighted how the micro-generation system had a technical and economic advantage compared to two single building systems.

Xia et al. [91] demonstrated how GSHP-PVT systems can improve long term system performance by maintaining the ground's thermal energy with charging from the PVT. Xia et al. [91] investigated the integration of a GSHP-PVT with an Australian two-storey house; the system supplied space and water heating and the system operation was modelled across 20 years. The first scenario did not have ground charging from the PVT, this resulted in a decreasing ground temperature over time. In senarios 2 and 3 (with PVT ground charging) the temperature remained relatively stable since the ground's thermal energy was maintained. Over the 20 years, the decline in ground temperature in scenario 1 resulted in an increase of power consumption since the heat pump needed to gradually work harder, whilst energy consumption remained constant in 2 and 3. Since the climate profile was the same for each year over the 20 years, there was some uncertainty in how the ground temperature may be affected when subjected to different projected weather profiles. The PVT electrical performance was not discussed even though it would have differed from conventional PV due to the thermal interaction within the PVT, PVT inlet temperatures were not provided in the study.

Given that the electrical output of PVT systems benefit the most from cooler inlet temperatures, it would be interesting to investigate how different configurations and controls could affect and improve the PVT electrical efficiency. Configurations and controls can make a huge difference to PVT and heat pump performances as demonstrated by Dannemand et al. [92] where a 2 tank configuration was connected to a PVT solar assisted heat pump (SAHP) system. The cold buffer storage tank linked to the source side of the heat pump functioned well, however, the heat pump COP was affected by temperature fluctuations in the cold buffer storage tank. In winter in Denmark, the heat pump COP could reach 3.4 at 12:30 but would drop to 2.3 once the cold tank decreased to 7°C. This demonstrates further how important well-designed controls are in optimising such systems and where further work could be carried out in the control for PVT-SAHPs.

3.2.5. Thermal Storage and PVT DH Integration

Great potential has been demonstrated for the use of various readily available thermal storages which could be used in PVT DH systems. Thermal storage can provide both short or long term storage to overcome the fluctuating nature of solar based technologies. No studies have been found specifically for control strategies of PVT DH with thermal storage, however they have been carried out for single dwelling systems. A study by Xia et al. [93] on GSHP-PVT systems found that the use of simplified adaptive models combined with the least squares estimation technique were capable of providing reliable system performance predictions. Compared to a conventional control strategy for the entire cooling, heating and transition (ground charging by PVT phase) periods modelled, the optimal control strategy in this study was found to save energy consumption by 7.8%, 7.1% and 7.5% and raise electricity production by 4.4%, 6.2% and 5.1%, respectively. Andrew Putrayudha et al. [94] found that their developed fuzzy logic controller was able to reduce the energy consumption by 18.3% of a GSHP-PVT system for a single dwelling in South Korea, when compared to a conventional on-off controller. This demonstrates how important advanced control strategies could be, especially when there are relatively high capital costs for both GSHP and PVT. These control strategies play an important role in the design optimisation and increase the feasibility. Further development of PVT DH-thermal storage control strategies, which are ready for use in real-time installations, would be beneficial to progress this option for 4GDH systems.

Even though STC-thermal storage DH systems are established, it is difficult to apply the same control strategies to PVT DH systems. PVT collectors have the added complexity of the integrated PV cells. Their temperature needs to be kept down in order to keep the PVT electrical efficiency from dropping due to temperature de-rating. In contrast, it would be easier for PVT-battery installations to follow similar control strategies to PV-battery systems. PV-battery systems and control strategies are well developed, already implemented widely in the market and used in current PVT installations [95]. There is a wide range of off-the-shelf inverters and solar charge controllers available with advanced customised controls, which can be programmed as desired.

4. District Heating

The drive to decarbonise energy-dense areas such as urban environments creates an opportunity for DH networks. These can optimise the conditions to fully utilise single or combined renewable sources to fulfil the heating and/or cooling requirements for a network of buildings, where the use of these sources would not be possible for individual dwellings. PVT is one such renewable resource where its uptake could benefit from the increase in DH installations. The following section will give a summary of the status of DH, disadvantages and benefits of such systems and the current situation for PVT DH installations and studies. There have been five generations of DH, each new one achieving a greater efficiency at lower heat source temperature levels. The fourth and current generation (2020-2050) is referred to as the LTDH or ULTDH depending on the temperature levels being used by the network. They can supply both space heating and domestic hot water. These DH networks will need to meet current challenges such as distributing heat with low grid losses, the ability to integrate with smart energy systems and ensure it is a strategic investment in line with transforming a sustainable future energy system [19].

With a promising technical potential for PVT DH, it should be noted that it shares disadvantages common to DH which include additional heat losses from transmission in pipes, high investment costs and the organisation structure of DH projects can be complicated with numerous third parties or stakeholders involved. DH also requires the necessary labour with technical experience and skills. Considering these limitations, it can result in lower heat demands, higher heat production costs, and a higher heat tariff for the consumer [96]. Ultimately, end-users will consider other alternative heat technology options if the DH heat tariff is too high. Strict legislation and lack of experience and knowledge in renewable energy integrated DH are why there are limited numbers of large scale renewable energy DH systems. However, the EU has been updating directives and providing policies and funding to help overcome these barriers [97].

PVT DH does also share many of the benefits that solar thermal DH systems have over other renewable sources. The energy source's global availability, not requiring any fuel, such as biomass, to generate energy, neither requiring specific locations to gain such energy, such as required for geothermal energy. This allows for greater flexibility in the installation location, utilising the roof area on buildings, urban wastelands or even landfills [79]. Furthermore, they can be installed close to the demand centres to minimise transmission losses. PVT also has the additional benefit of generating electricity and heat, with surplus energy being placed in electrical or thermal storage for later use. If there is a pre-existing DH network, PVT like solar thermal can be easily integrated into it. Overall costs of solar technologies are steadily declining compared to other renewables, especially when considering the running costs, which do not require fuel to be bought/made.

Over the past decade, there has been an increase in the uptake of renewable DH [98] and globally, countries are deploying DH to fulfil their heating needs. In 2014, Russia, China and the EU made up about 85% of global DH heat deliveries. By 2017, about 6000 DH networks were supplying 11-12% of the total heat demands of Europe [99]. In 2020, globally, renewables accounted for 14% of District Heating, this was up from 8% in 2015. It is predicted however that the renewables share will only grow to 15% by 2025 with the majority of the increase taking place in China and Russia which currently make up a combined 70% of district heat consumption, yet make up less than a fifth of renewable DH [100].

4.1. PVT DH Installations

As of 2020, there were 64 PVT DH systems installed in the world [30]. This was up from the previously reported 6 PVT DH systems which came from 2018 data within the 2019 Solar Heat Worldwide report release [101], this was the first time PVT was included in the solar heat worldwide report. The most recent 2021 report stated that *in recent years, a growing number of specialised providers of PVT technologies have established themselves, developing strong market momentum worldwide* [30].

With Switzerland's growth in GSHP technology and with PVT prices also dropping in recent years, this has in turn raised interest in HP assisted PVT systems. Uncovered liquid-cooled PVT collectors are the most regularly used collector type since it is suited to low-temperature applications since low-temperatures is where this technology achieves the greatest thermal output and electrical efficiency due to the PVT cooling effect. The use of this type of PVT collector is particularly beneficial in being used as the source side of heat pumps, it can also be used for other standard space, water and swimming pool heating applications.

Table 3 shows an overview of PVT DH installations, the table source comes from a combination of IEA task 60 documentation [95] and the 'PVT WrapUp' report from the SPF institute for solar technology [50]. The SPF institute of solar technology has documented various PVT pilot and demonstration projects: there are 6 district heating scale installations detailed, which became operational between 2016 and 2019. All installations used uncovered liquid-cooled PVT (130-3487m^2), with borehole fields consisting of vertical boreholes of varied depth connected to heat pumps. Only further operational details are provided for most of the PVT DH systems based in Switzerland. In the Nafels installation, over a period of 2.5 years, the yearly average additional electrical output from the PVT modules compared to the equivalent conventional PV modules was 5% due to the PVT cooling effect. This varied throughout the year due to weather and demand variance, being able to reach 9.33% on a sunny day in July. It was found that pre-heating the groundwater reduced the heat pump's electrical consumption, which amounted to being 3 times greater than the increase in electrical PVT yield. The savings of this was equal to about 17% of the annual production from a comparable PV system. With the heat output being low from PVT in winter, it was noted that applications with high summer thermal demand (sports centers, hospitals and hotels) could be most suitable for this system. 80-90% of the PVT thermal energy was used in the complex, with the remaining used to heat the groundwater. Since the PVT cooling water was taken from the tank used for pre-heating the groundwater tank, which also fed the heat pump source side, it was found that the PVT modules could not always be optimally cooled. The PVT inlet flow could rise up to 25 °C, which resulted in the PVT module temperature rising to 36 °C (the conventional PV cells reached 63 °C at the same time). Any cell temperature above 25 °C results in a $0.370\%/K$ power reduction according the PVT data sheet used in this installation. However, it also led to greater electricity savings from the heat pump operation. Similarly, the installation in Rotkreuz also came across some conflicts in the PVT-GSHP DH combination system. During summer, the PVT had to be turned off during periods of high irradiation to ensure that the groundwater network was kept below 17 °C as it was used for free cooling in summer. In Switzerland, the consideration of PVT operation under snowy conditions needed to be considered. The Nafels installation initially planned to melt the snow away with the groundwater heat, however, this was not possible since snow had also built up underneath the PV modules. As a result, the controls were adjusted to heat the PV modules whilst snow was falling to prevent it building up. However, due to the relatively low solar insolation during these times, it was questioned whether these controls were worth it for the small output. Other technical issues arose with inverter failures (across both PVT and PV systems), poor flow through the PVT meaning it had to be rinsed and de-aired and loss of system sensor measurements [102].

Table 3
Table summarising PVT DH Installations

City, Country	PVT Area (m^2)	PVT Type	System Description	Project date/completion
Ostermundigen, Switzerland	1320	Uncovered PVT	PVT & GSHP system, with PVT primarily regenerating the borehole fields during the summer. Each of the three buildings had 2 heat pumps, for HW and space heating. Each building had about 100 apartments. Heat pumps drew heat from either the borehole field or PVT system.	2014-2019
Reka, Switzerland	672	Uncovered PVT	Vacation village consisting of 60 apartments, reception, swimming pool and community centre. PVT & GSHP system supplied space heating and DHW at 45-60°C.	2014-2016
Rotkreuz, Switzerland	3487	Uncovered PVT	PVT & GSHP with PV supplying space heating DHW via individual heat pumps in each building. There were eight apartment houses and one school/office building. Buildings were cooled in summmer by free cooling via the ground storage and PVT heat was stored in the ground storage in summer.	2012-2016
Nafels, Switzerland	292	Uncovered PVT	Multipurpose complex containing sports centre, hotel and retaurant with PVT collectors and 1146m^2 PV collectors of the same electrical specifications supplying hot water to the complex via two water/water heat pumps. The heat pumps drew water heated by the PVT via heat exchanger from the groundwater storage tank. By the PVT increasing the heat pump's source temperature, it reduced the heat pump electricity consumption.	2014-2019
Scuol, Switzerland	130	Uncovered PVT	PVT-GSHP system supplying DHW and space heating to a building comprised of 8 apartments. PVT heat was used as both a direct source for the heat pump and for direct DHW preheating. The PVT primary use was DHW, secondary was space heating and ground charging via the brine buffer storage was third priority.	2015-2018

Table 3
Table summarising PVT DH Installations

City, Country	PVT Area (m^2)	PVT Type	System Description	Project date/completion
Obfelden, Switzerland	294	Uncovered PVT	PVT GSHP system with U-pipe boreholes and air/water heat exchanger supplying hot water to a total of 118 apartments.	2015-2020
Balearic Islands, Spain	147.6	Covered PVT	PVT panels supplying DHW to the storage tank, a gas boiler was used as an auxiliary heater to maintain the 9000L tank at 60 °C. PVT electricity was used in the resort, with grid as back-up.	2017
Alfajarin, Spain	264	Covered PVT	HW for truck washing. PVT panels heated process water to between 40 °C and 60 °C stored in 6000l tanks. When the tank temperature was lower than the setpoint the boiler heated it up.	2019
Canary Islands, Spain	200	Covered PVT	DHW for hotel and swimming pool. PVT heated DHW to between 40 °C and 70 °C, the outlet of the primary PVT 10,000L tank was connected to the existing tank which was heated to maintain the set point with a boiler.	2019
Sant Cugat, Spain	264	Covered PVT	Sport center DHW and swimming pool with PVT electricity used for self-consumption. PVT collectors heated water in 160,000L storage tank with back-up gas boiler, temperature range was 30 °C to 70 °C. The system contained a seasonal storage tank. 26% of electricity demands were met by PVT.	2019
Azud, Spain	55	Covered PVT	DHW for multi family home. PVT collectors heated a 300L tank, with the outlet of the primary tank feeding a secondary tank which had a back up gas boiler to maintain the temperature. Application temperature range was 40 °C to 60 °C. 60% of electricity demands were met by PVT.	2019
Sete, France	300	Uncovered PVT	Preheating swimming pool and DHW. PVT collector preheating a tank prior to the heatpump/gas boiler heat exchanger network.	2016.
Perpignan, France	300	Uncovered PVT	Same system as the Sete installation.	2016

Table 3
Table summarising PVT DH Installations

City, Country	PVT Area (m^2)	PVT Type	System Description	Project date/completion
Prerov, Czech republic	188	Uncovered PVT	DHW and space heating for multi family house. PVT primary use was for DHW 500l tank, sencondary use was for 300l storage tank feeding heat pump source, third priority was regeneration of boreholes. PVT electricity used for heat pumps and house consumption.	2014
Egedal, Denmark	165	Uncovered PVT	Space heating and DHW for sport club. PVT collectors supplied heat to a buffertank via heating coil. On warm summer days, the buffer tank could be heated up to more than 60 °C, during cooler days, the PVT supplied heat to ground storage which was used by the heat pump when required. A back up brine/water heat pump was used. The application temperature range was 25 °C - 60 °C.	2017
Katwoude, Netherlands	226	Concentrating PVT	Electricity for cheese production and HW for cleaning in a cheese factory. Concentrating PVT collector system was producing roughly $8m^3$ of water at 45 °C, where HW was needed 5 days a week at the factory. The PVTs pre-heate the tank to about 30 °C in winter and 75 °C in summer, where an $8m^3$ hygienic storage tank was positioned between the collectors and back-up gas boiler. A mixing valve delivered water at 45 °C to the factory, in 2018 it supplied about 54MWh of heat and 15MWh of electricity.	2017

As with all technologies, it presents some disadvantages. Installation options become more restricted in highly dense urban areas with high rise buildings and low roof area availability. PVT cannot supply all of the heat required by the network demand, especially during the winter months, therefore a complementary heat source needs to be installed, which adds cost and complexity to the overall system. Like all solar energy technologies, the availability of solar irradiation throughout the day and how long it overlaps with the periods of demand affect the system's performance. Therefore, the viability of using PVT in DH is dependant on the weather and location, which can vary greatly from country to country. Furthermore, retrofitting pre-existing DH networks with PVT can be stalled if the return temperature is too high and close to the PVT output temperature. This is because it becomes unfeasible as the larger the difference is between the input and output of the PVT, the higher the energy that is fed into the network. Also, lower temperatures at the PVT inlet would provide more cooling to the PV panel, high inlet temperatures would be counterproductive for this technology. Overcoming this would require the network to be refurbished and the temperature lowered by, for example, switching from steam to hot water, using absorption heat pumps to increase the temperature spread between

Table 4
Table summarising studies for PVT DH

Study	PVT	PV	SC	HP	Gas Boiler	HW Tank	Battery	Location
Herrando et al. [104]	×	×	×		×	×		Italy
Pakere and Blumberga [96]	×	×	×	×		×		Latvia
Pardo García et al. [105]	×			×		×		Prague
Behzadi and Arabkoohsar [106]	×					×		Denmark
Kang et al. [107]	×					×		England
Pakere et al. [75]	×					×	×	Latvia
Mi et al. [108]	×			×		×		Dalian, China

the supply and return or by indirectly coupling the system to buffer tanks or other sources to enable local temperature adjustments [79, 103].

4.2. PVT DH Studies

Several studies have investigated the integration of PVT into DH networks. These have included other complementary technologies such as heat pumps, batteries, or thermal storage to account for heat balancing during low solar irradiance periods or to store surplus energy. Table 4 shows what technologies have been included and the location of each study. The following section begins by discussing the role of PVT being used with HPs, where the studies which investigated PVT HP DH are compared. This follows onto a discussion on techno-economic findings from the two PVT DH studies which have explored this. Finally, a discussion on the role of ultra low temperature DH (ULTDH)/LTDH in PVT DH is explored by reviewing and comparing the findings from three studies which have focused on this.

4.2.1. PVT and HP DH Studies

Conclusions by Pakere and Blumberga [96] highlight the economic benefits of converting the excess power into heat with heat pumps, especially for large-scale solar systems. This study however only converted excess electrical energy to heat using the heat pump. The PVT thermal output was not used as a source for the heat pump, which could have improved its COP. A PVT HP modelled for a DH system in Dalian, China, was found to require only 30% of equivalent electricity consumption of an ASHP, and 12% that would have been required for an electric boiler DH system [108]. The study demonstrated how PVT HPs can significantly improve system efficiency and running costs. Limitations of both the study by Mi et al. [108], Pakere and Blumberga [96] was that the scenarios were based on Latvia or Dalian's specific irradiance. Further work would have to be done using these same methodologies in countries with less or more solar irradiance. Pakere and Blumberga [96] investigated the interaction between the heating technologies and the DH plant, so it would be interesting to extend this to look at the interaction between the end-user and technologies. A dynamic analysis could be carried out looking at aspects such as building efficiency requirements, occupant behaviour, and control aspects of the system to improve the performance. Since the study Dannemand et al. [92] demonstrated how important well-designed controls are in optimising PVT solar assisted heat pumps (PVT SAHPs), this is an important aspect that needs to be considered for any PVT SAHP.

Pardo García et al. [105] assessed the applicability of combining a HP supported by PVT into a LTDH network by modelling a 200 m^2 PVT array on the roof or a multi-family building. The HP was used an auxiliary unit to maintain the supply temperature at 60 °C, which was used mainly in winter when irradiation was low. The source side of the HP was linked to a waste water recovery system, which supplied a temperature of around 35 °C, thus maintaining a relatively high COP of around 3. PVT was found to be cost-competitive with favourable regulations such as access to feed heat into a district heating network and power into the electric grid. This improved system performance and profitability. However, taking note of findings by Pakere et al. [75], it may be more cost effective to convert PVT electricity to heat if the DH tariff is greater than the market electricity price. A weakness of the study was the lack of information that would permit scalability and comparison of the systems. There was no justification for choosing the multi-family house type, and the lack of occupant numbers or family sizes make future studies difficult to compare. The economic findings were only specific to the area of the study, Prague, with the installation cost of EUR 148,000 being likely to vary significantly across Europe. The study also reported a more efficient use of roof space; however, no comparison to PV and PVT roof space was reported. The study assessed three configurations with different relationships with the

DH network: firstly, no connection to the network; secondly, only excess heat exported to the network; thirdly, all heat produced sent to the DH network.

The final configuration was found to fully exploit the PVT system heat production potential by sending all heat generated to the DH network. It also had negligible thermal losses due to having the shortest path between the network and PVT system, also with greater support from the heat pump this improved the PVT efficiency. As there was no water storage tank, a more powerful heat pump was needed to ensure that an immediate hot water supply could be sent to the DH network. All electricity generated was sent to the grid. However, the study did not discuss thermal stress when the return line was used as short-term heat storage with overflow from hot supply line water. Fatigue fracture of steel tubes and failure of composite material due to shearing force could occur with a high number of full load changes [109]. Pipe joints are greatly affected by mechanical stress due to large temperature differences in the distribution network during operation or down time. Temperature fatigue in DH systems can result in high failure probabilities [110], and these pipe failures can be very economically costly, whilst also creating disturbance to the neighbourhood where they are found as most of the pipes are underground.

4.2.2. Techno-economic studies on PVT DH

Pakere et al. [75] investigated the optimal integration of PVT into a DH system. They compared eight different scenarios, all with varying sizes of PVT areas and excess power utilisation setups, analysing the hourly thermal and electrical outputs. The results showed that it is economically beneficial to convert any excess power produced to heat (using an electric boiler in this instance), only if the market price of electricity is lower than the DH heat tariff and if the heat demand is higher than the PVT thermal energy produced. This can work well since DH has a high base load heat demand, higher than the thermal output from PVT, so the electrical output can be converted to cover heating loads. The PVT thermal output can be 10-15% higher when the PV modules of the PVT are not connected to a load [111]. Therefore, it would also be interesting to investigate how disconnecting the PV modules when the electricity market price is below the DH heating tariff or when there is excess electrical power output, would affect the overall technical and economic feasibility. This could be studied further using methods such as the work done by Kang et al. [107] who developed a novel PVT model in Modelica with mode switching between open and closed circuit PV in preparation for analysis into control strategy opportunities. Pakere et al. [75] also found that a relatively high solar fraction for a total power consumption of 38% could be reached for large scale PVT systems in cooler climate zones in northern Europe. However, this particular scenario had the highest costs. This scenario had a 3000 m^2 PVT system linked with lithium-ion batteries used to store the electrical power accumulation, with 66% of excess electrical power stored and the rest exported to the grid at market price. It was found though that scenario without electrical power storage was associated with a higher amount of total avoided emissions since all of the power was converted to heat or exported to the grid, thus covering more of the demand. As DH heat has the highest emissions factor, utilising all energy generated to contribute to it gives the highest avoided CO_2 emissions. Herrando et al. [104] also investigated the avoided CO_2 emissions but from a combined cooling, heating and power PVT system. It was found that compared to annual CO_2 emissions reduction from an SC (386 tons CO_2/year) and PV (784 tons CO_2/year) DH system, PVT far outperformed the systems with 911 tons CO_2/year .

4.2.3. LTDH/ULTDH PVT DH

Pakere and Blumberga [96] modelled a DH network which initially had a heat supply temperature of 63.7 °C and a return temperature of 45.2 °C. The authors found that by lowering the DH supply temperatures by 10 °C, making it into a LTDH network, both the STC and PVT systems would increase their net present values, thus increasing its overall performance. The study did not however analyse the economic effects of lowering the DH supply temperature even further to make it a ULTDH network, which would have expected to see a further improvement of overall performance. Likewise, Pardo García et al. [105] supplied the PVT collector with a DH return of around 30 °C. PV collector efficiencies start to decline beyond a 25 °C cell temperature, therefore PVT supply temperatures above 25 °C could actually be counterproductive to cooling the PV cells. Also, in winter, higher PVT supply temperatures could equate to a lower collector thermal efficiency since this is reliant on the temperature differential between the ambient and collector temperature.

Nevertheless, the beneficial use of PVT with lower supply temperatures was in line with findings from Behzadi and Arabkoohsar [106], which found that ULTDH was most suitable for PVT to be integrated with. Behzadi and Arabkoohsar [106] also undertook analysis on the integration of a small PVT array in three different types of DH networks: 3GDH, LTDH and ULTDH. The results showed that the ULTDH network was the most suitable DH type for this system to be integrated with, where the supply temperature was 40 °C and return was 25 °C. This was due to the system having a lower panel temperature, thus producing the greatest amount of electricity and heat in comparison to the other two DH types, reaching maximum overall efficiency of 74.51%. Neither of the aforementioned studies [106, 96] investigated how different PVT DH configurations could affect a PVT DH system performance. Following on from the findings by Behzadi and Arabkoohsar [106], Kang et al. [107] investigated various configurations for a ULTDH PVT DH system. Whilst providing space heating for a block of 12 2-bedroom terraced houses in winter in the south-east of England, lower flow rates through the radiators in each zone reduced the the DH return temperature, ranging from 24 to 19 °C for flow rates between 0.04 to 0.01kg/s. It was also found that DH return temperatures could be lowered with a separate low-temperature buffer tank between the PVT and main HW tank, and with a counterflow heat exchanger on the DH return for pre-heating DHW. With this configuration and a radiator flow rate of 0.01kg/s, the DH return fluctuated between 11 and 18 °C. The study demonstrated how variable flow rates and optimal configurations may be integrated as part of well designed control strategies for 4GDH.

5. Discussion

PVT is a technology that could be used for DH. It could be implemented with other sources such as heat pumps, or used stand-alone. A benefit of PVT comes from simultaneously producing electricity and heat, whilst also cooling the PV cell temperature which increases the PV electrical efficiency. This could be especially beneficial when studying district heating systems with space limitions in urban areas. The following sections discuss the impact of the Covid-19 pandemic on the PVT market, the promising outlook for PVT HP systems in DH, opportunities that have been identified for development in PVT DH and final conclusions drawn from having carried out the review.

5.1. Impact of Covid-19 on PVT DH

As part of the after-effects of the Covid-19 pandemic, we may see a reversal to the predicted trend of populations moving towards cities. In a survey conducted from February to March of 2021 with a sample size of 385 individuals whose responses were weighted by ethnicity and economic activity using the 2011 Census to represent the London population as accurately as possible [112], 43% of the participants wanted to move to a new home due to the pandemic. Of these participants 54% wanted to move either out of London or to an outer borough. Therefore, we may see more cities evolve into wider metropolitan areas. Even if this trend continues, many residential areas and new building developments outside cities are grouped, so the need to explore heating systems in urban areas is still relevant. No studies on the impact of Covid on the PVT market have been conducted, however it is likely to follow similar trends to PV and STC being a hybrid of the 2 technologies. The global health crisis caused by the Covid-19 virus in the first quarter of 2020 necessitated the use of drastic measures to contain the transmission of the virus, this caused a decline in growth for both the PV and STC sector due to significant economic implications and reduced commercial, industrial and construction activities [6]. The declining trends are expected to be short term with medium-term prospects remaining on track for both sectors, however uncertainty surrounding a strong recovery are dependent on the global economic recovery rate, government policies and the Covid-19 crisis [113, 114].

5.2. PVT with heat pumps in DH

PVT HPs have great technical potential for operating a highly efficient system whilst overcoming the limitations of noisy outdoor ASHP systems. In September 2021, a Dutch company launched a commercial heat pump specifically made for use with PVT. With the novel use of propane refrigerant in a water-to-water heat pump, the heat pump has a wide operating range. The heat pump is compact and can be carried into an attic in two 25kg pieces making it easier to install than conventional heat pumps. This is particularly beneficial for new builds which tend to be smaller houses or flats. The heat pump can also switch to provide cooling in summer months which could be beneficial as climate change will lead to more extreme summers [115]. The development of this commercial PVT heat pump is pointing towards an increase in market uptake and progressive future for PVT HP DHC systems.

Future work could investigate the opportunities for utilising GSHPs and studying how a GHSP-PVT system would perform in urban scenarios, building upon work by Xia et al. [91]. University College London has recently successfully demonstrated a highly efficient building design in the student centre, which can regulate temperature and use minimal energy with an EPC rating of A [116]. An open-loop GSHP borehole system provided free cooling through the connection to the cooling pipes underneath the floor slabs and cooling coils of the air handling units. The GSHP could also provide low-grade heat when required using the heat pump. A 400 m^2 50KWp PV array was installed on both the student centre and the neighbouring building's roof, which provided electricity. This project demonstrated how GSHP solar systems could successfully be integrated within a city in highly efficient new builds. With other successful projects around the world, it should be noted that borehole energy storage systems are likely to play a role in 4th Generation DH, in providing low-grade heat to LTDH systems and forming part of a flexible smart network.

5.3. Opportunities for development in PVT DH

A review of all the components that make up PVT DH has demonstrated how global emission reduction targets are ultimately pushing a global transition towards renewable energy. The high demand for solar PV has naturally pushed PV costs down and improved technology efficiency. This plays an important role in the success of relatively new promising PVT technology. Since renewable energy is intermittent and often requires storage to meet demands, the electrical and thermal storage industry has been progressing at exciting rates to provide more efficient, low-cost technologies. The review process has highlighted the following opportunities for future work to address in the context of PVT DH:

- There is a research gap in control strategies, which implement PVT DH whilst optimising the overall system and PVT array performance. Installations have required control adjustments once the system has been operational, and some performance conflicts between counterparts of the PVT-GSHP DH system have been discovered once installed. The experience gained and modelling studies on control strategies for PVT DH installations is valuable to advance the subject field, however studies are limited to certain technologies and information is not widely dispersed on the subject. In particular the interaction between PVT DH with thermal storage requires development since existing STC DH - thermal storage control strategies cannot be applied due to the PVT's added complexity of the integrated PV cells. The PV requires low temperatures to keept the PVT electrical efficiency from dropping due to temperature de-rating. Further work in this field would be important in progressing this concept since numerous beneficial thermodynamic, and electrical synergies between system counterparts could be utilised and optimised in control strategies.

- PVT technology could play an important role in 4GDH; however, more work into expanding its market, lowering costs, streamlining certification processes and ensuring PVT is not left out of policymaking will be required to help the technology take off.

- Storage will be vital to PVT DH systems due to the diurnal/seasonal nature of the technology energy supply. With exciting progress in thermal and electrical storage technologies, spurred on by the renewable energy and electric vehicle market, many viable technologies are ready to be implemented with PVT DH systems. Further investigation into PVT-storage configurations and control strategies would be beneficial for future demonstrations and projects.

- With PV technology costs dramatically reduced over the past decade and forecast to drop even further; this will have a knock-on effect for PVT and storage technologies. It can be expected that PVT DH will become a competitive option in certain urban scenarios which do not have much space. PV installers being trained in plumbing, customer and installer information distribution, project knowledge share, appropriate policies and incentives will all be important factors in the initial start-up of PVT DH systems.

- The extensive technological advancement and research that has gone in to PV and STC technology is all relevant and can be beneficial to PVT technology. Being a hybrid technology of both PV and STC, PVT can also help the conventional technologies overcome some hurdles such as PV temperature degradation at high temperatures, and the stalling STC market which is competing with technologies such as heat pumps. Used in conjunction with heat pumps, PVT can improve heat pump performance, whilst synergistically also improving the PVT thermal and electrical output.

5.4. Conclusions

The investigation on photovoltaic thermal district heating (PVT DH) has been presented as a comprehensive review on subjects including policy, legislature, trends, buildings, urban environments, markets, designs, storage, efficiencies, and pros and cons for PVT DH and the integration of subsystems. The studies and projects discussed have demonstrated how PVT DH systems can have greater performance, compared to conventional solar technology, where the annual PVT electrical output is greater due to the cooling of the PV cells. When the PVT heat output is used to supply the source side of heat pumps, the electricity consumption of heat pumps can be reduced. In particular, the use of PVT with heat pumps presents an exciting opportunity within the context of future PVT DH systems due to the mutually beneficial synergy between electrical and thermal counterparts of each system and the higher efficiency achieved compared to individual heating systems. In addition to PVT assisted heat pump district heating systems, there are many other configurations of the various PVT types with a range of electrical and thermal storage, which are open for research and demonstrations in different applications. The PVT market is quite dynamic with various new manufacturers and designs emerging over the past few years. Currently, although increasing, knowledge and in-depth technical information on existing demonstrations is limited and not widespread. It is essential for further demonstrations and studies to be completed with the findings widely disseminated, to be able to gain further knowledge of its technical potential together with any advantageous complex synergies that can be developed between the components of a PVT DH system and other technologies. In particular, research should be focused on the control strategies for PVT DH with thermal storage and/or heat pumps since there is great opportunity for this within 4th generation district heating systems.

To summarise, there have been various external drivers identified, which could make PVT DH an attractive option when considering clean heating systems to install in urban areas. These drivers can be summarised as; progression towards 4th generation district heating, solar technology and storage technological advancement and cost reduction, mutual system performance improvement with heat pumps, and green legislation/policies. With almost all buildings with available roof space and sufficient solar insolation forecast to be equipped with solar thermal water heaters by 2050 [10], the push for improved building energy efficiency and a transition toward 4th generation district heating networks, this review has identified that there is naturally a great opportunity for implementing PVT DH. The Paris agreement, gas boiler ban, efficient new builds and home energy renovations all work in support of PVT DH systems. Additionally, as the world has already transitioned to a smart network enabling age, through the use and development of sensors, remote monitoring and the impressive improvements of microcontroller technology, the tools are all ready to implement 4th generation district heating photovoltaic thermal district heating. By expanding further knowledge and working experience of PVT DH systems, the performance can be improved, which ultimately could make it an attractive and viable option which is important particularly to systems with relatively high capital cost such as ground source heat pumps or photovoltaic thermal collectors.

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CRediT authorship contribution statement

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