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Solar-Thermal and Hybrid Photovoltaic-Thermal Systems for Renewable Heating

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Headlines

- Heat constitutes about half of total global energy demand. Solar heat offers key advantages over other renewable sources for meeting this demand through distributed, integrated systems.
- Solar heat is a mature sustainable energy technology capable of mass deployment. There is significant scope for increasing the installed solar heat capacity in Europe. Only a few European countries are close to reaching the EU target of 1 m^2 of solar-thermal installations per person.
- One key challenge for the further development of the solar-thermal market arises from issues related to the intermittency of the solar resource, and the requirement for storage and/or backup systems. The former increases investment costs and limits adaptability.
- An analysis of EU countries with good market development, suggests that obligation schemes are the best policy option for maximising installations. These do not present a direct cost to the public budget, and determine the growth of the local industry in the long term.
- Solar-thermal collectors can be combined with photovoltaic (PV) modules to produce hybrid PV-thermal (PV-T) collectors. These can deliver both heat and electricity simultaneously from the same installed area and at a higher overall efficiency compared to individual solar-thermal and PV panels installed separately. Hybrid PV-T technology provides a particularly promising solution when roof space is limited or when heat and electricity are required at the same time.

Contents

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Introduction

The energy sector is in transition worldwide because of increasing demand for energy; significantly fluctuating oil prices; stronger desire for energy supply security and independence; and in response to sustainability, conservation and environmental considerations. In 1992, the Rio Convention on Climate Change[1] established a framework for actions aimed at reducing fossil-fuel consumption and limiting associated emissions. In 2015, over 190 countries signed a legally-binding agreement at the Paris Climate Conference[2] with the intention of keeping the rise in the average global temperature below 2 °C [3]. The mass deployment of renewable and low-carbon energy technologies has the potential to make important contributions towards these goals.

Solar energy has the potential to provide a significant proportion of the renewable energy required to meet these and other national and international targets and obligations[3]. Sunlight is available without geographical restrictions and supply-chain limitations. Considering that nearly 50% of the global energy consumption is finally used for heating purposes and with 70% of the world's population projected to live in cities by 2060, solar heat is poised to play a key role in delivering a clean and sustainable future energy system. Of interest are small-scale distributed solar installations, which are affordable and readily integrated into cities[4].

This paper highlights the potential for existing and emerging solar-thermal and hybrid photovoltaic-thermal (PV-T) systems in meeting growing global demand for renewable and sustainable thermal energy (heat). The paper also outlines the barriers and opportunities for the mass deployment of solar-thermal technologies and offers a vision for the future of solar-thermal systems.

The importance of heat

Approximately half of the global energy demand is used for heating purposes[5]. At present, this demand is served largely by conventional energy sources such as oil, gas and coal[6,7], either directly or indirectly via electrification. In the UK, for example, the domestic sector accounts for just over half (53%) of total energy demand, nearly two-thirds (64%) of which is used for space heating[6]. In the US, final consumption of electricity for space heating and hot water accounts for one fifth (20%) of the total electricity use in the residential sector, or about 730 kWh of electricity per year per person. Across the economy, heating is important for functions such as sanitary hot water preparation, domestic and working-space comfort, cooking and food preparation and preservation, and in many industrial and manufacturing processes.

Electricity is often used for heat generation, often due to simplicity, cost considerations, and the lack of distributed heat provision when heat generation and consumption are separated by large distances. Current technology limits transport between generators and consumers to a few hundred metres owing to high heat losses and costs[8]. Direct electricity-to-heat conversion is not thermodynamically efficient, however, even when the inclusion of some renewable electricity has been considered.

Solar-thermal and hybrid PV-T technologies are affordable solutions that can be implemented within local energy systems to cover a large fraction of the corresponding heat demands at high efficiency, low cost and with low associated emissions, therefore enabling the emergence of such distributed systems.

Solar energy-to-heat conversion

Solar energy can be exploited in various ways to generate electricity, either with PV technology or via thermodynamic power cycles[a] in concentrated solar power (CSP) systems, as well as for heating or cooling[b]. In this paper, we focus on the potential for solar energy-to-heat conversion (see Box 1).

Solar-thermal applications

Depending on the application, heat may be required at varying temperatures, most of which are compatible with available collector technology (see Box 1). Conventional stationary non-concentrating (or low-concentration) collector designs can achieve outlet fluid temperatures from 50 to 150 °C.

The collector design selected for an installation also depends strongly on economic factors. Unglazed collectors are the cheapest option, but these are not considered suitable for use in cold, low-irradiance climates due to their relatively high thermal losses, low efficiencies and limited operating temperature range.

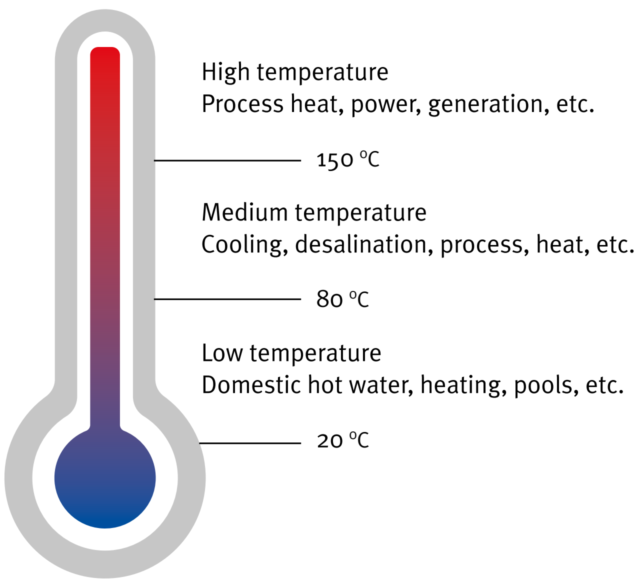


Figure 1: Different Temperatures levels meet different needs.

Flat-plate glazed collectors, on the other hand, are relatively affordable and operate with acceptable efficiencies at outlet temperatures of up to 80-100 °C [13]. This type of collector is considered suitable for deployment in medium-temperature applications. When temperatures above 100 °C and up to 150 °C are required, evacuated-tube collectors and heat pipes need to be considered, while concentrated collectors can reach temperatures in excess of 200 °C. Heat pipes allow a heat-transfer fluid to change phase within the collector, thereby enhancing heat transfer and allowing higher operating temperatures.

Most domestic and commercial applications fall in the low- and medium-temperature ranges (e.g., domestic hot water in the UK is typically required at 60 °C [14]), making solar-thermal installations a suitable option. Low-temperature heat is, in fact, the largest fraction of the total final consumption of heat. In the UK, space heating accounts for 80% of the total heat demand, with close to 80% of the energy consumption related to space heating covered by gas boilers and 8% covered by electricity[6]. Examples of successful worldwide solar-heating applications are shown in Figure 2.

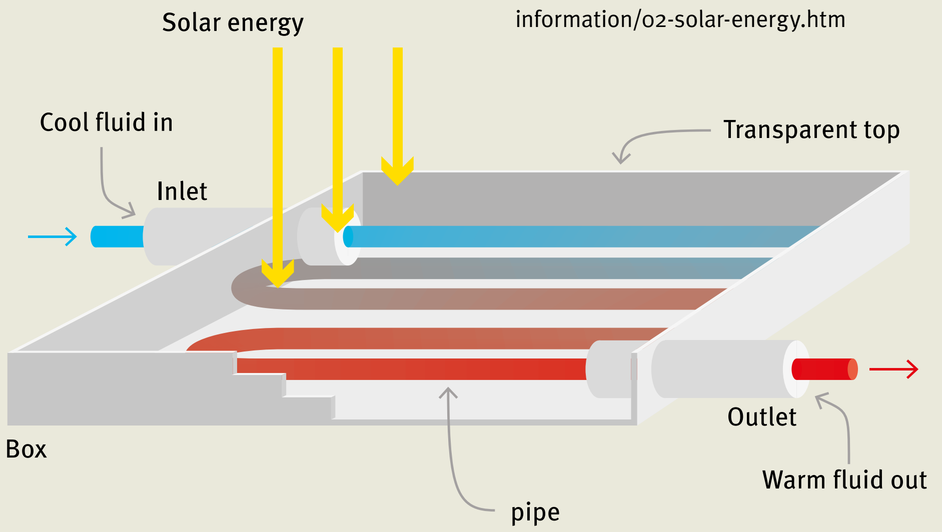
Benefits of solar technologies

Solar energy is available worldwide and can play a key role in facilitating energy independence and resilience at the regional, national, local and household level. Low- and medium-temperature solar-thermal technologies can generate heat for many diverse residential, commercial and process heating applications, which can form natural distributed energy provision systems with high reliability. The renewable energy sector employs 9.5 million people worldwide, of which 3.7 million are in the solar sector (including photovoltaics -PV-, solar heating and cooling)[23]. Small-scale thermal and standalone applications create opportunities for local economic development in a very localised value chain covering design, manufacture, installation and maintenance. In addition, solar systems are insulated from the instabilities of oil price fluctuations, conflicts and financial uncertainty.

Box 1: Solar energy-to-heat conversion

Sunlight is converted directly into thermal energy in solar-thermal collectors. The sunlight is absorbed by a material, converted to heat and transferred to a fluid stream.
The heated fluid (generally air, water, or antifreeze liquid) can be used for several purposes such as space heating, hot-water heating, process heating, and even cooling[9-11 i].
Several designs of solar collectors are available, including with or without single or multiple glass covers, or with a vacuum for reducing the heat losses in so-called unglazed, glazed or evacuated collector designs. High-performance collectors feature thermal absorbers with special selective coatings that maximise the sunlight absorption and further reduce heat losses. Black chrome over a nickel base is often used on copper plates, or alternatively, a titanium-nitride-oxide layer[12]. By reducing heat losses, the presence of a glass layer or vacuum allows operation with higher efficiencies at higher temperatures over an extended temperature range.
A particularly interesting design is the evacuated-tube collector with heat pipes, in which the fluid evaporates and condenses in tubes as it transfers heat, in a relatively efficient and affordable design.

Adapted from: http://www.makeitsolar.com/solar-energy-information/02-solar-energy.htm



i Cooling can be achieved with solar-thermal systems using various solar cooling cycles, in which the energy collected by the solar collectors is used in thermally-driven chillers (contrary to conventional, electrically powered chillers).

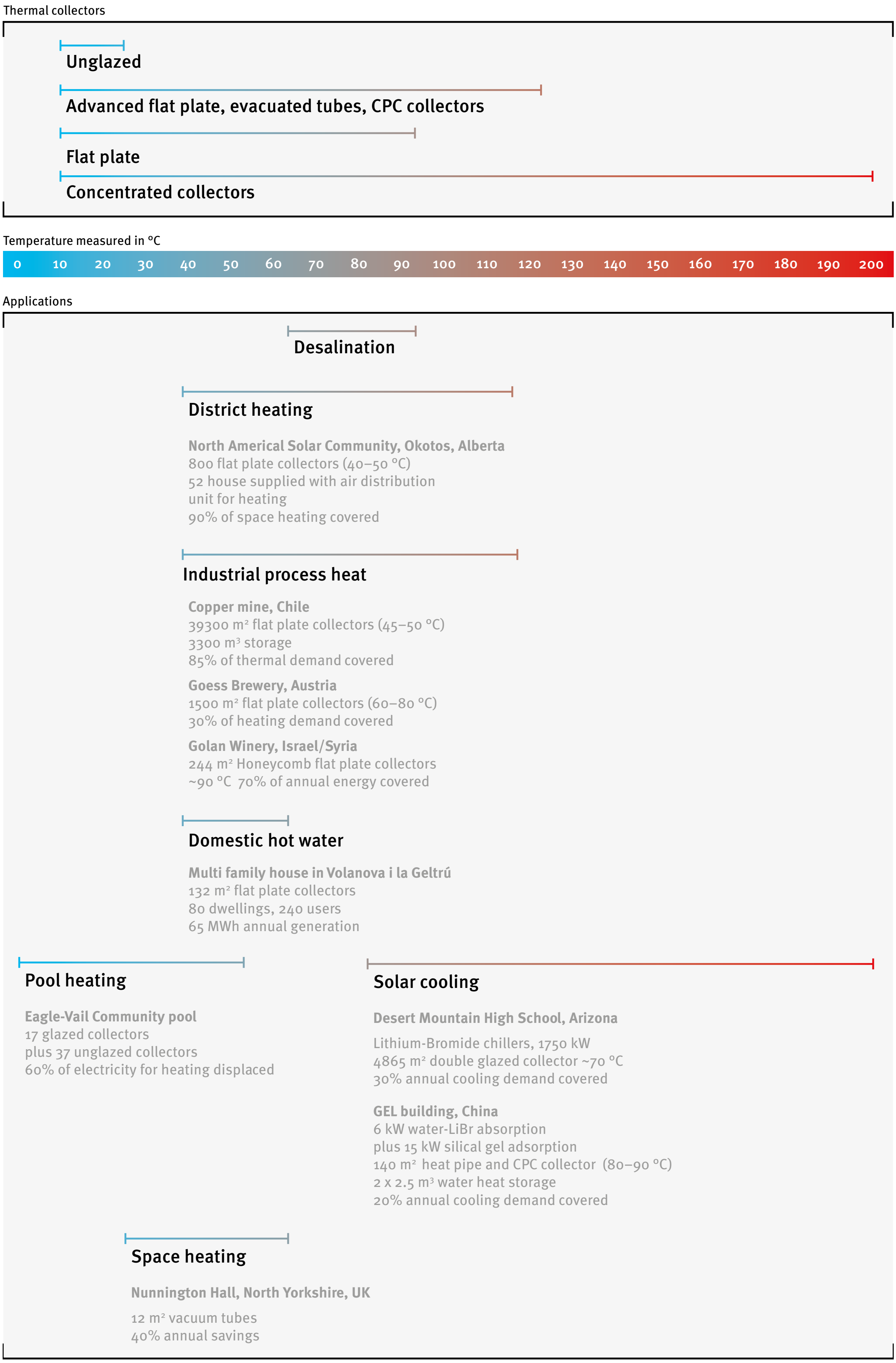


Figure 2: Examples of existing installations of solar-thermal systems covering a wide range of energy needs[15-22].

Solar-thermal collectors can deliver heat over a wide range of temperatures with solar-conversion efficiencies in the range 40-70% [ii]. Domestic systems are well-established and commercially mature, with collector design-point efficiencies often exceeding 75%. Although solar-thermal systems require relatively high initial investments for system installation [iii], typically in the range $1000-2300 per m² [24,25], compared to the $290-860 per m² for small-scale PV systems [iv] [26,27], they have relatively few moving parts and, consequently, low operating and maintenance requirements. Running costs can be as low as $100 per year[28],with 20-year lifetime guarantees to maintain.

At the same time, solar-thermal collectors allow the design of heating systems with low-cost integrated thermal storage. As the solar resource follows largely predictable annual and daily cycles, the output of solar systems is also largely predictable, and this forecasting can help with the integration of storage. The thermal output can be stored with low losses in cost effective hot-water storage tanks or other thermal energy storage (TES) media [v] [29,30], for later use in a wide range of services including hot-water provision, space or process heating, or even refrigeration or water desalination[29]. Hot water storage tanks are already commonly employed in heating installations. For example, in domestic hot water (DHW) applications, solar collectors are commonly coupled to the existing hot water cylinder, either directly or indirectly via a heat exchanger and separate fluid loop[9,10].

Solar heat market

The current market for solar-thermal technologies is relatively small but growing quickly. Considerable potential with important drivers exists for this strong growth to continue.

Current market

Renewable energy sources provided 13.8% of the world's total energy supply in 2015[31]. Although solar energy remains a small fraction of this total (below 2%), it has a fast growth rate compared to other renewable sources (solar-thermal: 11.7% per year, PV: 46.2% per year, both on average since 1990). This growth has been made possible by the implementation of national policies that have supported renewable projects in Europe, and by the Chinese policy of high subsidies for PV[31,32].

The solar heat market represents a notable share of the global heating market, mainly in providing space heating and DHW[24]. The cumulative capacity of installed solar water heaters has reached 435 GWth and saved 116.4 million tons of CO2 equivalent [c] [24]. This capacity increased by more than 6% in 2015 despite a market slowdown in China (which accounts for 77% of all new installations) and Europe[33].

Whilst the market for PV is well established in Europe, the annually-installed solar-thermal area in the EU lags that of PV. For example, 16.5 million m² of solar-thermal collectors were installed in Germany by 2012, compared to 230 million m² of PV[34]. Although solar-thermal technology is mature and ready for mass deployment, significant market development is still needed in most EU countries.

Potential market for solar-thermal technologies

Solar-thermal technologies can play a leading role in meeting the decarbonisation targets set in Europe and beyond. The IEA Energy Technology Perspectives 2012 35 shows solar heating has the potential to cover more than 16% of the low-temperature heat use in an energy mix scenario that ensures a global temperature rise below 2 °C (2DS scenario) by 2050. In Europe, this share translates into 45% growth of the installed solar-thermal capacity by 2020, setting a challenging target of 1 m² of collector area installed per European citizen by 2020 and of 1.3 m² by 2050[5,33,35,36]. A large effort is needed to reach these goals because of the current fragmentation of the solar-thermal market as shown in Figure 3[24]. The cases of Cyprus (where the installed capacity has reached 480 Wth per capita) Austria and Greece are particularly promising when contrasted with the opposite extremes of the UK, France, Italy, Spain and Portugal (below 10 Wth per capita). It is evident that a significant potential for solar-thermal exists in some countries that receive similar solar energy to Greece and Cyprus and more than Austria, and where the installed capacity per person is 10 times below the target.

Important factors that influence the solar heat market are the cost of local alternatives (oil, gas, coal, biomass, electricity, etc.), the characteristics of the local energy infrastructure and the economy of key industrial sectors, such as construction. Denmark, for instance, has had a strong solar-thermal market segment. Despite having one of the lowest irradiance levels in Europe, it has seen a growth of solar installations due to fact that most installations are connected to local district-heat networks.

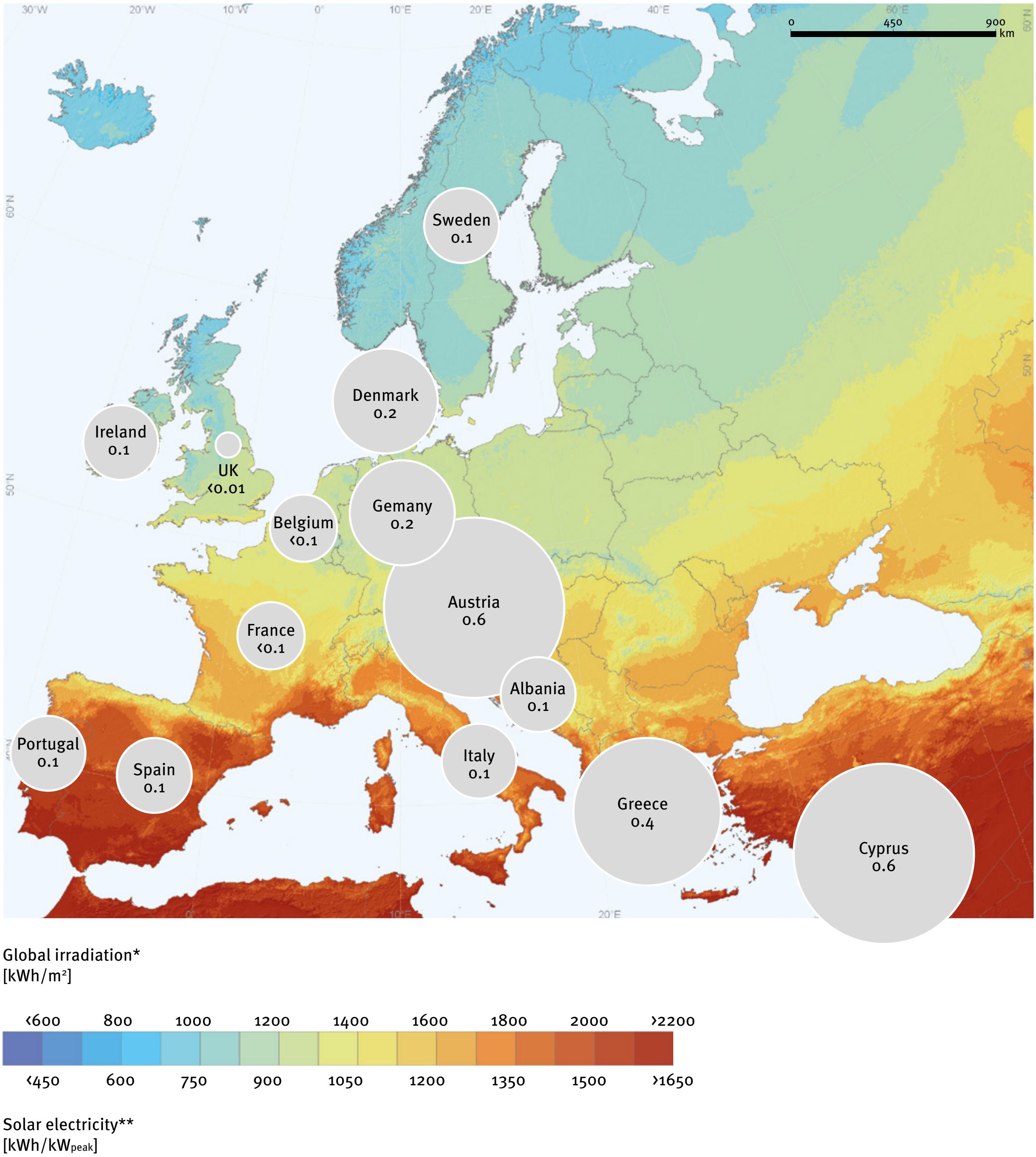
ii Between three to five times less area is necessary to cover a certain demand for heat (in kW) by means of solar-thermal collectors than that which would been required to cover the same electricity demand (in kW) by solar PV panels.

iii In the UK, according to Energy Saving Trust, solar water heaters costs range between $1000 and $1700 per m².

iv PV system costs vary from country to country and depending on the specifics of the integration of these systems into buildings, the degree of innovation, the learning costs in project management and the price of custom-made modules. In the UK, small (i.e., < 4 kW) residential PV systems had a capital cost of ~$400 per m² in 2014.

v Low-temperature heat can be stored in hot water tanks at a cost of $0.10-0.50 per kWh of heat, but also in phase change materials (smaller volume but more expensive, and less mature with a limited market). By comparison, the cost for storing electricity ranges from $400 to $1000 per kWh for the more mature lead-acid and Li-ion batteries in domestic and neighborhood-scale systems.

Photovoltaic Solar Electricity Potential in European Countries



* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules
** Yearly sum of solar electricity generated by optimally-inclined 1kW$_p$ system with a performance ration of 0.75

Figure 3: Area of installed solar-thermal per inhabitant in Europe obtained from the area installed per country and population data reported in Reference[24]. The available solar energy is indicated by the colours ranging from red (highest value of 2200 kWh per m^2) to blue (lowest value of 600 kWh per m^2).

Barriers and opportunities

Technical and non-technical barriers are acting to limit the extensive and consistent adoption of solar-thermal systems across Europe.

Integration into existing systems

Renewable energy sources have been increasingly penetrating major electricity markets, leading to challenges for electricity generators and grid operators. At a national level, identifying pathways for integrating renewable energy generation into existing energy systems is desirable, especially when generation is highly intermittent. This integration requires technical solutions such as centralised control and flexible operation of power stations; improvements to renewable energy generation predictions; enhancement of operational tools and practices; and development of technologies supporting demand response[37]. These challenges decrease in small-scale applications, where on-site thermal storage is affordable and electrical storage may not be needed[38]. Moreover, small-scale energy systems contribute to distributed energy generation, which facilitates the integration of renewables in the existing energy systems[39-42]. In Europe, Germany, Denmark and Sweden are good examples of the deployment and integration of renewable distributed generation with high penetration into the electricity market[43]. An example of an integrated solar system is illustrated in Figure 4.

Solar systems have limited adaptability and flexibility, since they require specific designs for different buildings, user behaviour (demand profile) and climate. There are also technical limitations associated with the scaling of systems and the components associated with both thermal and PV applications. For example, thermally driven chillers do not generally exceed a cooling capacity of 20 kW, which required around 60 m² of roof area for solar-thermal collectors, limiting their applications[44]. Therefore, the integration of solar technologies into wider energy systems is generally a challenge.

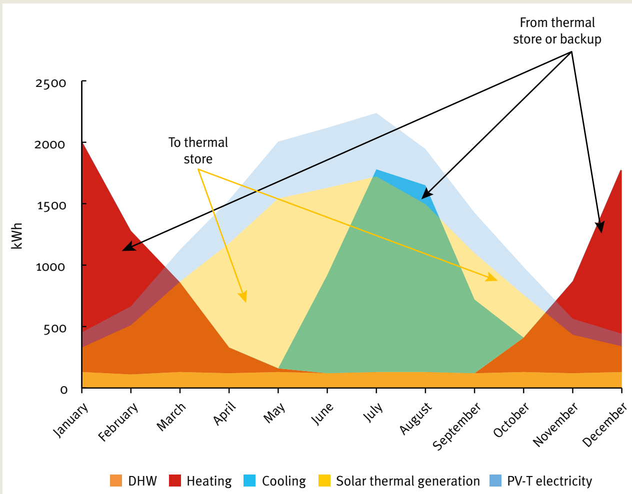
As with off-grid renewable electricity, the reliable provision of solar heat while maximising the use of the solar resource requires thermal energy storage (see Box 2). The main challenge associated with storage is that it requires an unoccupied area that may not be available in small houses. Nevertheless, when hot/cold water is stored it can be used during different times of the day or of the season, depending on the design of the store, thus increasing utilisation of the system. Infrastructure for heat storage and distribution such as district heating and cooling networks (other than distributed heat storage systems) allow for high quality heating provision and maximises the use of available heat.

Access to capital and uncertainty about cash flow

Rooftop solar installations often face the so-called 'landlord dilemma', whereby the person paying for the investment in the solar unit does not benefit from the savings[46]. This split

Box 2: Thermal energy storage

The thermal energy generated by a PV-T solar-thermal collector is compared to the demand for DHW, space heating and cooling over a year. In more details, the energy generated by a 15-m² PV-T collector array with a 40% thermal efficiency and 15% electrical efficiency is compared with the energy demand for heating and cooling in a building in Rome, Italy, with a 100 m² floor area and with monthly energy requirements defined in reference[45]. In this system, excess heat can be stored seasonally and used at a different time during the year when this is required. In this case, the solar system generates enough heat to cover over 95% of the annual thermal demand, but a large portion is generated in the summer when it is not required, while in winter the system can generate only 30% of the demand. A seasonal store makes the excess heat in summer available to provide heating in winter. The use of a daily thermal storage is also necessary to cover the demand daily when hot-water consumption occurs during the night or at times of low irradiance.



incentive arises because of the large number of rented houses, combined with the high initial costs (see Box 3) that landlords need to pay for a solar-thermal system[47]. The breakdown of the investment cost of a solar-thermal system is shown in Figure 5[48], alongside the corresponding costs for a PV system. A large portion of the capital investment is for the modules, and for planning and labour while installing the system. The lack of local retailers and trained onsite personnel affect the costs for installation[28, 49, 50], and the maintenance cost which is ~1% of the initial investment per year[28, 49]. Because of the high initial costs, access to capital is a common barrier for domestic solar technologies.

Despite its high initial cost, solar heat is already cheaper than natural gas and electricity in central and southern Europe[24]. Similarly, in Denmark solar district heating is competitive with gas heating[64]. The cost competitiveness of the heat generated varies with the availability of solar irradiance, the characteristics of the building thermal load, the system costs, and the costs of the available alternatives.

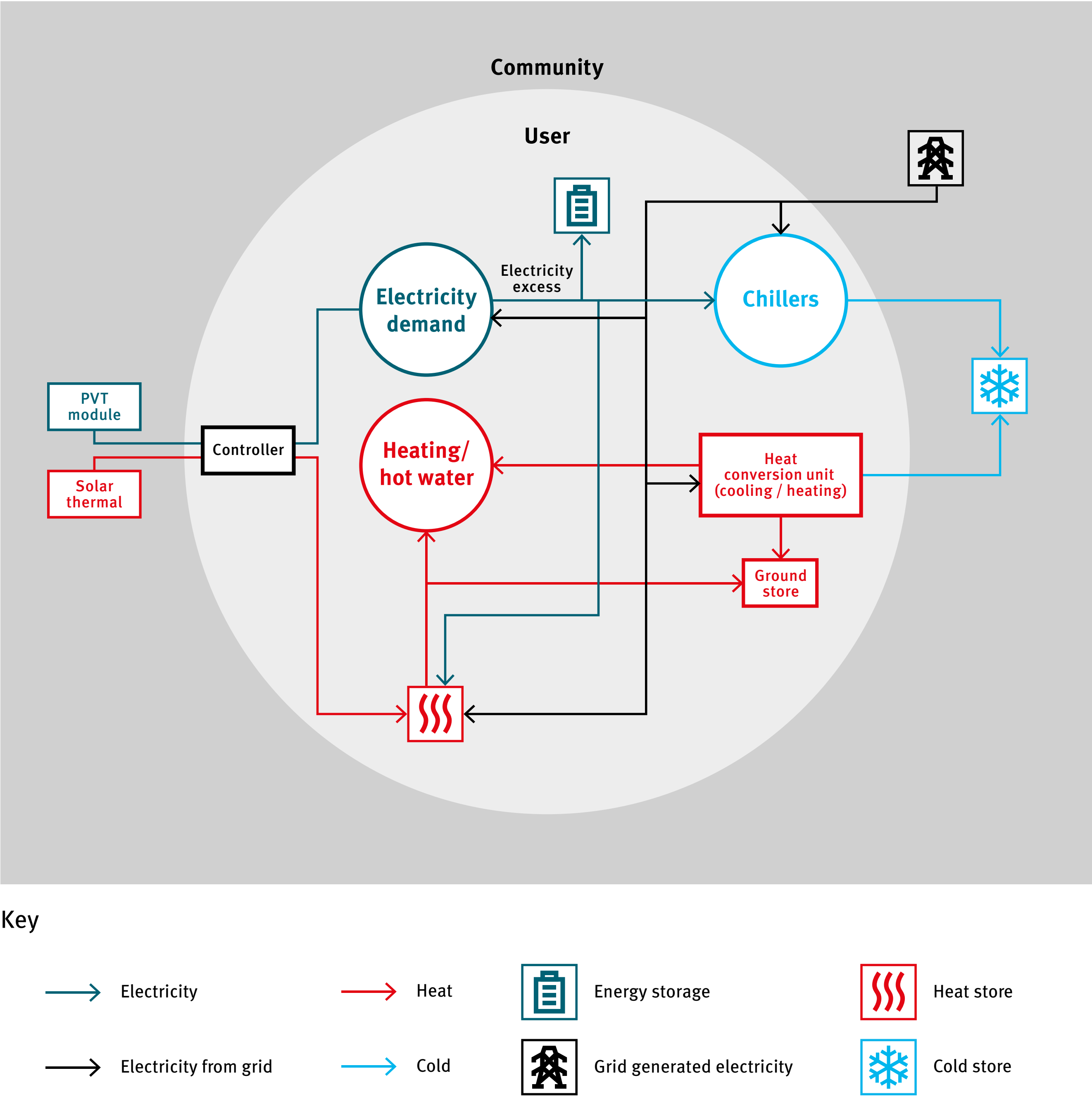


Figure 4: Integrated solar system for electricity, heat and cooling generation. The system is connected to the local grid and to the heat stores at a user level (stand-alone system) or at a community level (if district heating or cooling networks are made available).

The cash generated over a system's lifetime depends on variable external factors such as energy prices. Consequently, incoming cash flows are uncertain, while the expenditure is certain and immediate. Investors need to hedge this risk through adequate financial structures. Nevertheless, households do benefit from predictable bill savings when heating is provided by solar energy. These savings are larger when heat is originally generated with electric heaters due to the high cost of the primary energy. In the UK, for example, if heating is provided by gas boiler the cost is ~$0.06 per kWh and ~$0.23 per kWh [65,66] if provided by electric heaters, compared to $0.11-0.32 per kWh if provided by solar-thermal collectors (see Box 3).

Future market development and technological innovation can lead to significant reductions in the capital costs and improved installation cost competitiveness.

Administrative barriers

Depending on the local or national regulations, either ground mounted or roof mounted solar installations may require permits that may create delays and have fees and associated legal costs[67]. These administrative barriers disappear with market development and with the adoption of policies aiming to facilitate the development of solar systems.

Box 3: Costs of photovoltaic (PV) and solar-thermal systems in the UK (2015-2016)

Hot water generated by small-scale domestic solar-thermal systems worldwide costs \$0.11-0.32 per kWh depending on the location. This is comparable to the Levelised Cost of Electricity (the lifetime total cost including construction, maintenance etc.) generated by PV of \$0.10-0.40 per kWh[26]). The system cost in Europe, including the installation, ranges from \$1100 per m^2 in mature markets[vi] to \$2300 per m^2 in less mature markets [24 vii]. The price of solar-thermal energy decreases to \$0.04-0.09 per kWh for large solar-thermal plants and for solar district heating networks. The capital cost of residential grid-connected PV systems is between \$280 and \$850 per m^2, however, a decline in the capital investment for small PV installations in urban areas has been observed due to the decreasing module prices, which constitute up to 40% of the total cost[26].

The UK constitutes one of the smallest solar-thermal markets in Europe at the moment, with only 0.01 m^2 of installed area per person, compared to 0.2 m^2 of installed per person in Denmark or Germany [24]. The typical installation cost of a solar water heating system in the UK is estimated to be in the range of \$1000-1700 per m^2 [48, 51 viii]. By means of comparison, small household-scale PV systems in the UK below 4 kW had an initial cost ranging from \$280 to \$335 per m^2 in 2015[52].

The cost of a solar-thermal system may vary by up to 20% from the average[24, 26] depending on the building, the system and collector design, and the learning costs in project management. Installation costs can account for up to 40% of the total capital investment[28, 50], and these can be reduced by market development or with the adoption of standardised fixing components and assembly procedure.

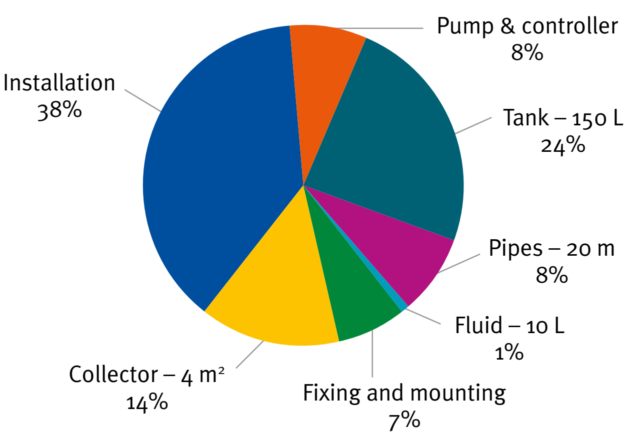
The role of policies and subsidies

As mentioned above, there is significant scope for increasing the total installed solar-heat capacity in Europe, with only a few European countries being close to reaching the EU target of 1 m^2 of solar-thermal installations per person. A decreasing trend in the capital costs of solar technologies is predicted, along with a growing market. Indeed, the cost of solar-thermal modules has decreased by 23% in Europe with a doubling in the installed capacity[68, 69], which is comparable to the drop in PV module prices that has been seen with increased deployment – with a reported learning rate of 16-30% in global scale studies[70].

In Europe, the barriers limited the adoption of mature solar heating and cooling technology can be overcome by creating appropriate public support schemes, such as financial incentives and obligations. However, policy support in the renewable heating sector has advanced at a much slower pace over the past 10 years than those in the power sector. Whilst financial incentives can kick-start the industry in the short term, these have proven difficult to sustain as the market volume increases. Obligations are more effective for creating a self-sustained market in the long term[71].

Renewable heat obligations in new buildings create a predictable established and growing market for solar or other renewable heating projects, leading to an economy of scale in the manufacturing processes and of the installation and services chain[71]. Obligation schemes are currently in place in 21 countries worldwide, setting a minimum share of heating demand met by a renewable technology in buildings with a very limited impact on public budget. The experiences of countries that have adopted solar obligations show that those measures have positive effects on the voluntary market as well as the regulated market, due to increased awareness, availability of local installers and architects and by creating economy

Cost of solar-thermal system



Cost of solar PV system

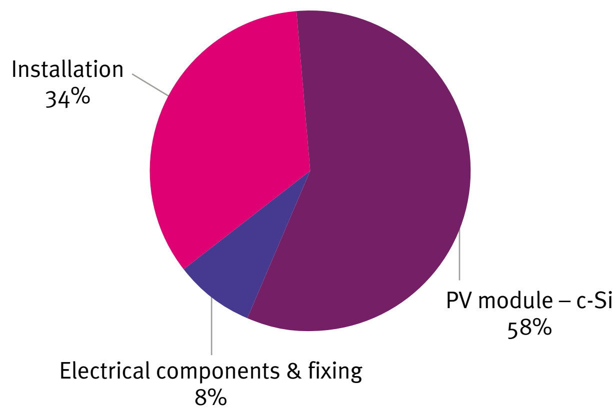


Figure 5: Breakdown of the investment costs (including installation) of a solar-thermal (left) and a PV system (right). Prices are from UK retailers' specs [54-63].

vi For example, in Austria where an average solar-thermal system consists of a 6-m^2 collector array with a 300-L thermal store.
vii For example, in France where an average solar-thermal system consists of a 3.2-m^2 collector array with a 200-L thermal store.
viii The cost per area for PV module is calculated assuming a nominal conversion efficiency of 16%, that is the average module efficiency for mono-crystalline silicon products regarded as standard in mid-2015[53].

of scale thus cost reduction[71]. In most of the cases analysed (see Box 4), solar obligations in Europe are adopted at the local level (municipalities and regional government) and have been the result of a discussion and agreement with the local players in the construction business and the community, thus raising awareness and acceptance.

Retrofitting existing buildings is technically possible, but suffers from high upfront costs and time-consuming permission and authorisation processes. Thus, measures focusing on the voluntary market – such as financial incentives and awareness – in the short term are also necessary. Two financial incentive mechanisms have been used in Europe: grants/subsidies, and tax credits or reductions. The incentives are usually removed once a technology becomes mature, as demonstrated by the development of the solar-thermal market in countries such as Greece and Austria. In some cases, financial incentives may lead to increased costs as a consequence of increased demand. This effect was experienced in France and in Sweden, where the cost of solar water heaters started to rise with increasing market penetration after financial support schemes were adopted, as discussed in detail in references[72, 81].

Public policies can also help provide accelerated and transparent permission procedures. For example, public authorities can provide a list of technical solutions for the integration of solar systems to be applicable to as many buildings as possible. In the case of rented houses or multifamily blocks, new regulatory frameworks and standards for shared investments are required. Consequently, investors (e.g., Energy Service Companies) can provide innovative financing models, such as contracting or leasing models, or can operate the solar plants and sell heat to the user(s) or to the local district heating utility[82]. In the UK, one-time investment support was available until 2015 (the 'renewable heat premium payment' scheme[83]) that lowered the initial capital needed. In addition, innovative financing models, such as crowdfunding, can help overcome the high upfront costs.

Case-specific regulatory frameworks and promotion schemes may also be required. For example, where district heating networks are available[84, 85], the best way to increase the share of renewable heat is to invest in the network itself by means of specific financial incentives provided to network operators.

To conclude, policies such as obligations, incentives and financing schemes to support private customers in accessing capital, as well as fast and transparent procedures in response to regulatory frameworks, are key components for the further development of the solar-thermal sector.

Box 4: Support schemes for solar-thermal technologies in Europe

Germany: Germany has supported the solar-thermal industry with grants since 1995. The financial incentive scheme has developed over years, with strong fluctuations in stability and market adoption, but with a long-term vision and leading to successful market development. Beyond financial incentives, Germany experienced a form of obligation in the municipality of Vellmar as part of the local energy policy. As a result, 80% of newly constructed buildings had solar systems installed[71].

Ireland: Since 2005, many Irish local authorities have established building energy. One of the requirements is that half of the demand for hot water and heating has to be provided with a renewable energy source. This is beyond the national target for energy efficiencies in buildings and several local companies have welcomed these new standards[71].

France: France introduced an incentive scheme – mainly a tax credit – making it the most subsidised solar hot water market in the EU in 2006. Consequently, solar hot water costs increased[72].

Sweden: As in France, the subsidy scheme launched in Sweden in 2000 led to an increase in the solar-thermal installations but also to higher costs of the systems, as the result of an increased demand that could not be met. Consequently, the effect of the support scheme in Sweden was disappointing. In Sweden, the market for heat pumps constitutes a very strong competitive alternative to solar-thermal, and the availability of solar irradiance is one of the lowest in Europe[72].

The Netherlands: Subsidy schemes were implemented from 1988 to 2003, leading to an increase in solar-thermal installations. Since then, new solar-thermal systems have been installed mainly in new buildings, showing that the solar-thermal market was strongly stimulated by the incentives. However, despite having strict energy efficiency requirements, it is still encouraged to include installations of solar-thermal systems in new buildings[72].

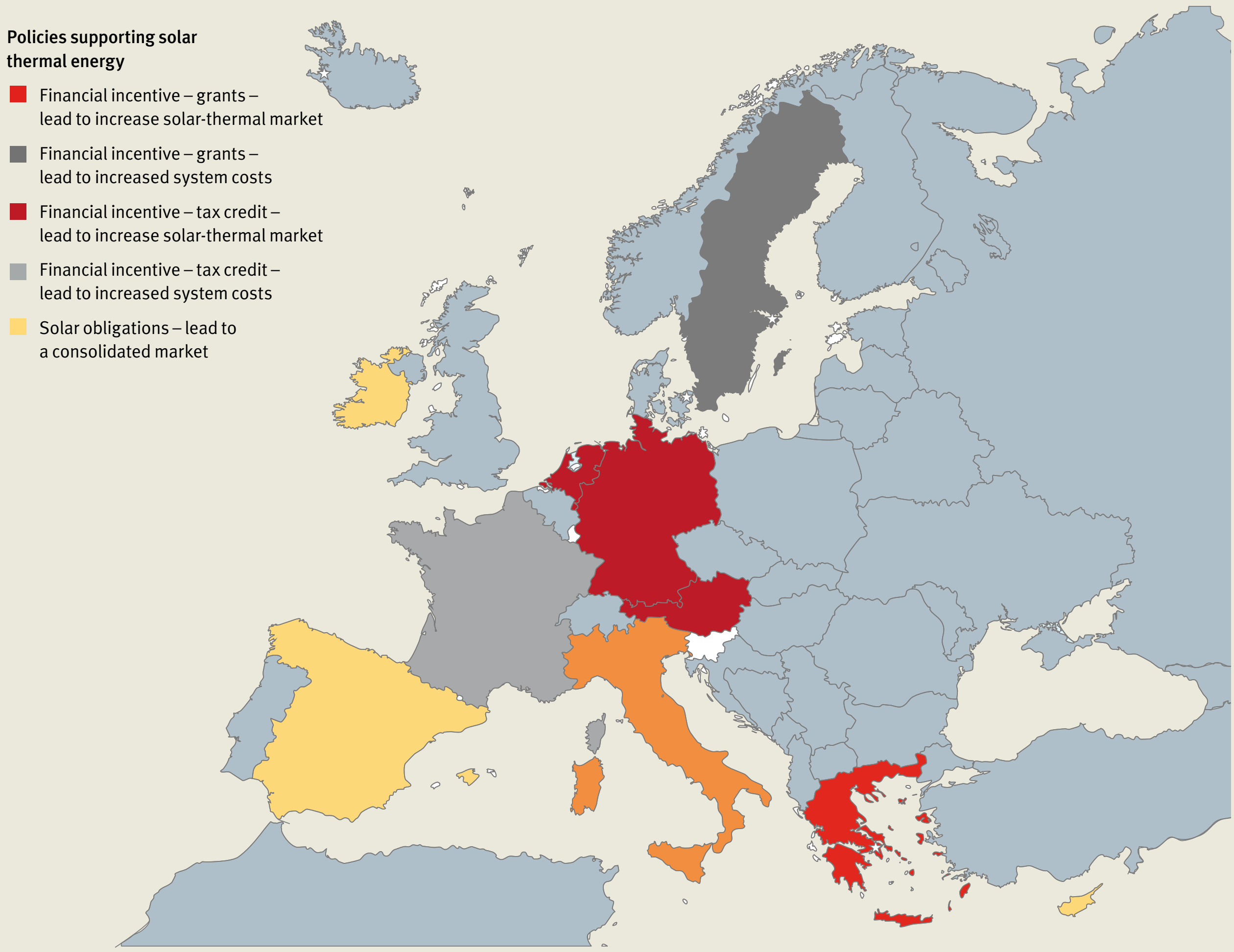
Austria: Has supported the installation of solar-thermal systems for 30 years. The continuity of the subsidy scheme, requiring a minimum of 4 m^2 of collector area for domestic hot water installed, led to a high dissemination of solar-thermal in all regions. Some, regional building regulations also have obligations to install solar-thermal on single or multifamily houses (e.g., in the state of Styria). Since 2010 large solar-thermal systems (>100 m^2) receive a financial incentive for large industrial heating and cooling projects, process heating and innovation[72, 73].

Italy: Since 2007, the government has promoted a 55% tax deduction on new solar-thermal installations aiming to promote energy efficiency, resulting in the growth and consolidation of the solar-thermal market. Locally, municipalities and regional governments have also adopted renewable heat obligations (the national obligation is yet to be approved). One example is the municipality of Carugate that introduced an obligation to meet at least half of domestic hot water demand from solar-thermal energy in 2003. Since then, around 220 kW of new solar-thermal systems have been installed or approved, reaching a solar energy use 30 times higher than the national average. It should be mentioned that the additional cost of solar-thermal constitutes only 0.5% of the total cost of the building[71, 72, 74, 75].

Spain: Solar obligations are introduced at the local level for buildings, pools and industrial use up to 60 °C. The penetration of solar-thermal in Barcelona increased by a factor of 20 since the adoption of the obligations[71]. Other than solar obligations, public financial schemes are available for energy efficiency measures[76].

Greece: The solar-thermal market was supported centrally by a scheme comprising a tax reduction directly proportional to the household income from 1970 until 2002, by which time the solar market in Greece was considered mature and established[72, 77].

Cyprus: In 1974 the government introduced a solar obligation, leading to a boom in the construction industry. Since 1984, the solar collector area installed in Cyprus has grown from 25000 to 690000 m². A combination of growth of the construction industry, obligatory solar water heaters, high electricity prices and favourable weather conditions determined a fast growth of the local solar-thermal industry[78-80]. Today, Cyprus is the leading country globally for solar-thermal installations, with 0.6 m² of collector area per inhabitant.



Pathways for innovation

Many successful solar-thermal projects have been already implemented worldwide in a wide range of applications and settings (Figure 1), providing ample best-practice examples for designers and energy planners. Further opportunities will rise from technological innovation, encouraging the adoption of more efficient and cost-effective systems. The main pathways for innovation include cost and performance improvements to existing technologies, and novel solutions that combine heat and power generation for applications where heating, cooling and electricity is required simultaneously. Amongst others, hybrid PV-T technology (which is at the focus of this briefing paper) is particularly promising in the urban environment where efficient use of space is essential.

Solar-thermal systems

In the context of distributed heat and electricity generation, whereby generation is spread out amongst individual homes or localities rather than in centralised locations, space becomes a premium and the ability to generate the greatest quantity and quality of energy from a given area is a competitive advantage. Simultaneously, there is an urgent need to reduce systems costs and improve performance. The development of several innovations for solar-thermal systems is already underway:

Polymeric materials are being used for manufacturing of solar thermal absorbers, reducing the module cost due to lower raw material and manufacturing costs. Polymeric absorbers are also lighter in weight than conventionally used copper or aluminium, providing additional benefits to the installation of the overall system[86].

Technological developments are still required for making solar-thermal applications between 250 °C and 400 °C commercially feasible. This requires the development of high-efficiency collectors with advanced features for improved heat transfer, such as transparent covers with anti-reflective coatings for high optical transmission[87], switchable coatings to reduce the stagnation temperatures[88, 89], new absorber materials with low emission coatings[90], temperature-resistant super-insulating materials, and the use of high vacuum or noble gases.

Automatic and advanced control and monitoring could be used to guarantee the expected long-term performance of the systems, provide demand response strategies, while reducing maintenance costs. When a solar-thermal system fails, underperforms or the irradiance is too low, thermal energy is often supplied from a backup system which generally relies on conventional energy sources. Monitoring of flow rates, temperatures and weather data is required to assess the system's performance and to predict potential failures. In addition, the operation of the solar system can be adjusted according to weather forecasts and user behaviour statistics, achieving an optimum output that maximises savings[91, 92].

Market development and innovation can reduce the high initial cost of the collector (~15%) and other system components (BOS). Collector production costs have shown a learning curve of 23% in Europe[93], similar to the reduction in the costs of PV modules[70, 94]. For example, the BOS of PV systems learning rates has been 22% in the German PV market for the period 1992-2001, with a learning rate for inverters in the range of 4-9% over the period 1995-2002[94]. Standardised hydraulics components, connections and 'plug and function' concepts[93] have the potential to improve installation models, reducing costs and improving systems reliability.

Hybrid PV-thermal systems

The widespread adoption of solar-energy systems requires low system costs and maximum high-quality energy to be generated per m^2 of roof coverage. Hybrid PV-T systems, which combine the basic principles of PV and solar-thermal collectors, generate both electricity and a useful thermal output from the same aperture area (see Box 5). By benefitting from integration synergies, a liquid PV-T collector can generate up to 40% more energy than PV and solar-thermal panels installed side by side over the same area, despite lower sun-to-electricity and sun-to-heat conversion efficiencies with respect to the separate panels[95-97]. These systems are best for small and weak roofs where installing two arrays side by side is not ideal, or applications where heat and electricity are required simultaneously.

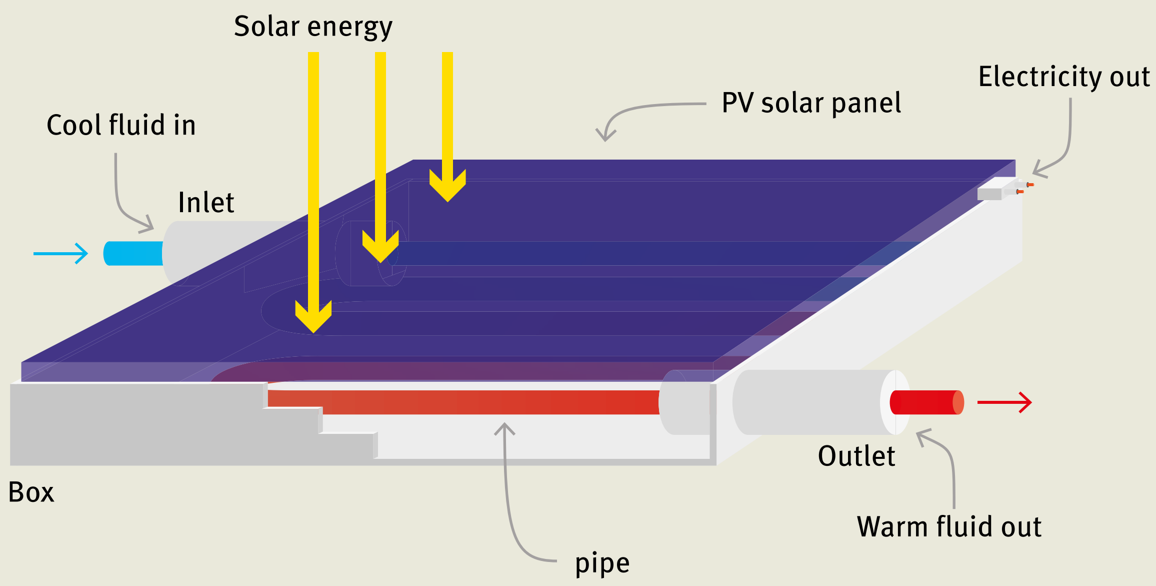
Despite the lack of long-term system performance data from demonstration projects, the potential of PV-T systems has been confirmed with predictive simulations using reliable computational tools, such as TRNSYS [102]. It has been estimated that PV-T systems can cover ~60% of the heating demand[48,103] and more than 50% of the cooling demand[48] of average residential buildings in southern Europe. In addition, PV-T collectors that heat air can be used for ventilation and space heating, or air pre-heating purposes, and can be easily (and aesthetically) integrated into building walls and roofs[104, 105]. Building-integrated modules on facades with a ventilation air gap behind the module create natural ventilation and reduce the heat losses through the wall, providing renewable heating and reducing the energy demand at the same time. These systems are scalable, as demonstrated by the CIS Solar Tower in Manchester, which incorporates 391 kW of ventilated integrated PV modules on the building's façade, making it the largest commercial solar facade in Europe and one of the largest power systems in the UK[106]. Building-integrated air PV-T systems have the potential to reduce the primary energy required for heating and cooling from conventional systems by 30%[107], and in pre-heating applications where the fluid temperature is kept low, such as in combined PV-T/heat-pump systems, the electrical output can be enhanced by 4-10% compared to an equivalent non-cooled PV system[108].

Box 5: Operation principle of hybrid PV-T collectors

In a PV-T collector, a thermal absorber and the PV cells are integrated into a single module. The sunlight that is not converted to electricity, and not lost to the surroundings, is transferred to the rear thermal absorber and to the fluid. As a result, both heat and electricity are generated from the same panel. The same considerations apply to PV-T regarding the variety of module designs as for thermal collectors.

In a conventional PV module, 90% of the sunlight is absorbed, but only ~15% of this is converted to useful electricity [98, 99]. The rest is partially stored as thermal energy (which is why PV modules can reach temperatures up to ~80 °C during operation on hot days) and ultimately lost to the environment. In a PV-T module, a useful fraction of the heat loss is instead transferred to a fluid stream at the back of the solar cell resulting in a thermal output that can be used in various applications.

The efficiency of silicon solar cells drops by 0.4% per °C temperature rise from 25 °C [100, 101]. If heat is required at low temperature (e.g., for heat pumps or pool heating at ~40 °C) the PV module is cooled down by the fluid so that the module itself operates at a higher efficiency, making the electrical output of the PV-T system higher than that of an equivalent conventional PV system. This means that on a sunny day, when the module temperature reaches 80 °C, a PV module with an 18% peak efficiency at the standard temperature of 25 °C will operate with an efficiency of about 14% if no cooling takes place.



A PV-T module increases the longevity of the PV cells as these are operated at lower temperatures, especially in applications such as swimming pools, hotels, heat pumps and underfloor heating, which require a large amount of low-temperature heat. This benefit arises from the fact the solar cells in PV-T collectors suffer lower temperature stresses, which are known to give rise to major causes for PV system failures due to cell breakage, encapsulation discolouration and delamination[109].

Moreover, PV-T systems enable 'self-consumption' – the generation and use of electricity on site. Self-consumption is the cheapest way to generate energy with renewables and reduce the stress on the local grid at the same time[26, 110]. PV-T systems can be integrated with heat pumps or cooling systems and the electricity generated in excess could be stored in the integrated thermal store, or in the ground to be reutilised by ground-source heat pumps[111-115]. Careful planning of the energy use (demand-side management) may also be important in the effective operation of the system[111, 112].

Even though PV-T systems combine the benefits of solar-thermal and PV technologies, only a small number of manufacturers are producing PV-T systems and the market remains small. In the UK, there are only a few hundred such installations[116]. The capital cost of a PV-T system in the UK is up to \$750 per m^2, of installed area, twice the cost of an equivalent PV system[116]. The main system-cost component is attributed to the collector and there is a large potential for designing and manufacturing cost-competitive modules. Estimates conducted in the framework of the International Energy Agency (IEA) Task[35] indicate a potential cost reduction of roughly 10% for PV-T installations compared to the combination of separate systems with market development[117].

Technology drivers for disruptive market innovation

Technology drivers that offer opportunities for disruptive market innovation (DMI) include:

Higher efficiency/lower cost PV: Current norms are in the order of the efficiency range 14-21%[118]. Promising studies include work on gallium-based cells with efficiencies of the order of 40%, under concentrated sunlight, and the potential to operate at higher temperatures[119], as well as highly affordable advanced thin-film PV technology. A roll-out of these would transform the PV-T sector, reducing footprint or increasing yield for a given footprint.

Improved heat transfer technology: Interesting developments in enhancing heat transfer include the use of nanoparticles suspended in heat transfer media[120], and the use of heat pipes[121] or thermosyphons (e.g., the Virtu product range produced by Naked Energy[116, 122]). Passive-active heat-transfer methodologies also offer an interesting potential for use in PV-T installations.

Packaging: Of significant potential are innovative approaches to packaging, installation and connection. Influential barriers to market entry are the cost of installation and the required skills[116]. 'Plug and play' approaches offer an opportunity for new types of install, new business models and even DIY.

Enclosures: Use of spectrally selective materials to improve and enhance optical performance and optimise PV-T effectiveness for variable conditions[87, 123, 124].

Energy storage: Chemical, thermal and electrical storage technologies continue to advance. Any reliable and cost effective solution to energy storage could transform the PV-T sector, negating the effectiveness and meaning of any policy interventions in place.

Possible future scenarios and conclusions

Figure 6 shows the global cumulative installed solar-heat capacity, which has grown by 16% per annum on average since the turn of the millennium. The IEA has projected that, by 2050, solar heat capacity could reach 7700 GWth [5,35], which represents a more modest growth rate of 8% per annum from the present day onwards. The IEA 2050 projection corresponds to 1.3 m² of installations per person by 2050 and 1 m² of installation by 2020 [125]. This is not far off what has already been achieved by champion nations including Austria and Cyprus, which both installed 0.6 m² per person in (2014), Greece with 0.4 m², China with 0.3 m², and Germany, Turkey and Denmark with 0.2 m² [24]. This list includes nations with a broad range of annual irradiances and GDs, thereby attesting to the technical and economic feasibility of this goal. The key to realisation lies in policy and incentives at national, EU and global levels.

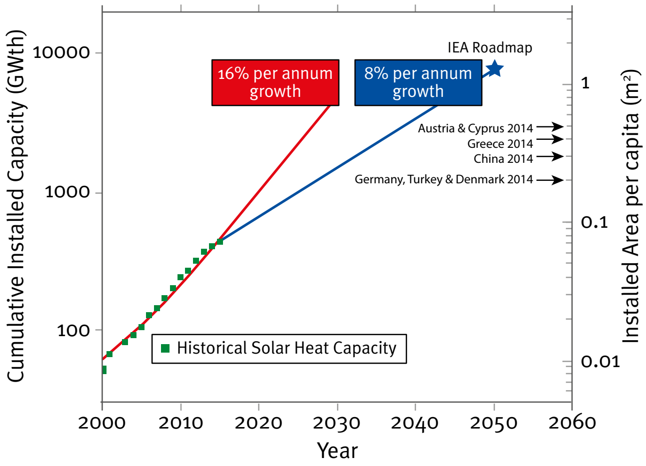


Figure 6: Global cumulative installed capacity of solar heat and future trends.

Due to the difficulty in transporting and storing thermal energy, solar-thermal collectors are most often installed close to the point of heat use. In order to assess the feasibility of the IEA's 2050 projection, we estimate that at least 3.8 m² per person of roof space is available in London for solar PV and thermal installations[126]. Hybrid PV-T collectors will be especially competitive in this context, as they provide heat and electricity from the same area, thus making the target set by IEA achievable.

As stated above, a combination of support schemes (obligations or/and incentives), local conditions (resource availability or/and fuel prices) or local opportunities (district heat network availability) will determine the market growth of the solar-thermal industry. These factors will help capitalise on the significant potential for increasing the total installed solar heat capacity in the UK, Europe and beyond.

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Glossary of terms

Power generation cycles:

a Thermodynamic power cycles: Thermodynamic systems that generate electricity from heat through a fluid that is heated at high pressure and expanded through a turbine or another expansion machine.

b Solar cooling cycles: Thermodynamic systems that use solar heat as a primary energy source to generate a cooling effect (also referred to as thermally-driven chillers); may also require an electrical input.

c CO_2 equivalent: A measure used to compare the emissions from various greenhouse gases and it is based upon their global warming potential.

d District heating/cooling network: Technology that connects multiple thermal loads with a piping network to achieve improved utilisation of various energy vectors such as combined heat and power generators, industrial waste heat and renewable heat.

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