



Large-scale solar thermal systems in leading countries: A review and comparative study of Denmark, China, Germany and Austria

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HIGHLIGHTS

- Comprehensive analysis of country-specific boundary conditions and success factors.
- National heat supply systems and incentive policies are essential.
- Role of district heating utilities in Denmark for solar district heating success.
- Technological solutions and best practice examples of large-scale systems.
- First-hand market research on China shows higher market penetration than assumed.

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ABSTRACT

Large-scale solar thermal systems are a cost-efficient technology to provide renewable heat. The rapid market growth in the last decade has been concentrated on a small number of countries, with the outstanding position of Denmark followed by China, Germany and Austria. This paper provides a comprehensive overview of the market and common technological solutions for large-scale solar thermal systems in these countries. Country-specific factors, including solar resources, heat supply systems, competing technologies, promotion schemes and business models, which put these countries in a leading role, are analyzed in detail using an integrated assessment framework. For each country, a best practice solar heating system is introduced. The analysis shows that heat supply by large-scale solar thermal systems is a mature technology with a broad field of applications and that mainly country-specific boundary conditions regarding the heat supply system and incentive policy are responsible for the preeminent role of these four countries. The unique role of district heating utilities in Denmark, which are subject to a national emissions trading system and often act both as investors and operators of large-scale solar thermal systems, can serve as a role model for other countries.

1. Introduction

About 50% of the total final energy consumption in the world attributes to heat used in the residential and industrial sector [1]. Space heating and domestic hot water can reach up to 80% of the final energy consumption in the residential sectors of EU countries [2]. 84% of the heating and cooling energy consumption in the EU is still based on fossil fuels while only 16% is provided by the renewable energy sector [3]. To reach the climate and energy goals of the Paris agreement and international and national energy policies, decarbonization and energy

efficiency increases cannot be limited to the electricity sector. The transformation of the heat sector must also be accelerated [4].

Solar thermal supply of low temperature heat demand (not exceeding 95 °C) can play a significant role in the future energy mix and could reach more than 16% of total final energy use (16.5 EJ) for low temperature heat by 2050 worldwide [5]. For many European countries, the overall solar thermal potential is estimated to be in the range of 3–12% of the total heat production [6]. There are good prospects for China as well. The Chinese government aims to reach 3.5 billion m² space heating area using renewable energies by the end of 2020, while

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Nomenclature

CHP	Combined Heat and Power
CPC	Compound Parabolic Collector
DH	District Heating
DHW	Domestic Hot Water
DNI	Direct Normal Irradiance
ETC	Evacuated Tube Collector
ESCO	Energy Service Company

FPC	Flat Plate Collector
LCOH	Levelized Cost of Heat
O&M	Operation and Maintenance
PTC	Parabolic Trough Collector
PTES	Pit Thermal Energy Storage
SDH	Solar District Heating
SH	Space Heating
TRY	Test Reference Year

the area of space heating using renewable energies by the end of 2016 was only 700 million m² [7]. The total installed area of solar thermal systems in China should be above 800 million m² by the end of 2020 [7]. With an estimated turnover of 16.9 billion USD in 2017 and 672,000 people working on production, installation and maintenance of solar thermal systems worldwide, the solar industry is already a major economic factor [8].

Solar thermal heat supply systems range from small installations for single-family houses, medium scale installations for multi-family houses, smaller heating networks and process heat plants to large-scale solar thermal plants [9]. Economies of scale make community sized SDH systems perform better in terms of system efficiency and energy costs than separate heat supply systems of single buildings [10]. Large-scale solar thermal plants are defined as systems with more than 500 m² collector aperture area or 350 kW nominal thermal power [8]; a factor of 0.7 kW thermal power per m² collector aperture area is typically used to convert collector area to nominal power [11]. The most common application of large-scale solar thermal systems is heat supply to DH networks and local heating networks with residential, commercial and public buildings, which makes up 88% of the total installed and operated capacity. Solar process heat, which is mainly used in the mining, textile and food industry, amounts to 12% [12].

By the end of 2018, the total installed and operated capacity of large-scale solar thermal systems reached 1.55 GW (2.2 million m² collector area) [8]. Although the installed capacity in large-scale systems is still relatively small with less than 1% of the total installed capacity of small-scale solar thermal systems, it is quickly rising in importance. The market has been experiencing rapid growth recently, with an average 15.5% increase per year in the main markets of Denmark, China, Germany and Austria between 2010 and 2018. This contrasts the global solar thermal market, which has been shrinking by 2.8% per year in the same period [13].

The driving force for large-scale solar thermal systems has been SDH applications in Denmark, where by the end of 2018 a total of 118 plants with a capacity of 970 MW were in operation, making up 63% of the capacity worldwide [8]. Denmark is followed by China (212 MW, 55 systems). China could become the leading market driver and surpassed Denmark regarding newly installed capacity in 2017 and 2018 for the first time. Market data for China might substantially underestimate the total and newly installed capacity (see Section 4.1). Germany (45 MW, 27 systems) and Austria (27 MW, 23 systems) successfully established niche markets for large-scale systems, ranking number three and four if the two big solar process heat plants in Oman (104 MW) and Chile (28 MW), which were singular installations and not part of a broader market development in Oman and Chile respectively, are not considered. Besides these four countries and Oman and Chile, only Saudi-Arabia and Sweden reach more than 20 MW total installed capacity in large-scale solar thermal systems. Denmark, China, Germany and Austria have a combined market share of 81% in the world [8].

The deployment of large-scale solar thermal systems being concentrated on a small number of countries and the diametrical developments of the markets for large-scale and small-scale systems call for a twofold analysis. First, a country-by-country analysis of Denmark, China, Germany and Austria is used to identify conducive boundary

conditions for large-scale solar thermal systems. These countries are particularly suitable for such an analysis, as they are home to the four main markets for large-scale solar thermal systems and have their own distinct boundary conditions. Second, the success of large-scale solar thermal systems can be analyzed on a technological level, addressing the benefits and challenges of upscaling solar thermal systems.

Although heat supply by large-scale solar thermal systems is a mature technology, empirical work on its success factors is still scarce. Most of the literature such as [6], focuses on the potential of the technology rather than existing conducive boundary conditions, or remains on a strategic level, lacking a clear link to existing markets. Available market statistics, like Solar Heat Worldwide [8], do not provide in-depth analysis of market dynamics. Recent review articles such as [14], are limited to the technology.

The article fills this gap by providing the first comprehensive and comparative study on large-scale solar thermal systems in the most successful countries (Denmark, China, Germany and Austria), in order to identify crucial country-specific factors which made these countries successfully deploy large-scale solar thermal systems. The integrated assessment framework includes geographical, techno-economic and environmental boundary conditions. Risk minimizing strategies such as yield prediction and performance guarantees, which have been largely neglected in research, are analyzed. The article highlights the unique role of district heating utilities in Denmark for the deployment of large-scale solar thermal systems. Country-specific success factors are related to market characteristics, which evolved from the national boundary conditions. A new market survey on China, whose market is still very little documented, is provided based on first-hand data collection from plant designers and institutions. The article also summarizes key features of wide-spread technological solutions. Both large-scale solar thermal systems for heating applications and solar process heat are included in the analysis. Additionally, a best practice example for each country is provided to demonstrate a successful project within the country-specific boundary conditions. The analysis of the technological solutions is limited to the solar collector circuit, which consists of one or multiple collector arrays and forms the core part of large-scale solar thermal systems.

2. Previous work and analysis framework

An extensive study on SDH identified 24 strategic approaches in the categories funding, financing, regulations and taxes and additional measures to facilitate the success of SDH [15]. According to the study, the success of SDH is a multifactor combination of technological conditions (e.g. low cost of solar thermal integration into existing networks), energy policy measures (e.g. taxes on fossil fuels), financing and business models (e.g. cheap loans) and most importantly low LCOH (e.g. realization of economies of scale). In Denmark, solar thermal systems bigger than 7 MW (10,000 m²) with diurnal heat storage reach LCOH of 36 €/MWh on average, and the LCOH of systems bigger than 35 MW (50,000 m²) with seasonal heat storage (which is a major cost factor) are 49 €/MWh [16]. The optimal integration of seasonal storages in SDH systems regarding design and operation were studied by [17]. Another study highlights the importance of cheap land for

ground-mounted collector arrays [18]. The study concludes that economies of scale of solar thermal systems with ground-mounted collector arrays often compensate for the extra cost of transmission pipes if the collector array is set up outside a town as opposed to smaller solar thermal systems on the rooftops within a town. As highlighted by [19], an important success factor is also the involvement of one or several strong local actors with the knowledge and interest to build solar thermal systems, such as local city governments, utilities and manufacturers. The lifetime of the solar collectors is very important too. It has an influence on the possibilities to get loans for a plant [20].

In a broader perspective, the construction and operation of large-scale solar thermal systems is the realization of a renewable energy potential. A generic and integrated approach to assess renewable energy potentials is provided by [21]. According to this approach, the renewable energy potential is divided in a geographical, technical and economic potential, followed by the implementation potential which determines if and how fast the geographical, technical and economic potential is realized, e.g. through subsidies, feed-in tariffs, business models and regulations. In this paper, crucial aspects of these four categories are addressed. A core part of the techno-economic potential lies in the solar collector circuit technology, which is described on a transnational level, as it is available in all leading countries and accrues to the technology as a whole. Transnational factors intermingle with country-specific boundary conditions. Table 1 provides an overview of the used categories to describe crucial aspects of the four potentials.

A systematic techno-economic analysis of system parts other than the solar collector circuit is beyond the scope of this paper, but some aspects of the overall system design, operation and integration are highlighted within the best practice examples in Chapter 6. Although the dimensioning, design and operation of the solar collector circuit depends on the overall system integration and control strategy, many techno-economic innovations for the solar collector circuit can be treated relatively independently of the remaining system. Furthermore, local conditions within a country can influence the renewable energy potential [22]. They are not part of this analysis and should be addressed in subsequent studies in more detail where necessary.

3. Large-scale solar collector circuit technology

The solar collector circuit consists of one or multiple collector arrays, typically operated with an anti-freezing liquid and separated by a heat exchanger from the demand side. Depending on the system design, plants include diurnal or seasonal heat storages and are combined with auxiliary heat sources, such as biomass and fossil fuel boilers, heat pumps, power-to-heat and waste heat. For DH networks, different options exist for system integration, such as return/supply connection (water taken from the return pipe of the DH network is fed to the supply line) and centralized/decentralized feed-in [14]. In general, the overall aim of the plant design is to minimize the LCOH by maximizing the solar yield over the lifetime of the plant while keeping the investment and O&M cost low. As large-scale solar thermal systems require high initial capital investment, risk minimizing strategies are needed as well. In this chapter key techno-economic features of the collector array technology, which are of special interest to large-scale applications, are summarized.

3.1. Collector design

Flat plate collectors (FPC) are the most common collector technology in the European market for large-scale systems [8]. Collectors have undergone a strong development in the last decades with regard to efficiency, quality, cost reduction and long-term reliability [20]. Collector modules used in large collector arrays usually have areas of 12 to 14 m² [23], whereas collector modules in small-scale applications have typically areas of 2 to 3 m² [24]. The larger size makes installation faster and more cost-effective by reducing the number of hydraulic

connections and mounting support. The large size also reduces heat losses by fewer cold bridges [25]. Aluminum strips are commonly used as absorbers. They are cheaper than copper, which was the main material in the last decades [24]. The absorber has a selective coating in order to absorb most of the radiation within the solar spectrum and have low emissivity of heat radiation at higher temperatures [26]. Given the large size of the collectors, several absorber pipes are connected in parallel, running from the inlet to the outlet manifold, to reduce the pressure losses. To reduce the heat losses of FPCs at higher operating temperatures, collectors with glass and foil or double glass instead of single glass are used. In some cases, collectors with single glass and with foil/double glass are deployed in the same collector array, the former at the beginning of the row and the latter at the end, to achieve the most cost-effective row composition [27]. For higher temperatures in the range of 80–100 °C, the efficiency of FPCs decreases due to increased thermal losses. Evacuated tube collectors (ETC) are more efficient than FPCs in higher temperature ranges and have been also successfully deployed in large-scale systems. Parabolic trough collectors (PTC) have been developed to achieve good efficiency in the temperature range of 70–150 °C. An advantage of PTCs lies in the reduction of the absorber surface by concentrating the radiation with mirrors. They have attracted attention for large-scale applications in recent years [28]. For ground mounted FPCs, mounting techniques using pile-driven or screw-in foundations instead of concrete pedestals have become widespread recently, because it allows faster and less intrusive mounting.

As collector designs have reached a very high standard, the focus has shifted to the optimization of the manufacturing process through automation. Large FPC manufacturers like Arcon-Sunmark A/S or GREENoneTEC GmbH use almost fully automated assembly lines. The main cost reduction has been reached in the production of the absorber. For harp and meander absorbers, which are most commonly used for large-scale FPC, tailoring of the manifold and absorber pipes, welding of the absorber pipes to the absorber plate and brazing the absorber pipes to the manifold have been completely automated. Meander absorbers use fewer absorber pipes compared to harp absorbers, which reduces the number of brazing spots. Robot manufacturing has brought down the share of labor cost [29].

3.2. Hydraulic layout

The objective in connecting collectors is to increase their hydraulic length, that is, the thermally active pipe length the fluid must flow through between inlet and outlet pipes. A higher thermal length allows to achieve a large and useful temperature increase with a low volume flow [30]. A homogenous flow distribution is important for an efficient operation. Heterogeneous flow distribution causes uneven temperature distribution in the collector array. In the worst case, it can lead to partial stagnation if parts of the collector array reach the boiling temperature of the heat transfer medium [31]. The main influence on the

Table 1
Integrated analysis framework to assess the solar thermal potential.

Factor	Category	Level	Section
Geographical	Solar resources	C	5.1
Techno-economic	Collector design	T	3.1
	Hydraulic layout	T	3.2
	Plant control	T	3.3
	Solar yield prediction and performance guarantees	T	3.4
	Heat demand and heat supply infrastructure	C	5.2
	Energy prices of competing technologies	C	5.3
Implementation	Promotion schemes	C	5.4
	Business models and regulations	C	5.5

C = country-specific, T = transnational.

flow distribution inside FPCs is the basic hydraulic collector type (harp or meander) and the dimensioning of the absorber and manifold pipes, i.e. the pressure drop ratio between the manifold pipes and the hydraulic elements they are connected to. Additional factors are the friction losses at the T-pieces, connecting the absorber and manifold pipes, and buoyancy effects [32]. Both within the collector and for the whole collector array, the flow distribution is influenced by the mass flow and temperatures. If a homogenous flow distribution is difficult to achieve (e.g. for non-regular layouts or very large fields), putting balancing valves at the entrance of each collector row has proven successful [33]. Additionally, gradually reducing the pipe diameter for the parts of the collector array with less volume flow can help to achieve a more homogenous flow distribution and save piping cost, but this requires exact advance calculations, as subsequent adjustments would be very expensive [30]. Remaining air/gases can disturb the hydraulic flow balance in a collector array and nowadays often vacuum degassing of the heat transfer fluid is used, at least at start-up of a plant [34]. Flow distribution has been a problem during the early stages in the design of large collector arrays, the solutions which have been developed during the last twenty years are now technologically mature.

3.3. Plant control

As a basic principle, the system design and control strategy of a large-scale solar thermal system should be smart and simple in order to reduce the complexity of maintenance and service as well as to achieve a high operational reliability. The low-level control of the solar collector circuit is embedded in the upper-level control of the whole solar thermal plant [35]. A minimum feed-in temperature or minimum temperature increase from inlet to outlet (preheating) is typically agreed with the heat customer. Depending on the required temperature level (e.g. the supply temperature of a DH network) and the overall system design (additional heat sources, storages, indirect use of solar thermal energy by heat pumps, etc.), a set point curve for the outlet temperature of the solar collector circuit is determined. The low-level control of the solar collector circuit is typically model-based, whereas the upper-level control can have other control strategies like model-based predictive control including long-term weather forecasts [36].

To achieve a set point outlet temperature curve, large-scale solar thermal plants use frequency-controlled pumps to adjust the volume flow depending on the inlet temperature, radiation inputs and thermal losses. A simple, but effective approach of a model-based control strategy is to set the volume flow to the level which achieves the desired outlet temperature according to the characteristic curve of the collectors [37], in combination with a moving average filter on the measured solar irradiance. A more advanced approach to factor in the dynamic behavior is to use a finite dimension state space model [38]. The pump is usually switched on as soon as the radiation in the collector plane oversteps a defined threshold and the ambient air temperature is high enough. In the morning and after long non-operation periods, preheating of the collector mass, heat transfer fluid and piping system in the array (and of long connecting pipes if present) is necessary before there is a useful heat gain. The pump is switched off if the available radiation and temperatures do not allow to reach the desired outlet temperature with the minimal volume flow. In order to avoid short-term operation of the pump, there are usually dead-bands defined for switch-off. The operation of the pump is also stopped if the heat provided by the solar collectors cannot be used (stagnation) [39]. To avoid stagnation and overheating, night cooling can be used to lower the storage temperatures, such that more heat can be fed to the storage on sunny days where the demand is low. If no or a low concentration of frost protection liquid is used in the solar collector circuit, a frost protection mode is activated if low ambient temperatures occur, by using heat from the storage or DH network return side and transferring it to the solar collector circuit. The temperature in the collectors only needs to be heated safely above the freezing point of the fluid [37].

3.4. Solar yield prediction and performance guarantees

Large-scale solar thermal systems have very low O&M costs. The main cost is the electricity of the pumps if the plant is operated alongside a DH plant [18]. An estimate based on Austrian experiences sets O&M costs to 0.5% of the investment cost for large-scale FPC fields [40], Danish systems have maintenance costs of about 0.27 €/MWh. But large-scale solar thermal systems require high initial capital investment. Successful projects do not only need to minimize the LCOH, but also have to develop a strategy to deal with the financial risk. The plant owner is usually paid a fixed price per produced kilowatt hour solar heat if he sells the heat to a third party. Crucial for the economics of a project is the total sold solar heat over the lifetime of the plant. Thus, the solar yield prediction is very important. The solar yield essentially depends on design, components and operation of the plant, load and environmental conditions and their interplay.

The prediction of the solar yield at the planning stage is done with simulation programs, such as TRNSYS [41] and PolySun [42]. Besides the simulation model, the reliability of the solar yield prediction depends on the input data. The crucial inputs are the efficiency parameters of the collectors (component parameter), an accurate estimation of the operating temperatures and load (operating conditions) as well as an accurate prediction of the direct and diffuse irradiance on the collectors (climate data). The efficiency parameters of collectors are obtained by testing a collector under standard laboratory test conditions according to ISO 9806, which offers a stationary and quasi-dynamic test procedure and is certified under the Solar Keymark certificate [43]. In recent years, the quasi-dynamic test procedure has gained popularity as its efficiency parameters describe the collector more accurately under non-stationary conditions than the stationary test and consider variable shares of direct and diffuse irradiance. As the conditions of the collectors tested in the laboratory and their operation in the field can be considerably different (soiling of glass cover, less-than-ideal stress of convection barrier foil, vegetation, etc.), in-situ testing of collectors to build systematic knowledge on the “real-world” performance is important. This is currently investigated in the research projects MeQuSo [44] and ZeKon in-situ [45].

If a new plant is planned, in many cases there is no reliable data about the yearly heat demand and its distribution over the year available. How to gain accurate assumptions of the heat demand still poses a problem for large-scale solar thermal systems, despite the existence of various simple load forecasting methods [46] and more advanced approaches [47]. Besides the load, the solar heat gain depends also on the operating temperatures. The higher the average operating temperature of the collectors is, the lower the efficiency becomes, because of higher heat losses of the collectors. For gas or oil boilers, this problem is much less severe, as the efficiency does not depend on the temperature levels (an exception being condensing boilers) and only to lesser degree on the heat demand (e.g. efficiency reduction due to partial load). The higher the solar fraction covered by the solar thermal system and the smaller the buffer storage capacity compared to the collector area, the higher is usually the dependency of thermal performance on load and environmental conditions. Lowering the solar share reduces this dependency and can be a strategy for risk mitigation.

Furthermore, an accurate prediction of the solar yield requires reliable data on the direct and diffuse irradiance of the location. The quality of the available data needs to be thoroughly investigated [48]. Many countries face a slow increase of the available solar radiation in recent years. Especially the DNI and total radiation on a tilted surface is increasing [49]. The increase can be in the range of 10% compared to standard long-term data for periods like 1961–1990. The reason for this increase is not fully understood yet, but there is a correlation to emission control especially of sulfur into the atmosphere [50]. The use of modern solar radiation data is therefore recommended for design and sizing of plants. A sensitivity analysis on parameter changes can help to quantify the effects of modeling and input uncertainties to obtain more

reliable estimates.

Performance guarantees for large-scale solar thermal systems are an increasingly important tool to minimize the risk associated with building a solar thermal plant. The performance guarantee can refer to single components (collectors, storages, etc.) or parts of the plant. A method to check the thermal power output which has been used in Denmark since more than twenty years compares the measured thermal power output against the estimated output based on the collector datasheet parameter when running the collector array under stable conditions close to full power [51]. It has been proposed as an ISO standard, and a working group under ISO/TC 180 is currently elaborating the standard. The main advantage of this method lies in its simplicity and easy applicability. The method is not suitable to check the solar yield for which new test methods are under development [44].

4. Market overview

4.1. Installed capacity

The newly installed capacity in large-scale solar thermal systems between 2010 and 2018 in Denmark, China, Germany and Austria is shown in Fig. 1. The data includes heating applications and solar process heat. Data for Denmark [52], Germany [53] and Austria [54] is based on regularly conducted market surveys. For China, a new market survey was done. Data from the main designers of large-scale solar thermal systems – Sunrain, Five Star, Linuo – and the institutions China Academy of Building Research, Chinese Academy of Science, IMSIA and Solrico were collected. A distinct characteristic of Chinese DH networks is that they typically only provide space heating (see Section 5.2). DHW systems are mostly installed for local grids, which are not connected to DH networks. These systems can be much larger than 500 m² collector area. In the market survey on China, only data for space heating and industrial applications were considered. According to these data, there are 55 systems with a total capacity of 212 MW in operation by the end of 2018. As there are plenty large-scale DHW systems and data for space heating and industrial process plants might still be incomplete, the Chinese large-scale market is presumably much bigger. The figures are significantly higher than [8], which list only 21 large-scale solar thermal systems in China.

In 2010, all countries together installed a capacity of 38 MW (55,000 m²). In the record year 2016, a total of 366 MW (523,000 m²) were installed. The main driver was Denmark, with a record of 348 MW (497,000 m²) installed capacity in 2016. In 2017 and 2018 the market declined rapidly, due to a decrease of the installations in Denmark. A major reason was the temporary exclusion of collector arrays connected to DH networks from the Danish emissions trading system (see Section 5.4). For 2019, the Danish market is expected to recover, as a new

agreement has been reached, which allows solar thermal systems to rejoin the emissions trading system. Installations in China made a significant step in 2017 and 2018, mainly due to PTC arrays. The market in Germany got a significant boost in 2016, which was caused by a new subsidy scheme and is expected to double in the next years [55]. The Austrian markets had a stable subsidy scheme during the last decade and no clear trend in market development is visible. All markets show a high dependency on promotion schemes (see Section 5.4).

4.2. System characteristics

The leading countries exhibit remarkable differences regarding the characteristics of their typical large-scale solar thermal systems (Table 2).

Denmark has a mature commercial market for large-scale solar thermal systems with distinct characteristics. Almost all systems provide heat to DH networks, there are no significant industrial applications. In the typical business case, a large-scale solar thermal plant feeds into an existing DH network and replaces a CHP plant which has become unprofitable due to low electricity prices [56]. All centralized and most decentralized CHP plants in Denmark sell electricity at the market price in the Nordic power market [57]. Selling prices for electricity have significantly dropped since 2010 [58], although in Denmark household electricity prices after taxes are the second highest in the EU [59]. The necessity of cheap and suitable land near DH network supply points typically limits SDH projects to small towns and villages. System sizes have been growing over the last years. Most of the largest SDH plants worldwide are in Denmark. The so far largest FPC system, located in the Danish town of Silkeborg with a capacity of 110 MW (157,000 m²), started its operation in 2017 [16]. For plants without a seasonal storage, system sizes are limited by solar fraction. If the solar fraction becomes too large, heat production can become inefficient due to stagnation during the summer months. Eight plants have seasonal heat storages. Average yearly yields of SDH plants are around 400–500 kWh/m² (collector aperture area) [60]. Low heat prices can be achieved by highly standardized system concepts, reliable components, low land cost, favorable financing and existing low temperature DH networks.

China has dominated the market for small-scale solar thermal systems for many years, accounting for 89% of the installed capacity by end of 2016 [16]. Large-scale solar thermal systems for space heating and industrial processes have only started to be installed in recent years. In comparison to Denmark, where most plants use FPCs, ETCs and PTCs are also widespread in large-scale applications. One 75,000 m² PTC plant for DH supply was constructed in Inner Mongolia in 2017.

As in Denmark and Austria, large-scale systems in Germany mainly

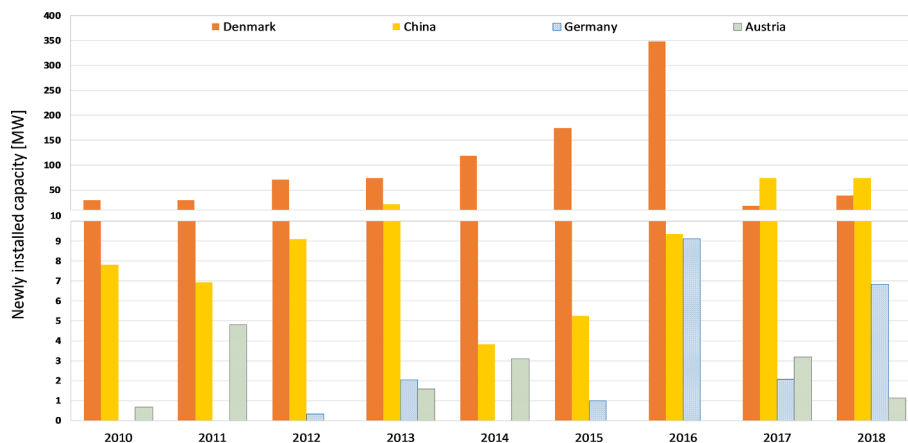


Fig. 1. Development of large-scale solar thermal systems from 2010 to 2018.

Table 2
Characteristics of large-scale solar thermal systems.

	Denmark	China	Germany	Austria
Number of plants (2018)	118	55	37	23
Total installed capacity (2018)	969 [MW]	212	45	27
Installed capacity per 1000 inhabitants	167 kW	0.15 kW	0.55 kW	3.08 kW
Total installed collector aperture area (2018)	1,384,000 [m ²]	304,000	65,000	39,000
Average collector area	11,700 [m ²]	5,500	1,800	1,700
Collector type (main)	FPC	ETC, FPC, PTC	FPC, ETC	FPC
Mounting (main)	Ground mounted	Ground mounted	Ground mounted	Roof mounted
Seasonal heat storage (main)	Water pit storage	Borehole storage	Multifunctional short- and long-term storage	None
Typical solar fraction	7–20% (diurnal storage), 40–50% (seasonal storage)	Up to 90%	7–20% (diurnal storage), 40–50% (seasonal storage)	10–20%
Applications (main)	SDH including SH and DHW typically for small towns	Industrial processes, SH with fixed heating season, separate DHW systems	SDH including SH and DHW, typically for villages and city quarters	SDH including SH and DHW, typically for villages and city quarters
Heat price (typical)	36 €/MWh (systems > 7 MW, diurnal storage); 49 €/MWh (systems > 35 MW, seasonal storage)	Not available	50 €/MWh	Not available

use FPCs, but ETCs have a relatively high share of 34% of installed collector area. A special system design with ETCs was developed, where the solar collector circuit is operated with water and not with an anti-freezing liquid as usual. This gives the possibility to omit the heat exchanger between the solar collector circuit and demand side, but requires heating of the solar collector circuit if temperatures are below freezing point [61]. Germany has a long history of seasonal heat storage deployment. In eleven pilot plants, built between 1996 and 2001, with the aim of reaching 50% solar fraction, different seasonal heat storage technologies (underground aquifer, borehole, pit and tank storage) were developed and monitored. Multifunctional short- and long-term storages for all heat producers have also been integrated into the system [62]. SDH applications range from small villages and rural areas, to SDH for districts and SDH in cities and urban centers. For cities and urban areas, SDH systems are usually combined with CHP plants, heating plants, waste incineration or industrial waste heat. Large-scale solar thermal plants can be used in a broad variety of industrial processes but this market is much smaller. Realized plants are providing heat for brewing, an absorption chiller in steel production, greenhouses, cleaning processes in food production and car washing [12]. Because of the good incentives, the solar process heat market is expected to grow [63]. Depending on the system size and efficiency of the solar thermal plant, heat production costs below 50 €/MWh can be reached without incentives [39].

The Austrian market is similar to the German market regarding system sizes and applications, although no systems with seasonal storage have been realized yet. Unlike in Denmark, urban applications are widespread. For urban applications, collectors are usually mounted on roofs of tower blocks or boiler houses. This limits the system size. Systems in the medium range of 100–500 m² are common in Austria, with around eight times more systems built in this range between 2010 and 2016 compared to large-scale systems [64]. Recently, combining large-scale solar thermal systems with heat pumps has become more common.

4.3. Solar industry

These four countries also have a strong solar thermal industry. Arcon-Sunmark A/S, the main manufacturer of FPCs in Denmark, installed more than 80% of the large-scale solar heating plants in Europe as a turn-key supplier [65]. China is the largest producer of ETCs [66] and was the leading country in FPC production in 2017 and 2018 [67]. Chinese companies seek to intensify economic ties with European manufacturers and turn-key suppliers. A joint venture between Arcon-Sunmark A/S and the world's largest collector manufacturer Jiangsu Sunrain Solar Energy was established in 2016 [68]. The Austrian based company GREENoneTEC GmbH, the world's leading FPC manufacturer [69], has been majority-owned by the Chinese Haier Group since 2017 [70]. The Swedish PTC manufacturer Absolicon set up a first production line in Sichuan province [71]. In Germany, the company Ritter XL Solar developed a large-scale solar thermal system concept for ETCs [61]. Consolidation of the solar thermal industry is likely to continue. On April 2 2020, Arcon Sunmark A/S announced that GREENoneTEC GmbH acquired key assets of its business and the Chinese Solareast Group (which owns the Sunrain and Micoe brands) bought the shares of the Chinese-Danish joint venture [72].

5. Boundary conditions

Besides the large-scale collector array technology and the overall system design, operation and integration (which is beyond the scope of this paper), the success of large-scale solar thermal systems crucially depends on country-specific boundary conditions. Each of the four investigated countries provides a particular framework which determines if large-scale solar thermal systems can be economically viable and how successful particular system concepts are.

5.1. Solar resources

The available solar radiation is one of the main factors affecting the solar yield of a large-scale solar thermal plant. For non-concentrating systems with FPCs, the achievable daily yield is usually approximately a linear function of the received total irradiance on the collector plane, where the slope of this function depends on the temperature difference between the operating temperature of the solar collector circuit and the ambient temperature [73]. Lower temperature differences are favorable for the solar yield, i.e. the slope of the curve increases. Concentrating systems deploy tracking to follow the sun and use the DNI. Non-tracking collectors have a fixed tilt and azimuth. The yearly irradiance on an optimally tilted and aligned surface is a good indicator for the achievable solar yield for non-tracking collectors. Although overview calculations for some regions exist [74], only data on global irradiance on horizontal surfaces is typically available from weather stations. Subsequently, data on global irradiance is used.

The global irradiance in the four countries is depicted in Fig. 2. Denmark belongs to the Nordic area. The solar radiation is not as favorable as in other regions, such as southern Europe [75]. Global radiation on the horizontal surface is between 1,000 and 1,150 kWh/m²/

year. DNI levels are around 800–1,100 kWh/m²/year [76]. The winter in Denmark is quite cold, with an average temperature of January and February just above freezing. The summer in Denmark is mild with temperatures about 13–17 °C [77]. In China, solar radiation resources vary a lot because of China’s different geographical situation. The lowest solar radiation areas are located at Chuan-Yu region (Sichuan-Chongqing) with around 950 kWh/m²/year [78]. The highest solar radiation levels are found in the Qinghai-Tibet Plateau with more than 2,200 kWh/m²/year. Two thirds of the land areas of China have DNI levels exceeding 1,095 kWh/m²/year (3 kWh/m²/day) [79]. Certain regions of the Qinghai-Tibet Plateau have even DNI levels of more than 9 kWh/m²/day. Solar radiation resources are very high in the cold regions in the west of China and Inner Mongolia. Global radiation in Germany varies from north to south between 1,000 and 1,200 kWh/m²/year and DNI between 750 and 1,150 kWh/m²/year [80]. The long-term average ambient temperature is around 8.9 °C [81]. In Austria most parts of the densely populated lower elevation areas in the western part have radiation levels above 1,150 kWh/m²/year [82]. The areas with the highest irradiance are located in the south with an irradiance above 1,250 kWh/m²/year. Typical DNI levels in lower elevation areas are in the range between 1,000 and 1,200 kWh/m²/year.

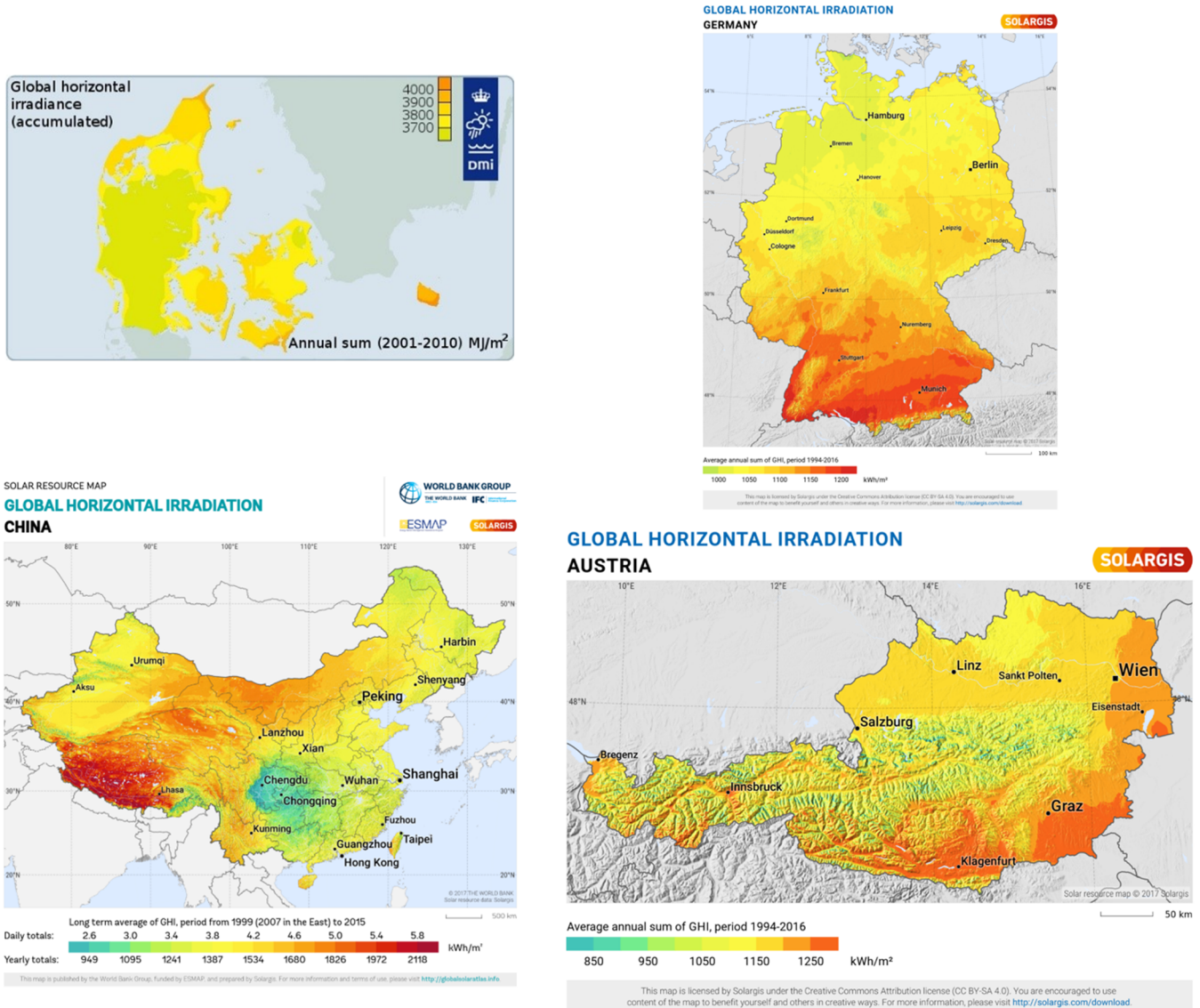


Fig. 2. Global irradiance in Denmark, Germany, China (mainland) and Austria; note that color scales differ among countries (source: Denmark [76], other: Solargis).

Long-term average ambient temperatures in major cities are around 10 °C [83].

5.2. Heat demand and heat supply infrastructure

Denmark has very favorable conditions for solar thermal integration into DH networks. The country has a long-standing tradition in DH. A total of 63% of Danish households are connected to DH networks [57]. Almost 70% of the DH supply is provided by CHP plants. Denmark has also a relatively high summer load [84]. Typical supply/return temperatures of DH networks are 75/35–40 °C [23]. DH networks include both SH and DHW. Initiatives to reduce individual heating are also favorable for the development of DH. A ban on the installation of oil- and gas-fired boilers in new buildings was put in place in 2013, and since 2016 the installation of oil-fired boilers is prohibited in existing buildings [57]. Danish researchers also proposed low temperature 4th generation DH networks in Denmark [85]. Lower DH network temperatures of 55/25 °C could significantly decrease the operating temperatures of the solar collector circuit and increase the thermal performance of FPCs in 4th generation DH networks.

The Chinese DH networks currently cover around 8.5 billion m² of building floor area (building floor area is the typical unit of measurement), having nearly tripled since 2005 [86]. As urbanization continues, the building floor area in China is projected to increase by 40% by 2050, reaching more than 80 billion m² from 57 billion m² today. The total building floor area covered by DH networks in Northern China tripled over the last decade, increasing nearly as much as the combined floor area growth in the northern urban heating (NUH) area (north part of China) since 2005. Solar thermal systems face extremely favorable natural conditions in these areas due to high heat demand and high solar irradiance.

A characteristic of Chinese DH networks is that they often provide heat only for space heating. DHW systems are separate and not fed by the grid [87]. Space heating systems in most places in Northern China are only put into operation for several months in winter heating seasons. For instance, the operation period of space heating systems in Beijing is November 15 to March 15 next year (4 months). There is no space heating supply in the rest of the year. Typical supply/return temperatures of new DH networks (radiator heating) in China are 75/50 °C or 85/60 °C. For the floor radiant heating systems, typical supply/return temperatures are 35/30 °C or 45/40 °C [88].

Only 1% of the DH supply in China is currently covered by renewable energies [86]. More than 80% of space heating in Northern China are supplied by coal boilers, which is a main reason for the air pollution in winter. China has a great need to lower the environmental footprint of its DH networks and the country has pursued assertive public policy decisions in recent years towards cleaner and energy-efficient DH.

In Germany, the final energy consumption was 2,542 TWh in 2016 with more than 50% used for heating applications [89]. Renewable energy technologies are supplying a growing part of the heat consumption. In 2016, the share of renewable heat amounted to 164 TWh (13% of the heat consumption). Solar thermal plants contribute to around 5% of the renewable heat consumption and to around 0.6% of the total heat consumption [90]. The share of households connected to DH networks was 14% in 2016 (5.8 million households) with a heat consumption of 49 TWh. Almost the same heat quantity is used in industrial applications (48 TWh) and an additional 22 TWh by other consumers [91]. The heat production is mainly provided by CHP plants from gas (41%) and coal (29%). About 14% of the heat in DH was produced with renewable energies, mainly from biomass and renewable waste heat [91]. As there are no country-wide statistics about all DH networks available, it is likely that a lot of smaller systems are not included. For SDH systems, typical values for supply/return temperatures of DH networks are 70–110 °C/40–80 °C.

The Austrian final energy consumption amounted to 161 TWh in

2016, with a share of 52% attributed to heat [92]. In the same year, the energy fed into DH networks was 24 TWh. The heat supply to DH networks is provided with CHP (58%) and heating plants (42%) [93]. The predominant fuel for heating plants is biomass with a share of 61.4% [93]. The use of renewables (solar thermal, heat pumps, geothermal) within DH networks amounts to 1.72% [93]. Separate data for the solar thermal share is not available. Typical supply/return temperatures of DH networks are in the range of 75–95/55–65 °C and can reach 90–145 °C in the transport pipes during the heating season [15]. The high supply temperatures in winter restricts direct solar thermal supply to the summer months and sets limits to the solar fraction at which a solar thermal installation can be operated economically.

5.3. Energy prices of competing technologies

The market potential of large-scale solar thermal systems depends on the availability, price and environmental impact of competing technologies and heat sources. Coal, natural gas and oil are the prevailing fossil fuels in DH networks and industrial processes both worldwide and in Denmark, China, Germany and Austria [94]. The major renewable heat sources in future DH networks besides solar thermal are biomass, geothermal, waste heat from industrial processes and waste-to-energy [95]. If a large amount of waste or excess heat is available, solar thermal heat supply usually becomes less of a viable option [18]. Biomass is typically both a competing and complementing heat supply option. Combined solar thermal-biomass systems, where the solar thermal systems cover the main share of the summer load (especially reducing partial load operation) and biomass provides an auxiliary fuel during the winter months, offers advantages for both technologies [96].

Natural gas plays a significant role in the European short and medium term transformation strategy towards sustainability, as the CO₂ emissions are lower than for other fossil fuels [97]. Current large-scale solar thermal projects, like the world's largest solar thermal system currently in the concept phase, usually use costs from heat supply with gas boilers as the reference scenario [98]. Prices of natural gas in Denmark, Germany and Austria before tax have been stable and on comparable levels over recent years. After tax, prices differ significantly between Denmark (71.2 €/MWh on average between 2010 and 2018), Germany (37.7 €/MWh) and Austria (39.6 €/MWh). As the fuel constitutes the principal cost component of heat supply by natural gas boilers [99] and efficiencies are close to 100% [100], competitiveness of solar thermal systems with natural gas boilers implies prices in the range of around 70–80 €/MWh in Denmark and 30–40 €/MWh in Germany and Austria. Taxes on fossil fuels for heating purposes in Denmark are among the highest in Europe, with significantly lower taxes for industrial applications (with the exception of coal) and zero tax on biomass [101].

Prices for heat provided by biomass depend a lot on the location of the heating plant, because a major portion of market activity remains on a regional level within a country [102]. A recent study on Austrian biomass heating plants based on 20 case studies shows LCOH of 69 to 106 €/MWh with an average of 84 €/MWh (before tax) [103].

In China, the energy sector is heavily regulated. The main policy maker is the National Development and Reform Commission (NDRC) alongside the central government pricing authority and provincial/local government pricing agencies. Reforms towards a greater market system are under way in various sectors, such as natural gas [104] or electricity [105]. Energy prices can vary greatly by region, e.g. up to 52% for the non-residential natural gas price [106]. The typical price of electricity in China is 69 €/MWh including tax (for district networks). The price of natural gas in China is 35 €/MWh for heat supply by DH networks.

5.4. Promotion schemes

The Danish government introduced investment subsidies during the 1990s to support CHP plants, renewable energy generation and energy efficiency measures. Most of these grants are no longer available for new DH investments. However, decentralized CHP plants operating in the electricity market receive a premium tariff (the so-called capacity credit) on top of the market price plus an electricity production subsidy (for gas and waste-fueled plants) or a surcharge (for biomass or biogas-fueled plants). Since the end of 2018, this premium is only available for CHP plants using renewable energies [57].

An indirect incentive to the Danish SDH development is the requirement for all DH utilities to obtain a certain amount of energy savings each year. If a utility cannot reach the required savings, it has to buy credits from another utility, which has a surplus of “energy saving points”, because it was able to exceed its energy saving target [107]. The credits are quoted on a stock market on their own, similar to the carbon emissions trading system, thus varying in price per MWh of saved heat. The average market price between 2012 and 2014 was in the range of 40 to 50 €/MWh [14]. Former agreements between the Danish Energy Agency and the energy distributors which allowed collector arrays connected to DH networks to be part of this market counted the first year of solar heat production as energy savings, thus creating a surplus of valuable credits for the utility, which could pay back part of the investment. By the end of 2016, an agreement expired and was not renewed. This situation led many DH utilities to refrain from investing in new solar thermal systems, waiting to see how the situation would develop. This was a major reason for the sharp market decline in 2017 and 2018 (see Section 4.1). In 2019, a new agreement was reached [108], which is expected to help the market to recover.

The Chinese central government set up the “Clean Heating Initiative” for the period 2017–2021 to control air pollution. By the end of 2021, the percentage of coal boilers should be reduced by more than 50%. The authority supports the exchange of oil boilers with renewable energy for space heating, including solar thermal energy. In rural areas, oftentimes there are no heating devices. The Green Energy Revolution is one of the main steps to achieve rural revitalization under the policy of the roadmap for rural vitalization (“No 1 central document” of 2018). Rural areas have very cheap land, which may be an emerging market for solar space heating in the near future. In addition, some flagship local governments, like Shandong and Hebei, have their own subsidy programs to promote large-scale solar thermal systems. Based on the national solar energy development plan (2015–2020), the number of large SDH plants should reach more than 200 and the total installed collector area for SDH plants should reach more than 4 million m² by the end of 2020 [66].

Germany’s transformation strategy to renewable energies (“Energiewende”) targets a share of renewable energies of the final energy consumption of at least 18% in 2020 and 30% in 2030 [109]. In the heating sector, final energy consumption is to be reduced by 20% and the heat from renewable energies is to be increased to 14% until 2020. To reach these shares, one possible scenario “Erneuerbare Energien” aims to increase the heat supply by DH networks to 75 TWh/a in 2050. Meanwhile, the contribution from solar thermal energy to the final energy consumption should increase from 3 TWh/a in 2008 to 80 TWh/a [110].

In 2009, an incentive scheme (“Marktanreizprogramm”) was put in place for solar thermal systems [111]. Solar thermal plants with collector areas larger than 20 m² receive a subsidy of up to 50% of the investment costs. Plants larger than 40 m² feeding into DH networks receive up to 40% of the investment costs. Alternatively, a performance-based incentive can be chosen, where a rate of 0.45 €/kWh of the yearly collector yield (according to the Solar Keymark certificate) is paid once. The subsidy is limited to 45–65% of the total investment cost. Additionally, incentives for DH networks and heat storages are paid. Since 2009, active market development is done by Solites together

with the German district heating association AGFW and other partners in international SDH projects as well as in the German projects SolnetBW I and II and Solnet 4.0 [55]. In July 2017, the German Ministry for Economic Affairs and Energy has established a new subsidy scheme for feasibility studies and realization of innovative “District Heating Pilot Projects 4.0” (“Wärmenetze 4.0”), which supply at least 50% of their annual heat consumption from renewable energy sources or industrial waste heat and have a maximum supply temperature of 95 °C [112]. For solar process heat applications, a new promotion scheme has been established in March 2019, which subsidises up to 50% of the additional investment cost of a solar thermal installation with a maximum amount of 5 million EUR per project [113].

In the framework of the EU agreement on the climate-energy package, Austria committed to increase the share of renewable energies to 34% of the national energy mix by 2020 [114]. As part of a large strategy to promote the use of solar thermal energy, a special program was designed to promote large-scale solar thermal installations in 2010 [115]. Installations with a collector area of 100 to 10,000 m² (2000 m² until 2015) are eligible. The funding is based on the additional investment costs for the solar thermal system (including piping, storage, system integration) compared to a fossil fuel reference system. The funding percentage is 40% (> 2000 m²: 30%, > 5000 m²: 20%; +5% for small and medium enterprises) with a limitation of 750,000 EUR per project. A combination with other funding programs is possible. An accompanying research program has been established to systematically evaluate optimization and technology development potentials [116].

5.5. Business models and regulations

DH in Denmark is mainly regulated by the Heat Supply Act since its publication in 1979. The idea of this regulation is that end-users can benefit from DH. All DH utilities which follow the Heat Supply Act are non-profit. Consequently, 99% of Danish DH companies are owned and controlled by the consumers. The non-profit orientation allows DH utilities to have a long-term investment horizon, which is favorable for the capital intensive solar thermal technology. DH utilities usually provide the investment in new solar thermal systems, take on the financial risk and operate solar thermal plants themselves. Oftentimes, the municipality guarantees on loans, which allows utilities to get good financing conditions. As large-scale solar thermal systems are widespread in Denmark and system concepts are highly standardized, district utilities have gained trust and experience with the technology. Turn-key suppliers further help to minimize the technological risk [117].

In China, large-scale solar thermal systems for space heating and industry process heat just started in recent years. Projects mainly rely on subsidies from the government at the current stage. For example, the Langkazi Tibet Solar Heating project (see Section 6.2) is 100% subsidized by the central government.

In Germany, solar thermal projects are often realized in bioenergy villages (“Bioenergiedorf”), see Section 6.3 for a best practice example. Bioenergy villages cover the main share of their energy demand from local renewable energies. The projects are usually initiated by citizens, who cooperate with the municipality, local craftsmen, building companies and consulting engineers. Oftentimes, the citizens set up a registered cooperative to manage the energy supply and distribution, which has the aim of long-term favorable prices instead of short-term profit maximization. Furthermore, it allows a high degree of co-determination and limited liability risks. For the heat supply, wood chip boilers and solar thermal plants can be used to supply heat to the DH network [118].

Another typical business strategy for large-scale solar thermal systems in Germany is the change from fossil fuels to renewable energies in DH systems. One regulatory reason for this effort is the reduction of the primary energy factor of the DH network. With a reduced primary energy factor new customers meet the legal requirements for using

renewable energies in new buildings by connecting to the DH network [119]. Furthermore, DH companies as well as industries benefit from long-term cost stability of solar heat.

In Austria, the ESCo business model (also known as Solar Contracting) has become widespread for large-scale solar thermal systems. To overcome the burden of high investment cost and perceived uncertainty connected to solar heating, the ESCo takes responsibility for the investment, design and operation of the plant and sells the heat to housing facility owners and/or DH utilities, which pays a contracted price. All risks are mitigated to the ESCo. The Austrian company S.O.L.I.D. is the main driver behind solar ESCo and was able to realize, among others, four large plants feeding into the DH network of Graz [19].

6. Best practice examples

The best practice examples show typical system concepts, while at the same time highlighting the diversity of applications. Best practice examples were chosen based on numerous scientific research projects for system evaluation and performance analysis conducted by DTU for Denmark [60], Solites for Germany [55] and AEE INTEC for Austria [120]. The best practice example for China was built in collaboration with the leading Danish turn-key supplier Arcon-Sunmark A/S. The large-scale solar thermal systems Dronninglund SDH in Denmark, Langkazi Tibet Solar Heating in China, Bioenergy Village Büsingen SDH in Germany and Salzburg Lehen in Austria are introduced in this chapter. The basic plant data are listed in Table 3.

6.1. Dronninglund SDH (Denmark)

Dronninglund Fjernvarme is a consumer-owned cooperative, which

supplies around 1,350 consumers with a 46 km DH network (2016). In 1989, Dronninglund Fjernvarme became the first Danish DH company to install natural gas-driven engines for CHP production. In 2005, the board and general assembly of Dronninglund Fjernvarme realized that they should replace natural gas with renewable energies. In 2007, Nordjyllands Vækstforum subsidized a pre-feasibility study, which showed that a large-scale solar thermal system with seasonal heat storage could cover up to 50% of the heat demand. Furthermore, the heat production price would not be increased for the consumers in case of a subsidized investment [9].

The aim of the project was to prove the feasibility of heat supply for DH networks with large-scale solar thermal plants and PTES. Furthermore, the utilization of PTES to store excess heat from waste incineration, industries and CHP production is analyzed. The plant started to operate in May 2014 (Fig. 3).

A simplified hydraulic scheme of the plant is shown in Fig. 4. The collector aperture area is 37,573 m² (2,982 solar panels). The tilt of the solar collectors is 35° to maximize the annual solar yield. Each row of the collector array has 21 solar collectors connected in series. This is a typical number for collector arrays with harp-type collectors as in Dronninglund, as the pressure drop becomes too high or the flow velocity becomes too small in the manifold pipes if more collectors are connected in series. Inlet temperatures of the collector array are around 40 °C in summer and can drop to around 15–20 °C in winter. Outlet temperatures reach 80–90 °C in summer and typically 30–40 °C in winter.

The seasonal pit thermal energy storage with a volume of 62,000 m³ was built in an abandoned gravel pit. The ground water level is approximately 3 m below the bottom of the storage and the soil consists of gravel and sand. The storage is insulated at the top with a floating cover. Insulation for the area which separates the water from the

Table 3
Basic plant data of best practice examples.

Plant		Dronninglund SDH (DK)	Langkazi Tibet Solar Heating (CN)	Bioenergy Village Büsingen SDH (GER)	Salzburg Lehen (AT)
<i>Latitude</i>	[deg]	57.2 N	28.9 N	47.7 N	47.8 N
<i>Longitude</i>	[deg]	10.3 E	90.3 E	8.7 E	13.0 E
<i>Global irradiance (TRY)</i>	[kWh/m ² /y]	1030	2110	1100	1090
<i>Operation start</i>	[y]	2014	2018	2013	2016
<i>Life time</i>	[y]	30	20	25	25
Application					
<i>Type</i>		SH, DHW	SH	SH, DHW	SH, DHW
<i>Supply/return temperature of connected (district) heating network</i>	[°C]	75/40	65/35	80/50	65/35–45
Collector array					
<i>Collector type</i>		FPC (glass and foil)	FPC (glass and foil)	ETC with CPC	FPC (single glazed)
<i>Aperture area</i>	[m ²]	37,573	22,275	993	1,858
<i>Slope (inclination)</i>	[deg]	35	40	30	45
<i>Orientation</i>	[deg]	180 (south)	180 (south)	180 (south), 175, 148	180 (south)
<i>Land area</i>	[m ²]	130,000	n/a	n/a	roof-mounted
Storage					
<i>Diurnal heat storage (size, type)</i>		865 m ³ steel	15,000 m ³ pit	100 m ³ steel	200 m ³ steel
<i>Seasonal heat storage (size, type)</i>		62,000 m ³ pit	none	none	none
Additional heat sources					
<i>Type, capacity</i>		CHP natural gas (6.4 MWth) 2 bio-oil boilers (15 MW) natural gas boiler (8 MW) absorption heat pump (4.7 MWth)	2 electric boilers (3.0 MW)	2 wood chip boilers (1,350 kW) oil boiler (730 kW)	DH (1.8 MW) heat pump (160 kW)
Performance					
<i>Measurement period</i>		2018	n/a (simulated values)	2015	08/2013 – 07/2014
<i>Irradiance collector plane</i>	[kWh/m ² /y]	1,244	2,300	1,396	1,359
<i>Heat demand</i>	[MWh/y]	35,726	16,769	4,469	3,388
<i>Solar yield</i>	[kWh/m ² /y]	493	966	603	533
<i>Solar fraction</i>	[%]	52%	100%	13%	29%
<i>Utilization ratio</i>	[%]	40%	42%	40%	39%

Source: PlanEnergi (DK), Sunrain (CN).



Fig. 3. Collector arrays (left) and PTES (right) of Dronninglund SDH (source: PlanEnergi).

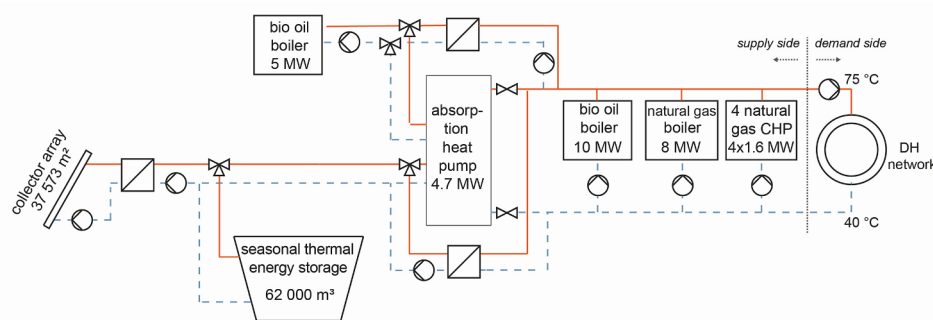


Fig. 4. Hydraulic layout (simplified) of Dronninglund SDH. Pumps indicate flow direction in inlet/return pipes with lower temperatures (blue dashed lines) and outlet/supply pipes with higher temperatures (red solid lines) (source: Solites).

ground is economically not feasible. In summer (non-heating season), the solar thermal energy supply exceeds the heat demand of the connected consumers in Dronninglund by far (Fig. 5). The surplus solar heat is used to heat up (charge) the PTES to a maximum temperature of 90 °C. The maximum temperature of the storage is determined by the maximum tolerance temperature and lifetime of the liner material. In autumn (heating season), hot water of the upper part of the storage is delivered to the DH network, while the cooler DH return flow enters the bottom part of the PTES with a temperature of around 40 °C (discharging). If the temperature in the upper part of the PTES is lower than the required DH supply temperature, the missing energy may be provided by the absorption heat pump with superheated hot water (160 °C), driven by the bio-oil boiler.

The storage can be cooled down from 40 °C to 10 °C (about 30 K below the return temperature of the DH network) by using the storage as a heat source for the absorption heat pump. This has several positive effects on the system efficiency. First, the storage capacity is increased, i.e. with the same storage volume more energy can be stored (higher temperature difference) and the storage can contain more heat in the next summer. Second, the average storage temperature is decreased, which reduces storage losses. Third, the efficiency of the solar thermal collectors is increased due to lower operating temperatures. In spring, autumn and winter, the bio-oil boilers and four gas engines cover the

major part of the heat load, which is the conventional DH supply mode. In the measurement period, the solar fraction was 52% (Fig. 5) [121].

Dronninglund SDH was financed by an EUDP (Energy Technology Development and Demonstration Programme) project supported by the Danish Energy Agency. The subsidy was granted for detailed design and for investments in PTES, piping, heat exchangers and a control system to connect the production units. The subsidy of 21 million DKK (2.8 million EUR) amounts to around 20% of the total system cost. The specific costs were around 389 €/m² collector aperture area. The heat price (before subsidies) is 50 €/MWh, which is slightly higher than typical SDH plants in Denmark due to the seasonal heat storage, high solar fraction and an advanced system concept with multiple heat supply sources.

6.2. Langkazi Tibet Solar Heating (China)

Tibet has the most abundant solar energy resources in the world, with the yearly global radiation on the horizontal surface exceeding 2000 kWh/m²/year. Conventional energy infrastructures, such as natural gas pipelines, are very expensive. The Chinese central government attaches much importance to standard of living improvements in Tibet and has allocated funds to build heating facilities for Tibetan people. Langkazi Town is located in a severe-cold and high-altitude area, where

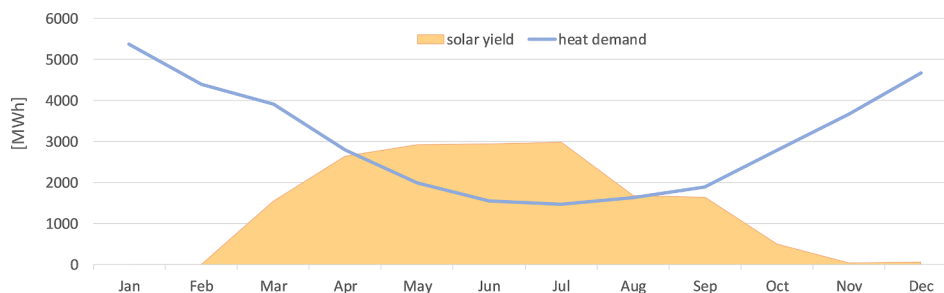


Fig. 5. Monthly solar yield and heat demand of Dronninglund SDH (data: Solites).

heating is greatly needed. The elevation is 4,200 m and the boiling temperature of water is 84 °C. The central and local governments started to construct a large SDH plant in 2017 (Fig. 6). Before, there were no space heating systems installed in the buildings. The project aims to prove the reliability and applicability of the deployed system concept and to provide a best practice example to solve the heating problems in Tibetan urban areas.

The project consists of a collector array, buffer storage, electric boilers, DH network and indoor heating terminal units. The project, as shown in Fig. 7, is divided into two phases. In Fig. 6, the first phase with 22,275 m² collector area is shown, which was finished in November 2018. The tilt of the solar collectors is 40°. The size of the water pit storage is 15,000 m³. The water pit storage is used as a short-term storage, not a seasonal storage, as storage losses would be too high for a cost-efficient seasonal storage at this elevation. The solar heat can be delivered directly to the DH network or the storage. The low supply/return temperatures of 65/35 °C of the DH network are favorable for solar thermal heat supply. Two electrical boilers (2 × 1.5 MW) were installed as back-up heat sources. In the first phase, 82,600 m² building floor area with 26 communities were connected to the DH network. In the second phase, 14,525 m² collector area will be added, when more consumers will be connected to the DH network in the near future. The collector array is located around 2 km south of Langkazi Town.

Fig. 8 shows the calculated solar yield and heat demand. The designed heating period is from September 23 to May 31 (251 days in total). The outdoor design temperature during the heating period is −14.4 °C. The indoor design temperature is 18 °C. The solar yield is higher in winter than in summer, because there is a lot of rain in summer and the irradiance is lower. The DH network provides only space heating and not DHW. As many DH networks in China, it is turned off during the summer months. In the future, DHW could be added to increase the summer load. The solar collector field aims to cover more than 90% of the heat demand.

Langkazi Tibet Solar Heating is a 100% subsidy project. The project received a grant of 175 million RMB from the central government. It was realized as a turn-key solution by a consortium of Beijing Heating Project Design Co. Ltd, Suneast Arcon-Sunmark and Sunrain Group. The project adopts the internationally advanced SDH technology of the Danish company Arcon-Sunmark A/S, that is responsible for the design and technical supervision of the collector array, storage and heat exchanger station. All critical equipment of the solar collector circuit was imported from Europe. The DH network and heating terminal units were designed by Beijing Heating Project Design Co. Ltd. The whole project is coordinated by Sunrain Group.

6.3. Bioenergy Village Büsingen SDH (Germany)

Büsingen is a German village, but forms a German exclave in Swiss territory, which leads to particular legal boundary conditions under Swiss economic law. The German renewable energy law is not valid and

therefore a widespread solution for bioenergy villages using a biogas plant was not feasible. For this reason, Büsingen is the first German bioenergy village realized with SDH, providing heat for more than 100 houses by biomass boilers and a large-scale solar thermal plant. The plant is an important best practice example for bioenergy villages in Germany.

The main part of the collector array is installed ground-mounted on a simple foundation of rammed steel profiles with an inclination of 30°. To maximize the total collector area, a smaller part is installed on the front of the boiler house with an inclination of 60° (Fig. 9). The collector area in combination with the inclination of the collectors was optimized for a high solar yield without too much stagnation in summer. A photovoltaic plant on the roof of the boiler house produces electricity for the operation of the plant.

The simplified hydraulic scheme of the plant is depicted in Fig. 10. All heat sources can feed in the buffer storage or directly to the DH network. For the heat supply in winter, two wood chip boilers are installed. Two buffer storages with a total storage volume of 100 m³ can buffer the produced heat up to a few days. If there is not enough solar heat in summer, the smaller wood chip boiler is operated and feeds the DH network and the storage. A short-term operation of the wood chip boilers is avoided in summer, because it would be uneconomic and produce higher emissions. Therefore, in summer the outlet temperature of the solar collector circuit is controlled by the frequency-controlled pumps to reach the supply temperature of the DH network to feed the heat directly to the network. In winter, the solar yield is maximized by allowing a lower outlet temperature using reheating with the wood chip boilers. The oil boiler is operated to cover the short-term heat demand in summer and serves as a back-up in case of failure and maintenance of the wood chip boilers [122]. The heat transfer medium both in the collector circuit and the DH network is water (“Aqua system” of Ritter XL Solar). The advantage of the “Aqua system” is that the number of technical devices, such as heat exchangers, can be kept as low as possible and the vulnerability of the overall system can be minimized.

The measured solar yield and heat demand for the year 2015 is shown in Fig. 11. In this year, the solar thermal heat supply covered the whole heat demand from the end of June until the middle of August. Because the heat transfer medium is water, frost protection is done by heating the solar collector circuit. These losses amounted to 4.8% of the solar yield [122].

Bioenergy Village Büsingen SDH plant was built by the regional energy supplier Solarcomplex AG, which aims to transform the energy supply of the Lake of Constance region to renewable energies by 2030. One of the business models is to transform entire villages in Baden-Württemberg to bioenergy villages by building renewable DH networks for the heat supply and photovoltaic plants for the electricity supply. The inhabitants of the villages are involved in the projects from an early stage in order to achieve a strong commitment and high share of consumers connected to the renewable DH network. For the trend-setting showcase project Bioenergy Village Büsingen, Solarcomplex AG won

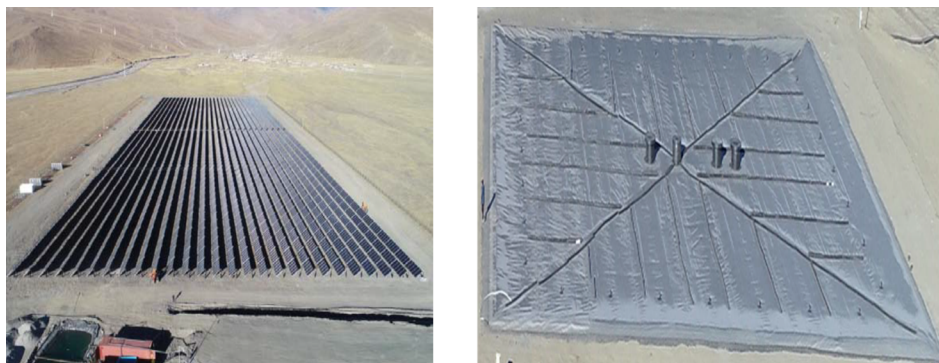


Fig. 6. Collector array (left) and PTES (right) of Langkazi Tibet Solar Heating (source: Sunrain).

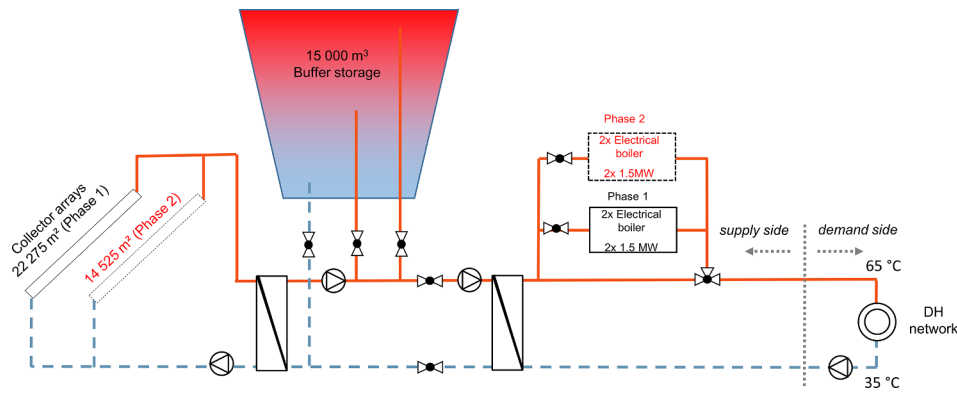


Fig. 7. Hydraulic layout (simplified) of Langkazi Tibet Solar Heating. Pumps indicate flow direction in inlet/return pipes with lower temperatures (blue dashed lines) and outlet/supply pipes with higher temperatures (red solid lines) (adapted from source: Sunrain).

the Georg Salvamoser prize 2014 and the Haus.Häuser.Quartiere prize in the category “Resource-Saving Urban Development”. Because of the replacement of about 400,000 l of fossil oil per year through renewable energy sources, the purchasing power stays in the region. For all future DH projects, Solarcomplex AG decided to install large-scale solar thermal systems if there is no possibility to use industrial waste heat [123]. In 2018 alone, five new bioenergy villages with a similar concept to those in Büsingen went into operation.

6.4. Salzburg Lehen (Austria)

The plant Salzburg Lehen is a good example of how to integrate large-scale solar thermal systems with a high solar fraction into an urban environment. From 2011 to 2016, a new residential area was established in a former industrial zone in the city of Salzburg, as part of an urban development project (Fig. 12).

The residential area comprises of 287 newly built, low-energy apartments in multifamily buildings, commercial spaces and a renovated high-rise building with a total gross floor area of 48,860 m² and total heat demand of 3,400 MWh/year. All buildings are connected to a microgrid heating network with a supply/return temperature of 65/30 °C. In addition to the primary heat supply by the DH network of the city, a solar thermal plant, buffer storage and storage integrated compression heat pump were installed. The evaporation energy for the heat pump is solely provided by the solar thermal plant. Fig. 13 depicts the hydraulic layout of the plant.

The collectors are installed on the roofs of 13 buildings. The storage integrated heat pump increases the stratification of the storage by lifting the temperature in the top part of the storage (condenser side of the heat pump) and decreasing the temperatures at the bottom of the storage (evaporator side of the heat pump). For the collector array, this has two implications. First, the low temperatures at the bottom of the storage provide low inlet temperatures for the collectors. Second, the solar yield below the heat supply temperature of 65 °C can be utilized by lifting the temperature with the heat pump (condenser side).

The fact that the solar yield with low temperatures can be utilized is reflected in the control strategy, which is based on the temperatures at the bottom of the storage (and not, as usually, based on the temperatures of the middle or top layers). The solar collector circuit is operating, when the outlet temperature reaches a defined level above the temperatures of the bottom of the storage. The solar collector circuit has a fixed speed pump, which means that the temperatures of the outlet pipe of the solar collector circuit will vary depending on the operating conditions. The variable speed secondary pump regulates the flow temperature to the set point of 65 °C. If this temperature cannot be reached, the pump runs at minimum speed. Furthermore, the plant has a night cooling mode for the storage, used as a stagnation prevention measure.

Monitoring data are available for a one-year period from August 2013 to July 2014 as part of a research project carried out by AEE INTEC [124]. The plant is dimensioned to cover most of the summer load, while avoiding overproduction (stagnation) during the summer months (Fig. 14). The collector tilt angle of 45° is steeper than the tilt angle of 39° which would maximize the total tilted solar irradiance on unshaded collectors for the location [125]. This design choice implies more yield in the winter months and less during the summer months, which reduces the risk of stagnation, but would not optimize the annual yield if the load would be sufficiently high in summer. The remarkably high yield of 533 kWh/m²/year was facilitated by low collector operating temperatures and good storage management, with virtually no stagnation even in the summer months. The inlet temperatures of the solar collector circuit in summer were around 40 °C, slightly above the return temperatures of the heating grid. In winter, the temperatures fell to around 15 °C, well below the return temperatures of the heating network, due to the cooling down of the heat pump. The share of direct solar yield, i.e. the solar yield reaching an outlet temperature above 65 °C, was 42% and the share of indirect solar yield was 58%. Due to the storage integration, the heat pump could run at times when the solar plant was not operating, reaching more than 4,000 operating hours. The electricity consumption of the heat pump compressor was

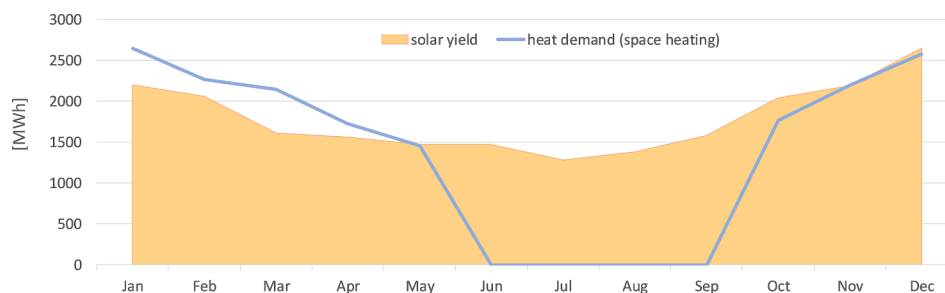


Fig. 8. Monthly solar yield and heat demand of Langkazi Tibet Solar Heating (calculated) (data: Sunrain).



Fig. 9. Collector array and boiler house of Bioenergy Village Büsingen SDH (source: Solites).

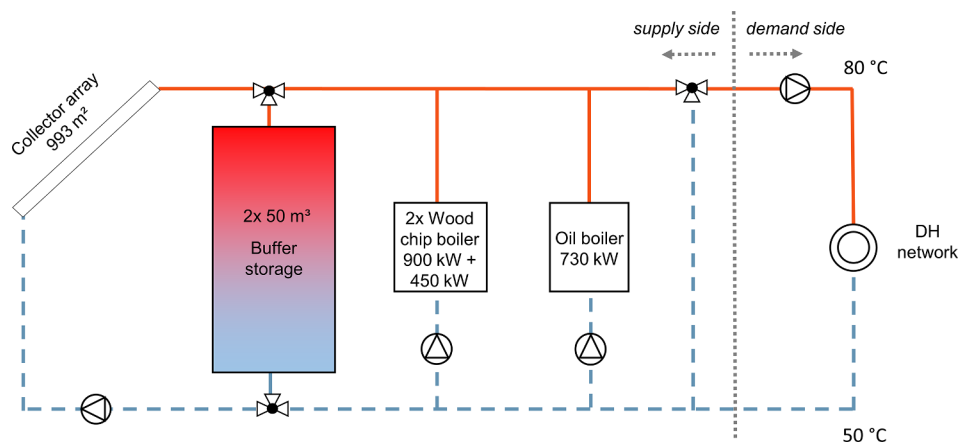


Fig. 10. Hydraulic layout (simplified) of Bioenergy Village Büsingen SDH. Pumps indicate flow direction in inlet/return pipes with lower temperatures (blue dashed lines) and outlet/supply pipes with higher temperatures (red solid lines) (source: Solites).

163 MWh/year or 16.4% of the solar yield. The heat pump had a Seasonal Performance Factor of 4.5. For a primary energy assessment of the whole system, the high solar yield needs to be weighed against the primary energy consumption of the heat pump, for which it is crucial if the electricity is from renewable sources. The storage integration also means that the electricity consumption of the heat pump can be directed to low electricity costs and surplus renewable electricity hours in the future.

The business model of the project is based on heat direct service (Wärme-Direkt-Service). The state-owned energy and infrastructure service provider Salzburg AG is responsible for the investment, operating and maintenance of the whole heating system including the distribution network. Heat customers pay a fixed amount per square meter gross floor area and variable cost per kWh of consumed energy, transferring the high initial investment of the solar thermal plant and the technical and financial risks to the energy service provider [34]. The

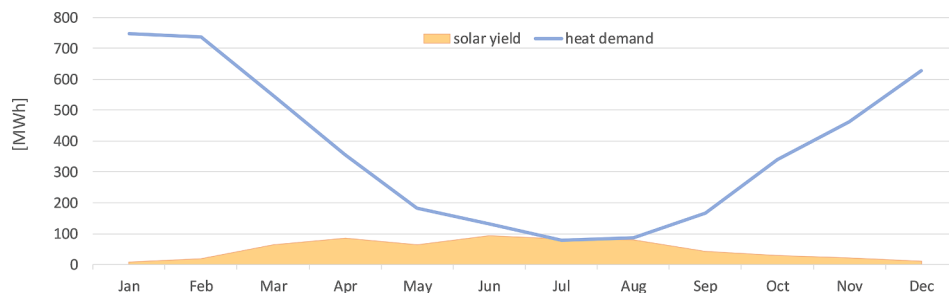


Fig. 11. Monthly solar yield and heat demand of Bioenergy Village Büsingen SDH (data: Solites).



Fig. 12. Mounting of the collectors of Salzburg Lehen (source: AEE INTEC).

total investment of 900,000 € for the solar heating system was financed with combined subsidies of 400,000 €. Key success factors have been the appointment of a coordination body and the implementation quality assurance agreement between the involved parties [34].

7. Discussion and future perspectives

The leading role of Denmark in the deployment of large-scale solar thermal systems is due to a unique combination of favorable boundary conditions for SDH applications. Fig. 15 shows a comparison of Denmark, China, Germany and Austria along nine axes of the five boundary condition categories described in Chapter 5. Outer positions along an axis indicate better conditions for large-scale solar thermal systems.

Germany and Austria have similar boundary conditions and some overlap with China. The outstanding position of Denmark is shown in six areas:

- high market penetration of existing DH networks, especially for the heat supply of households
- high compatibility of solar thermal heat supply with DH load, i.e. high heat demand and heat density of existing DH networks, substantial summer load and availability of cheap land for ground-mounted collectors near DH supply points
- low DH temperature levels
- high energy taxes on fossil fuels, which makes coal and natural gas fired CHP plants less profitable, while at the same time electricity selling prices for CHP plants are low
- availability of market-based subsidies for large-scale solar thermal systems as they are eligible for the national emissions trading system for energy distribution companies with subsidy rates based on the solar yield
- non-profit orientation, long-term investment horizon and availability of cheap loans for DH utilities

These favorable boundary conditions are combined with additional reinforcement success factors. Standardized, proven, low-cost system concepts and components from turn-key suppliers are both a factor and result of a thriving market as are positive experiences of DH utilities with solar thermal heat supply. Large-scale solar thermal systems in Denmark are on average bigger than in the other three countries and

make better use of economies of scale.

In Denmark, incentives are clearly tailored to DH with no significant industrial and small-scale applications. Targeting DH utilities is a very effective strategy to promote large-scale solar thermal systems, as they make the investment decisions for new plants, have detailed knowledge of their networks and heat demand, are able to operate solar thermal systems alongside the DH network and can drive the market towards transparency on solar yields and installation costs. Furthermore, Danish DH utilities are willing and able to take the financial risks involved with building and operating large-scale solar thermal plants. These assets seem to clearly outweigh the not so favorable solar resources with Denmark having the lowest irradiance levels among the four countries. Solar resources alone are not a good predictor for the success of large-scale solar thermal systems.

China, Germany and Austria have fewer installed systems than Denmark, but a broader range of applications encompassing rural and urban networks and industrial applications. This is partly due to investment-based subsidies which are not bound to a particular application and also allow for more expensive plants as subsidies usually cover a fixed percentage of the total investment cost. Contrary to Denmark, solar process heat applications are eligible for subsidies and Germany has even special promotion schemes for solar process heat applications.

The conditions for solar thermal integration in DH networks in China, Germany and Austria are not as favorable as in Denmark. DH is more widespread in Germany and Austria than in China, but DH temperature levels are generally high. In China, a high heat demand in cold areas with high irradiance levels is contrasted by DH networks which are only in operation in winter and do not provide DHW. The special role of DH utilities as project developers and risk takers for large-scale solar thermal systems is addressed in these countries by special business models, e.g. bioenergy village in Germany and ESCo in Austria. Learning from the Danish experience, providing incentives to DH utilities to reduce CO₂ emissions with market-based instruments (taxes on fossil fuels, emissions trading systems) could be an effective strategy for other countries as well. Compared to investment-based incentives, market-based incentives provide a direct motivation to build the most cost-effective systems and maximize the solar yield.

Collector designs, hydraulic layouts and plant control strategies have been optimized for large applications, making large-scale collector arrays a reliable and mature technology with a broad range of

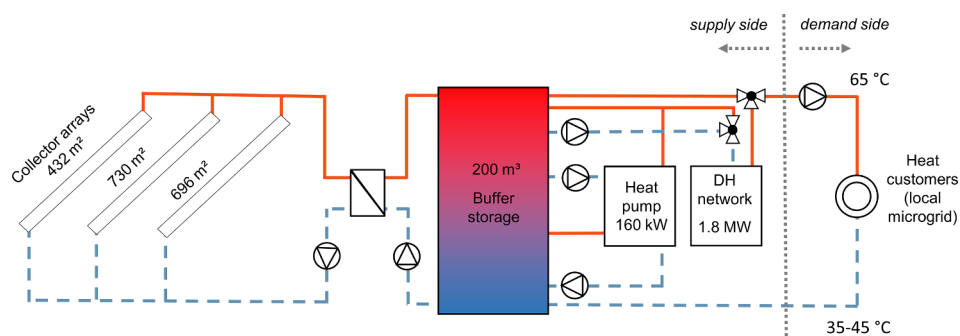


Fig. 13. Hydraulic layout (simplified) of Salzburg Lehen. Pumps indicate flow direction in inlet/return pipes with lower temperatures (blue dashed lines) and outlet/supply pipes with higher temperatures (red solid lines) (source: AEE INTEC).

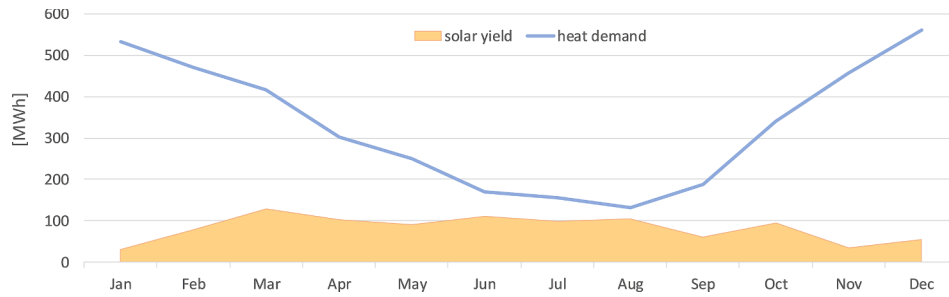


Fig. 14. Monthly solar yield (including indirect solar energy use by heat pump) and heat demand of Salzburg Lehen.

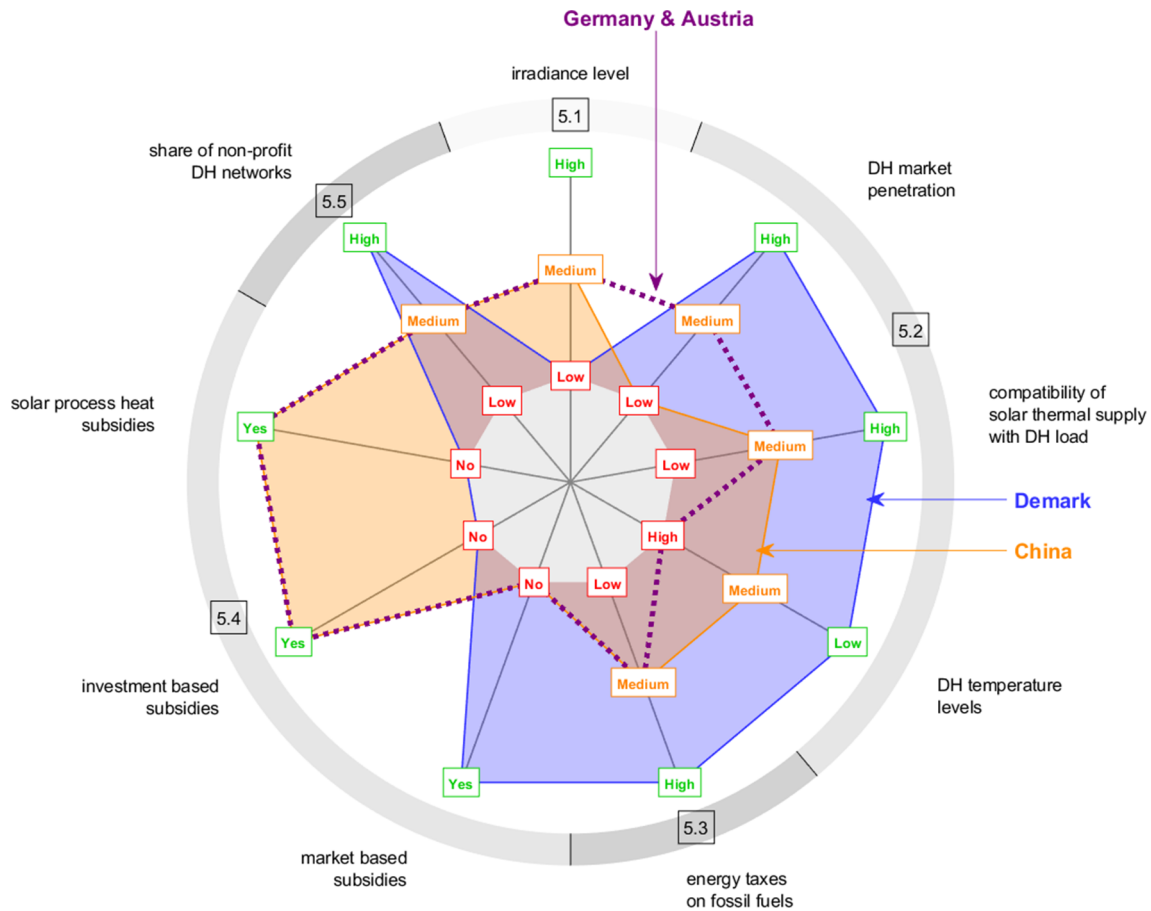


Fig. 15. Comparison of country-specific boundary conditions for Denmark, China, Germany and Austria along nine axes. Outer grey circle shows the five boundary condition categories (see Sections 5.1–5.5) these axes belong to.

applications. Denmark, China, Germany and Austria have built systems which can serve as best practice examples for the solar thermal technology. The Chinese market is very broad regarding collector technology (ETC, CPC, PTC, FPC). A new market dynamic could evolve where FPCs play a predominant role if recent projects like Langkazi Tibet Solar Heating prove viable and convincing. Joint-ventures will result in technology transfer and cost reductions.

Further developments will presumably not focus mainly on component development, but on optimal use of available technologies. In a pilot plant in the Danish town Taars which was put into operation in August 2015, FPCs and PTCs have been combined for the first time [126]. The plant consists of 5,960 m² FPCs (of which half are single-glazed without foil, half are single-glazed with foil) and 4,039 m² PTCs connected in series [127]. Each collector type operates on a temperature level where its efficiency is high (FPCs between 40 and 75 °C, PTCs between 75 and 95 °C) [128]. Another pilot plant in Condat-sur-Vezere in France with 3.4 MW installed capacity, providing heat to a local

paper mill, uses a one-axis tracking system for FPCs for the first time on a large-scale [129]. The use of other collector technologies like Photovoltaic thermal hybrid (PVT) collectors may also be suitable for large-scale applications in DH networks, as a recent study shows [130].

In the smart cross-sector energy system of the future, which links smart electricity and thermal and gas grids, there will be an increased interaction of solar thermal heat supply with other technologies, e.g. electric heat pumps driven by wind power or excess wind power converted to heat (power-to-heat) [75]. Digitalisation provides an opportunity to reduce the overall cost of decarbonizing DH by optimizing the operation and introduction of new business models [131]. Economic and environmental potential analyses for solar assisted central heating plants in the EU residential sector showed that a solar fraction above 90% can be achieved for many EU climate zones [132]. With more and more penetration of volatile renewable electricity such as photovoltaic and wind into electricity grids in the near future, the mismatch of electricity supply and demand will increase. Long-term and short-term

thermal storages are a cost-efficient option to add flexibility, as electricity storage is much more expensive than thermal storage [133]. Seasonal heat storages can be used both for solar heat and for excess electricity converted to heat, which increases the number of load cycles and reduces the cost of storages [3]. Seasonal thermal energy storage systems should be further analyzed to make solar heat available in winter [134]. In energy systems with a high share of renewables, solar thermal heat supply will compete with other renewable technologies. Here, the advantage to save CO₂ emissions compared to fossil fuels is not decisive anymore and needs to be replaced by other reasons, e.g. easing the pressure on scarce renewable resources like biomass [6]. Large-scale solar thermal systems which are part of district energy systems can benefit from 4th generation DH networks with supply temperatures of 40–50 °C, or even lower [85]. Low supply temperatures increase the efficiency of collectors and increase the storage capacity and utilization.

An advantage which is largely neglected is the long-term price stability of large-scale solar thermal systems as O&M costs are very low. Solar thermal heat supply is typically associated with high financial risks. The use of risk minimizing strategies could turn the perceived disadvantage into an asset.

8. Conclusion

In this paper, a comprehensive overview of the market and common technological solutions for large-scale solar thermal systems in Denmark, China, Germany and Austria is provided. Country-specific factors which put these four countries in the leading position regarding large-scale solar thermal systems are analyzed and a best practice example for each country is introduced in detail. The following conclusions may be drawn:

- Denmark is the leading country for solar district heating applications. A major part of the Danish success story is due to the unique role of district heating utilities, which are mostly non-profit and oftentimes act both as investors and operators of large-scale solar thermal systems. District heating utilities are given motivation to build solar thermal plants by high taxes on fossil fuels and a national CO₂ emissions trading scheme especially designed for energy distribution companies.
- China, Germany and Austria have a broader variety of large-scale solar thermal applications including solar process heat, partly due to incentive schemes based on installation cost of plants rather than market-based instruments like in Denmark.
- Differences in the availability of solar resources are a minor factor for the success of large-scale solar thermal systems in these countries, but rather the heat supply infrastructure (for district heating) and relative prices to competing technologies and promotion schemes are important.
- Besides low cost for solar heat provision, risk minimizing strategies are an important, often underestimated success factor to deal with the problem of high initial investment costs. Successful risk minimizing strategies are improved solar yield and heat load predictions and performance guarantees, turn-key suppliers, energy service companies and energy cooperatives. Risk-taking by district heating utilities like in Denmark can push the market.
- Heat supply from large-scale solar thermal systems is a mature technology with a broad field of applications. Optimized solutions for large collector arrays to realize economies of scale include hydraulic layouts leading to homogenous flow distribution and model-based plant control with frequency-controlled pump.

Recommendations for the future:

- District heating utilities should be targeted with market-based instruments and given incentives or economic motivation to reduce

CO₂ emissions. Non-profit orientation of operators can help to induce long-term investments.

- Market and solar yield-based incentives should have priority over investment-based incentives. The latter should be used, when national energy policies do not allow to target the CO₂ emitter in the short run, e.g. the industrial sector.
- Widespread use of risk minimizing strategies for investors should be regarded in solar business models.
- Long-term price stability of solar thermal heat supply due to low operation and maintenance costs and the long life time of solar collectors should be stressed more in solar thermal promotion strategies.
- The role of large-scale solar thermal systems in future energy systems needs to be evaluated on a system level, including the interaction with the electricity sector.

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Author contribution

Daniel Tschopp and Zhiyong Tian proposed the idea for this paper. Daniel Tschopp wrote the part on Austria and coordinated the description of key features of wide-spread technological solutions of large-scale solar thermal systems. Zhiyong Tian wrote the parts on Denmark and China. Magdalena Berberich wrote the part on Germany. Jianhua Fan contributed to the data collection on China. Bengt Perers and Simon Furbo contributed to the data collection on Denmark. Jianhua Fan, Bengt Perers and Simon Furbo revised the paper. Daniel Tschopp and Zhiyong Tian organized and wrote the final manuscript.

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