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The role and opportunities for solar energy in Finland and Europe

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List of abbreviations

CHP	Combined Heat and Power
CHCP	Combined Heat, Cooling and Power
CSP	Concentrated Solar Power
DH	District Heat
DHW	Domestic Hot Water
DR	Demand Response
EE	Energy Efficiency
EN	European Standard (developed by European Committee for Standardization)
GT	Gas Turbine
HP	Heat Pump
MAE	Mean Average Error
MVF	Motion Vector Field
NWE	North Western Europe
NWP	Numerical Weather Prediction
PC	Pulverized Coal
PCC	Point of Common Coupling
PV	Photovoltaic (power generation)
RES	Renewable Energy Source
RMSE	Root Mean Square Error
TSO	Transmission System Operator
VTT	Technical Research Centre of Finland
WP	Work package
µCHP	Micro Combined Heat and Power

1. Introduction

Climate conditions in Finland result only in about 20% smaller annual solar heat production compared to northern Italy. According to Figure 1, the annual solar irradiation levels are in the same magnitude in Finland and in Germany.

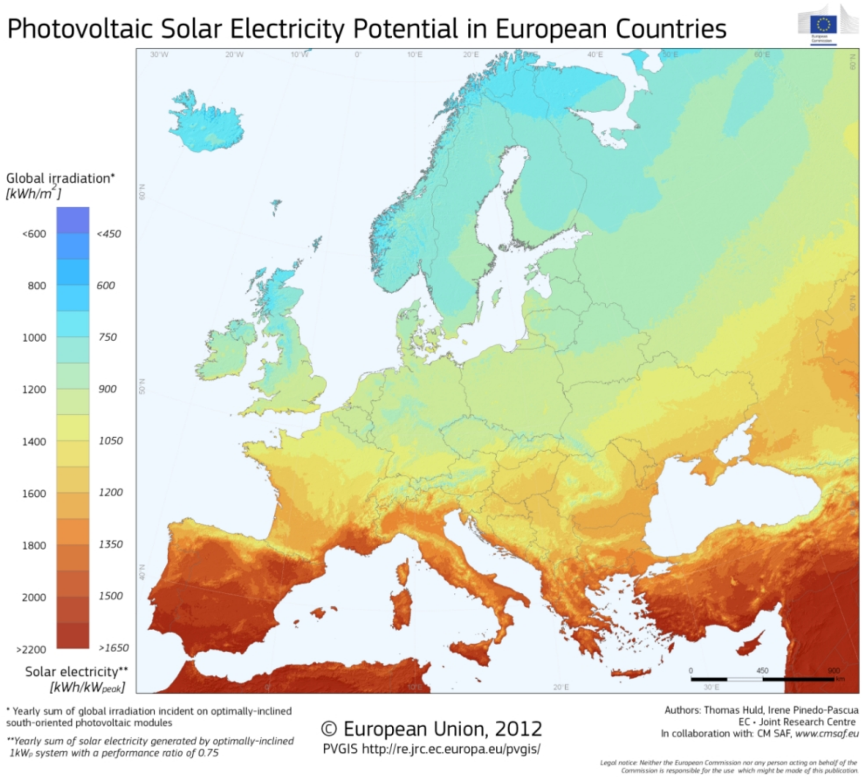


Figure 1. Annual solar irradiation in Europe (JRC, 2014).

Technically these irradiation levels enable significant potential to more self-sufficient, domestic and ecological heat and power production. Technical potential to utilise solar energy in Europe and even in Finland is several times more than energy consumption in these regions. The main technical challenges are related to intermittency of available solar energy (day-night and summer-winter cycles). Especially seasonal challenge is emphasized in Nordic regions (Figure 2) but there are technological solutions to overcome these challenges.

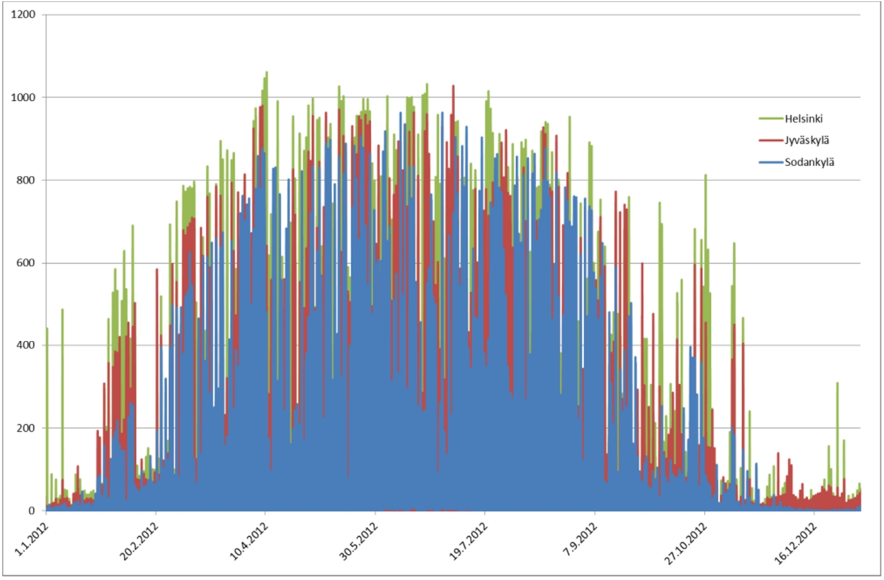


Figure 2. Total irradiation [W/m^2, hourly average] to example solar collector/panel (direction to south, 30° tilt from horizontal line) in different example regions of Finland during 2012.

Irradiation during different months could be calculated from the presented data but it is also presented for example regions by Pöyry (2013) and thus not repeated here. Even if the years are not alike, the difference in annual irradiation between years is not huge. However, the difference between for example Helsinki and Jyväskylä is significant (Table 1).

Table 1. Annual irradiation in example regions of Finland [kWh/m^2].

	2010	**2011**	**2012**
Helsinki	1082	1138	1095
Jyväskylä	957	970	892
Sodankylä	827	895	858

Economic potential is significantly smaller than technical potential. However, economic potential can be considered from several points of view. In terms of for example national economy or balance of trade, potential often increases in comparison to market potential without subsidies. In addition, self-sufficiency and different dimensions of sustainability are important drivers for solar energy.

In Europe, various state subsidies exist. Consequently, the amount of solar heating and photovoltaic has increased. The common political causes driving the increase of solar heat production in Europe are the renewable energy targets for the year 2020 and the energy efficiency directive of European Union (Pöyry, 2013). In addition, replacement of for example residential heating by oil reduces greenhouse gas (GHG) emissions and has positive impact on air quality. This is valuable, as the achievement of GHG reduction target for the sectors excluded from EU Emissions Trading Scheme (EU ETS) has been estimated to be more challenging and expensive than in EU ETS.

In Finland, regulation related to energy consumption of buildings has been changed stricter. Even if this might not be economically the most feasible way to utilise solar energy, it is one driver towards distributed production. Also some other potential future drivers for solar energy are discussed in the report of Pöyry (2013).

Solar energy technologies can be classified to different types:

- whether passive or active
- thermal or photovoltaic
- concentrating or non-concentrating

Passive solar energy means construction design so that solar heat is utilised effectively, for example large windows towards south. These solutions are not taken into account in this study. Concentrating solar power (CSP) has been analysed in another report of SANDWISH project (Hakkarainen, 2013), and therefore only minor attention is paid on it in this report. In addition, CSP may not be as potential solution for Central and Northern Europe as PV and heat collectors, as CSP requires higher irradiation and land area than often available. In Finland, solar heating is often more profitable investment than photovoltaic (PV) but the potential is limited by heat or hot water consumption. The consumption and required temperature level are very dependent on the system. From that point of view, estimation of the potential for PV is less ambiguous. Different PV technologies, systems and power storages are presented in recent VTT report (Pasonen et al., 2012). Therefore, the focus of this report is in different solar collector types, systems and applications. Available solar collector types for low temperature heating are flat plate collectors, evacuated tube collectors, air collectors and uncovered collectors. Heat can be produced also by concentrating collectors such as parabolic trough collectors, but these are not included in this report.

In this report, solar energy systems are divided also by size to “small scale” and “commercial scale”. In reality, this classification is ambiguous issue. For example, household may sell heat to district heat network or electricity to grid. Also commercial operator may install collectors or panels distributed on the roofs with various contracts.

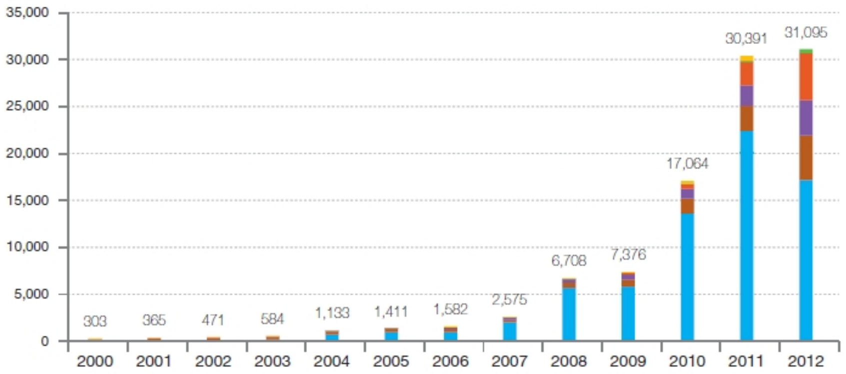
In the Scandinavian countries of Denmark and Sweden, but also in Germany, Austria, Spain and Greece commercial scale solar thermal applications connected to local or district heating grids have been in use since the early 1980s. District heating is a common way to heat houses also in Finland. Heat consumption in district heating network is vast in comparison to production of typical solar heating systems and therefore significant amount of solar heating systems can be connected to the networks. In addition, heat consumption in the district heat network is more stable than in single house, especially in summer time. This would improve the feasibility of solar investments but the feasibility strongly depends on the variable costs of replaced heat production as well. However, for the present there is a very small number of installations in Finland.

2. Current markets

As technologies have developed, subsidies introduced and prices have become more competitive, solar energy usage in Europe has increased. National subsidies play important role, which can be seen from the sudden changes in certain countries in the following figures.

2.1 Photovoltaic (PV)

The development of global PV markets is presented in Figure 3. Europe is leading in installed capacity, but also other markets are developing quickly. According to IEA, high rates of PV deployment resulted from attractive and secure rates of return for investors, while government-supported tariffs remained high and system prices decreased rapidly (in some countries PV system prices decreased by 75% in three years). However, the growth of PV has so far remained concentrated in too few countries (IEA ETP, 2012).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
🟨 ROW	88	56	80	77	29	10	105	42	76	80	284	508	-*
🟩 MEA	n/a	n/a	n/a	n/a	1	n/a	n/a	1	1	22	46	121	410
🟫 China	19	5	19	10	10	8	10	20	40	160	500	2,500	5,000
🟪 Americas	24	32	47	66	104	106	150	213	346	543	1,029	2,179	3,758
🟧 APAC	117	140	191	230	282	303	324	271	535	742	1,583	2,672	4,769
🟦 Europe	56	133	135	202	707	984	992	2,028	5,710	5,830	13,622	22,411	17,159
Total	**303**	**365**	**471**	**584**	**1,133**	**1,411**	**1,582**	**2,575**	**6,708**	**7,376**	**17,064**	**30,391**	**31,095**

* From 2012 onwards, these figures are directly integrated into those of the relevant regions.

Figure 3. Evolution of global PV annual installations 2000–2012 [MW] (EPIA, 2013).

According to IEA (IEA ETP, 2012), solar PV had a record market deployment year in 2011, with 27 GW of new capacity installed worldwide (17 GW installed in 2010). The values are slightly lower than presented in Figure 3 by EPIA (2013). In 2011, Italy was the first market worldwide (9 GW), followed by Germany (7.5 GW), which remains the country with the largest cumulative installed capacity (IEA ETP, 2012). In Figure 4, the distribution inside Europe is presented.

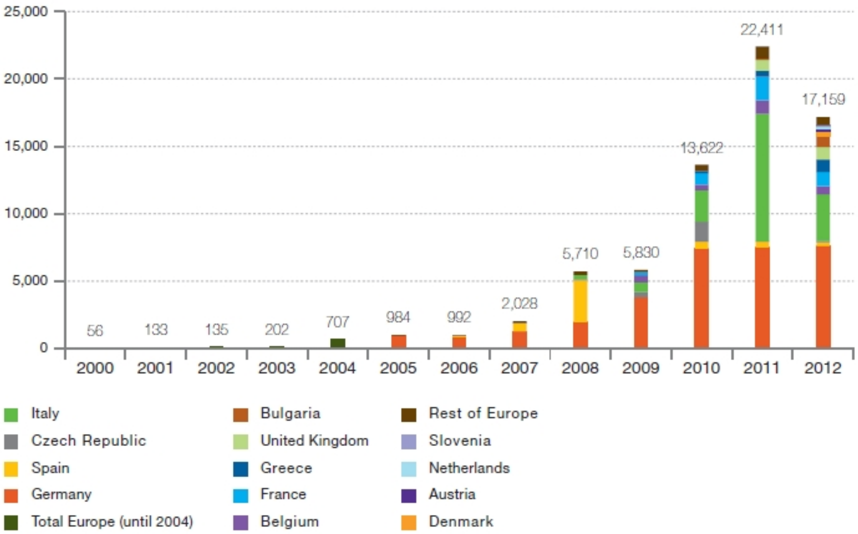


Figure 4. Evolution of European new grid-connected PV capacities 2000-2012 [MW] (EPIA, 2013).

In comparison to other technologies, PV was the most installed (as MW) power generation technology in 2012 in the EU 27 (Figure 5). However, on the annual level, the PV contribution to the electricity demand in the EU 27 was still rather small in 2012 (Figure 6). Finland is the last in that statistics.

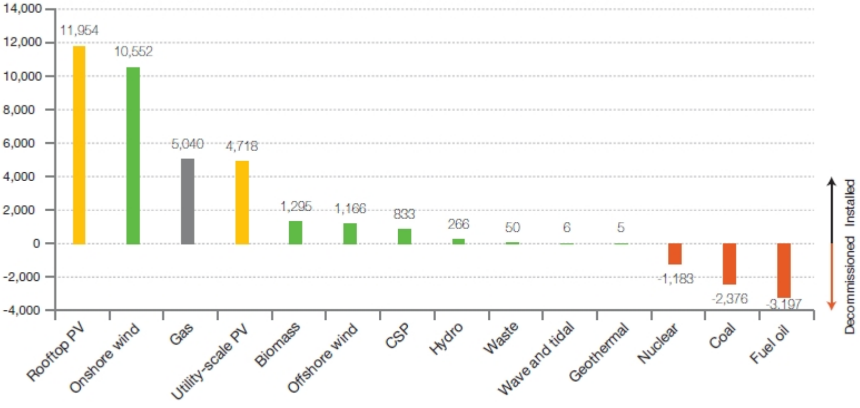


Figure 5. Net power generation capacities added in the EU 27 in 2012 [MW] (EPIA, 2013).

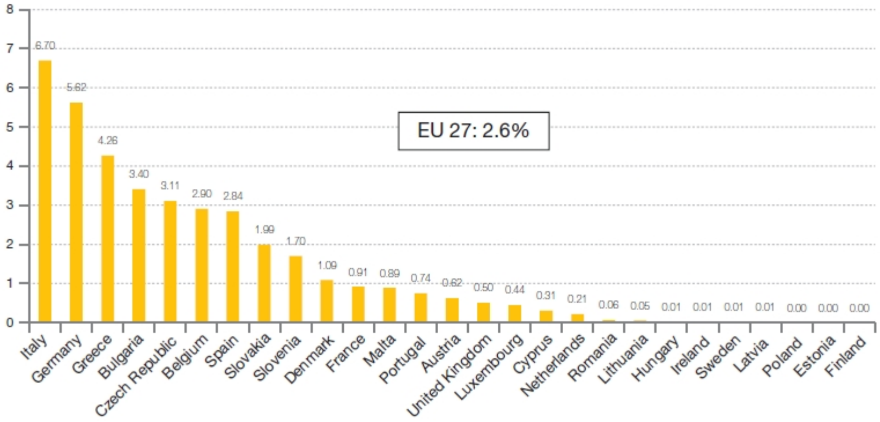


Figure 6. PV contribution to the electricity demand in the EU 27 in 2012 [%] (EPIA, 2013).

Small scale solar power sector in Nordic countries is dominated by installations to locations where electric grid is not available and PV-modules are competitive against the costs of a new grid connection (Pasonen et al., 2012).

2.2 Solar thermal

Amount of total and newly installed solar thermal capacity is introduced by European Solar Thermal Industry Federation (ESTIF) in Figure 7. Polarization of solar thermal market shares are shown in Figure 8. ESTIF (2013) estimates that there were 26 MW installed solar thermal capacity in Finland (4.8 kW installed per 1000 capita) by the end of 2012. According to ESTIF estimation there is 36 723 m^2 solar thermal collectors in operation in Finland. ESTIF uses in estimation the relation between collector area and capacity of 1 m^2 = 0.7 kW_{th}. According to Pöyry (2013), amount of solar heat production in Finland was less than 20 GWh/a. This seems to be a realistic magnitude in comparison with the capacity given by ESTIF, giving the calculated peak load utilisation rate less than 770 h/a. Total cumulative installed capacity in operation in Europe by the end of 2012 was 28 346 MW_{th} and number per 1000 capita was 55.6 kW_{th} (ESTIF, 2013).

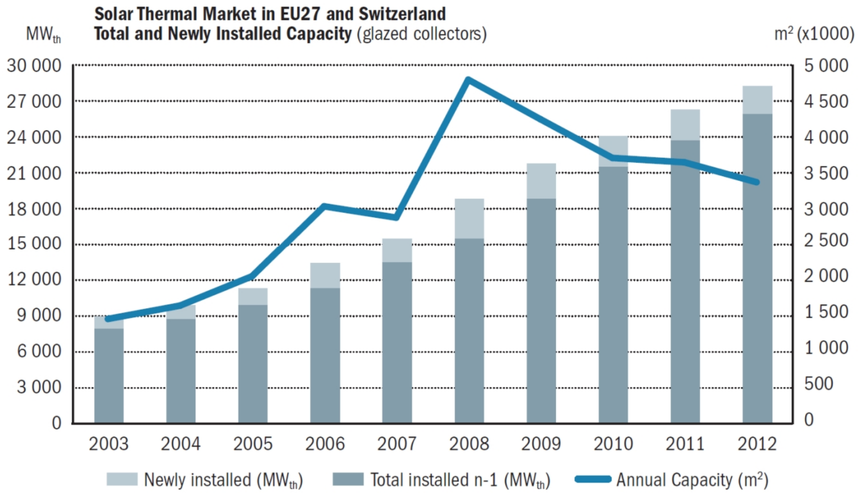


Figure 7. Total and newly installed solar thermal capacity in EU27 and Switzerland (ESTIF, 2013).

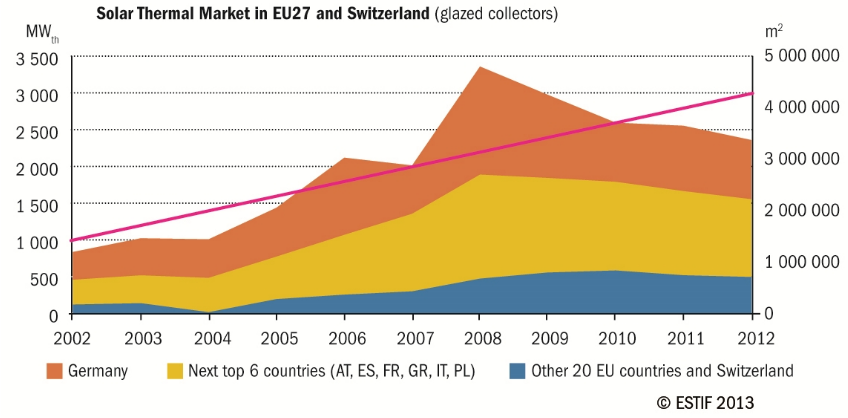


Figure 8. Distribution of new solar thermal installations in EU27 and Switzerland (ESTIF, 2013).

Distribution of the total installed capacity in the world by collector type in 2011 is shown in Figure 9.

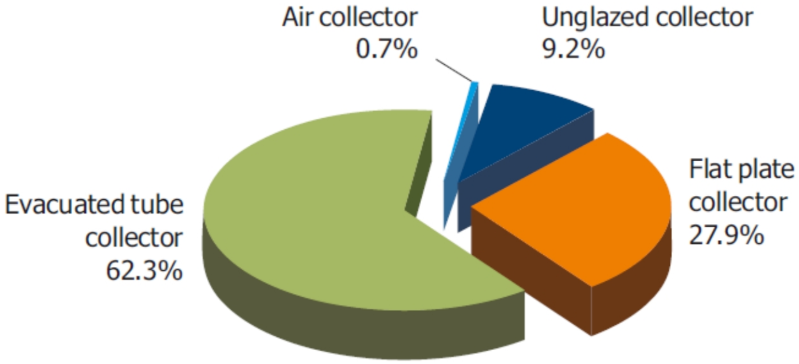
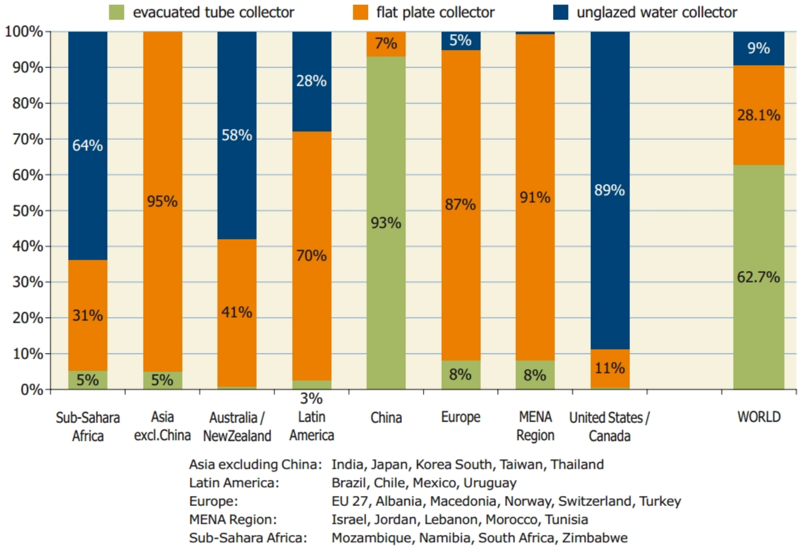


Figure 9. Distribution of the total installed capacity in operation worldwide by collector type in 2011 (Mauthner & Weiss, 2013). As visible in the following figure, global distribution is dominated by the large number of evacuated tube collectors in China.

Country and region specific distributions vary a lot. Distribution by type of solar thermal collector by selected regions for the total installed water collector capacity in operation by the end of 2011 is shown in Figure 10.



Asia excluding China: India, Japan, Korea South, Taiwan, Thailand
Latin America: Brazil, Chile, Mexico, Uruguay
Europe: EU 27, Albania, Macedonia, Norway, Switzerland, Turkey
MENA Region: Israel, Jordan, Lebanon, Morocco, Tunisia
Sub-Sahara Africa: Mozambique, Namibia, South Africa, Zimbabwe

Figure 10. Distribution by type of solar thermal collector for the total installed water collector capacity in operation by the end of 2011 (Mauthner & Weiss, 2013).

It is notable that share of the evacuated tube collectors is dominant in China. The situation could be explained with the low pricing of ETCs in China.

Distribution of the *newly installed* capacity by collector type in Europe in 2011 is presented in Figure 11.

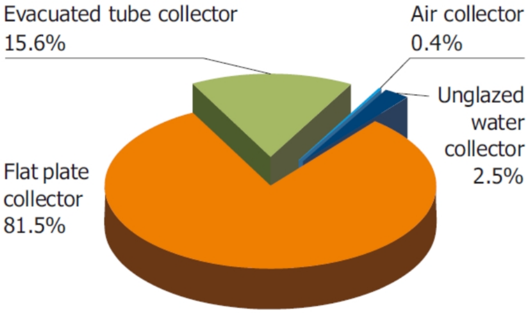


Figure 11. Distribution of the newly installed capacity by collector type in Europe in 2011 (Mauthner & Weiss, 2013).

2.3 Solar CHP, cooling, CSP and other technologies

It is possible to produce combined heat and power (CHP) by solar energy. One solution is a hybrid panel combining properties of PV and heat collectors. Other option is to cool PV panels and utilise that heat. Solar CHP applications already exist for example in Sweden. The solutions are presented in recent report from VTT (Pasonen et al., 2012) and therefore not analysed in this report in detail. CHP production may be feasible as the area requirement is smaller in comparison to separate PV and heat collectors, installation costs are lower and the efficiency of many PV technologies is better in decreased temperatures. The challenge is that if electricity production is optimised, temperature level of gained heat is relatively low. High temperature PV cells could be suitable for solar CHP production. Report (Pasonen et al., 2012) includes also some information about cooling solutions which are excluded from this report as well.

CSP is very promising technology for regions where annual irradiation levels are higher than in Nordic countries. CSP has been analysed in another report of SANDWISH project (Hakkarainen, 2013), and therefore only minor attention is paid on it in this report.

In addition to mentioned technologies, there are a lot of other potential applications to utilise solar energy. Already commercial products are available including for example air heaters and dryers, and even more are under development.

3. Solar heat systems and applications

3.1 Collector types

3.1.1 Flat plate collectors

Flat plate collectors (FPC) performs with best efficiency in relatively low temperatures as less than 60 °C but significantly higher temperatures are common as well. Basic design of a flat plate collector is shown in Figure 12. The absorber converts solar irradiation into heat and transfer it to heat transfer fluid (HTF) which is usually a mixture of about 60% water and 40% polypropylene glycol. On the contrary, air collectors use air to transfer heat. FPC is often permanently fixed in one position and does not require tracking of the sun. In the northern hemisphere collectors should be facing between southeast and southwest with tilt angle between 10-15 °. (Rommel et al., 2010; Tyagi et al., 2012)

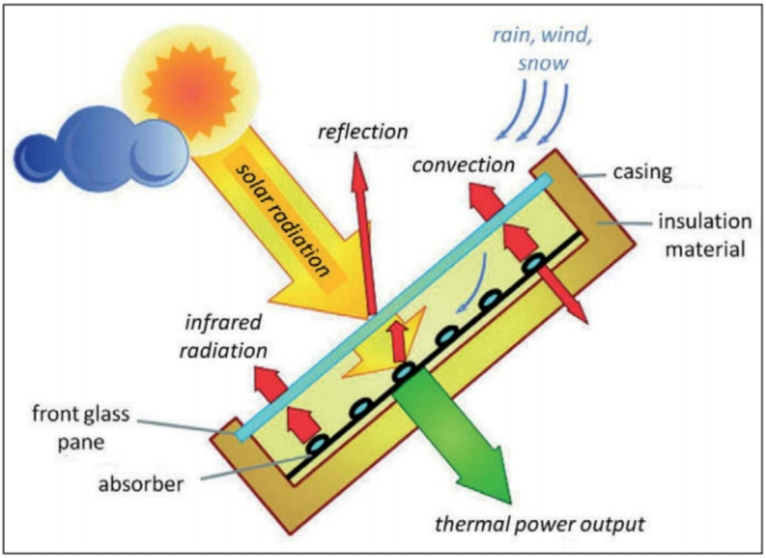


Figure 12. Basic design of a flat plate collector, including the physical effects involved in thermal efficiency (Rommel et al., 2010).

Absorbers with selective coating are common in flat plate and evacuated tube collectors for hot water and heating applications in Central and Northern Europe. Some FPCs cannot effectively absorb diffuse radiation or solar radiation from large incidence angles (throughout the day).

3.1.2 **Evacuated tube collectors**

Evacuated tube collector uses condensing and evaporating cycle of heat transfer liquid to transfer heat. Inside a vacuum-sealed tube is placed a heat pipe which is usually made of copper. Solar heat evaporates the liquid and vapour flows to upper part where it condenses and releases its latent heat to another fluid. After that, the condensed fluid returns to solar collector pipe and the process is repeated. Structure of evacuated tube collector is introduced in Figure 13. ETC has become useful especially in residential application for higher temperatures. (Kalogirou, 2004; Tyagi et al., 2012.)

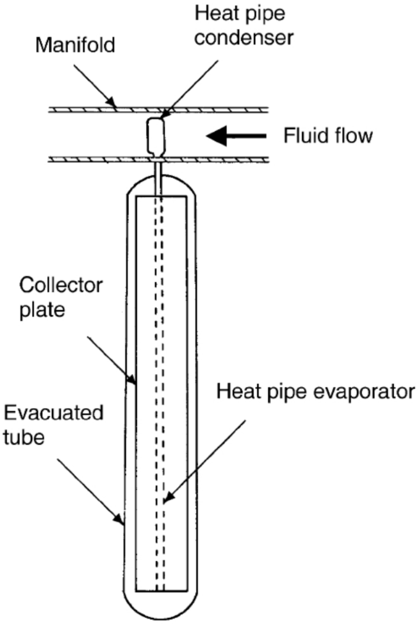


Figure 13. Glass evacuated tube solar collector (Kalogirou, 2004).

Structure of evacuated tube collector with U-tube is introduced in Figure 14.

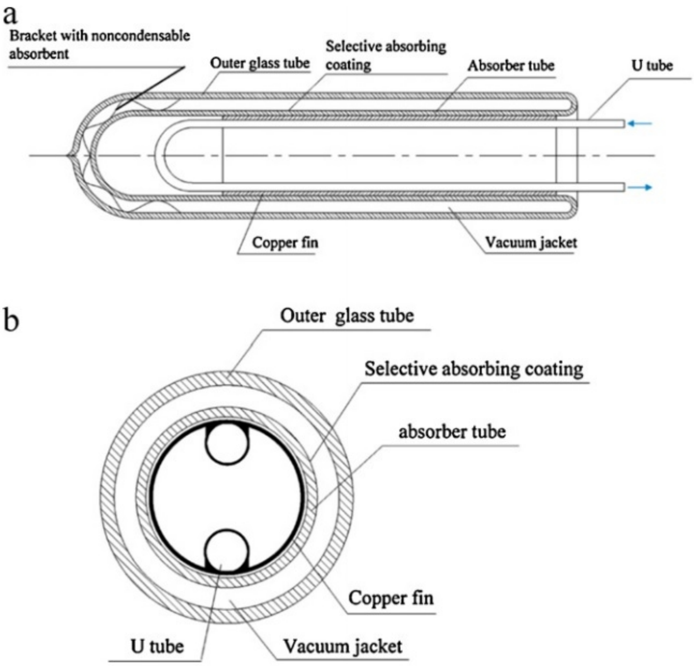


Figure 14. Glass evacuated tube solar collector with U-tube. (a) Illustration of the glass evacuated tube and (b) cross section (Tyagi et al., 2012).

Evacuated tube collector can supply heat in higher temperature compared to flat-plate collector. There are also ETC systems, which are designed to be installed on sharper angle (off the roof) to utilise irradiation from different directions. On the other hand, ETCs are not as durable as FPCs in harsh climate. Evacuated tube solar collector with parabolic reflector has better efficiency and is introduced in Figure 15. (Kardonar, 2013.)

Figure 15. Evacuated tube solar collector with parabolic reflector (Kardonar, 2013).

3.2 Thermal collector performance

According to the ISO 9806-1.2 Standard “Thermal Performance Tests for Solar Collectors”, the collector efficiency can be presented in two ways (Brunold et al., 1994):

1. efficiency based on the absorber plate area η_A
2. efficiency based on the collector gross area η_G

η_A gives more information about the components of the collector such as absorber and cover. On the other hand, when larger solar energy systems are designed η_G is often used (Brunold et al., 1994). Collector efficiency means the ratio between energy transferred to fluid and available irradiation. Therefore it does not take into account the impact of storage systems and dynamics of consumption, which are essential in terms of actual benefits gained from solar heating, but also very much application and user specific.

Solar thermal collectors reach highest efficiency when the temperature of the working fluid is closest to the ambient air temperature, whereupon heat losses are minimal (Abernethy & Raichle, 2012). In general, it can be concluded that efficiency of flat-plate collector is more dependent on temperature difference than the efficiency of evacuated tube collector.

According to standard EN 12975-2 the efficiency equation can be written as:

$$\eta = \eta_0 - a_1 T_{\mathrm{m}}^{*} a_2 G (T_{\mathrm{m}}^{*})^2 \qquad (1)$$

Where

$T_{\mathrm{m}}^{*} = \dfrac{t_{\mathrm{m}} - t_{\mathrm{a}}}{G}$ = reduced temperature difference $\left[\dfrac{\mathrm{m^2K}}{\mathrm{W}}\right]$

t_{m} = fluid average temperature in collector [K]

t_{a} = ambient temperature [K]

G = irradiance $\left[\dfrac{\mathrm{W}}{\mathrm{m^2}}\right]$

a_1 and a_2 are the parameters for second order equation (Zambolin & Del Col, 2010).

Jodat Ympäristöenergia Oy (2014) has very informative www-pages about solar heat systems including for example information regarding collector efficiencies (Figure 16).

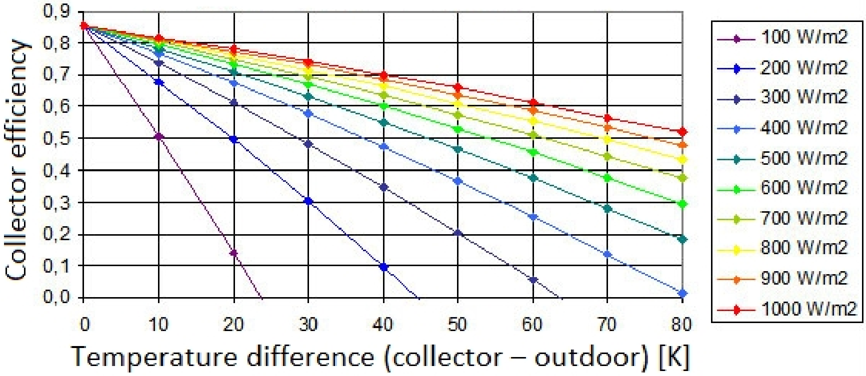


Figure 16. An example of informative way to present collector efficiencies with different radiation levels. Modified from picture presented in (Jodat Ympäristö-energia, 2014).

Test conditions according to standard EN 12975 are presented in Table 2.

Table 2. Test conditions and permitted deviations for the steady-state tests according to EN 12975 (Zambolin & Del Col, 2010).

Parameter	**Value**	**Deviation from the mean**
Global radiation G (W/m^2)	>700	±50
Diffuse fraction G_d/G (%)	<30	
Incidence angle beam irradiance (°)	<20	
Inlet fluid temperature (°C)		±0.1
Surrounding air temperature (°C)		±1.5
Mass flow rate (%)		±1
Surrounding air speed (m/s)	2-4	

Test conditions and efficiency curves for quasi-dynamic test procedure are shown in reference (Zambolin & Del Col, 2010).

3.2.1 Standards for solar collectors

List of standards used in different areas is collected to Table 3.

Table 3. European and International standards in the area of solar thermal collectors (Mehnert et al., 2012).

Area of appliance	**Standard**	**Description**
Europe	EN12975-1,2:2006	European testing standard for solar thermal collectors
Australia / New Zealand	AS/NZS 2712:2007	Australian testing standard for solar thermal collectors
North America / Canada	ISO 9806-1:1994 ISO 9806-2:1995 ISO 9806-3:1995	Part 1: Thermal performance of glazed liquid heating collectors including pressure drop Part 2: Qualification test procedures Part 3: Thermal performance of unglazed liquid heating collectors (sensible heat transfer only) including pressure drop
China	GB/T 17049-2005	Thermal performance of all-glass evacuated tube collectors
South Africa	SANS 6211-1:2003	Part 1: Thermal performance using an outdoor test method
	SANS 6211-2:2003	Part 2: Thermal performance using an indoor test method
	SABS method 1210:1992	Mechanical qualification test
	SANS 10106:2006	Installation, maintenance, repair and replacement of domestic solar water heating systems
	SANS 1307:2007	Domestic solar water heaters

3.3 Small scale systems

Every solar collector type uses the same idea of absorbing solar radiation to fluid and transferring heated fluid to heat exchanger which is usually inside a heat storage unit. Working temperatures of different collector types and suitable applications are introduced in Figure 17.

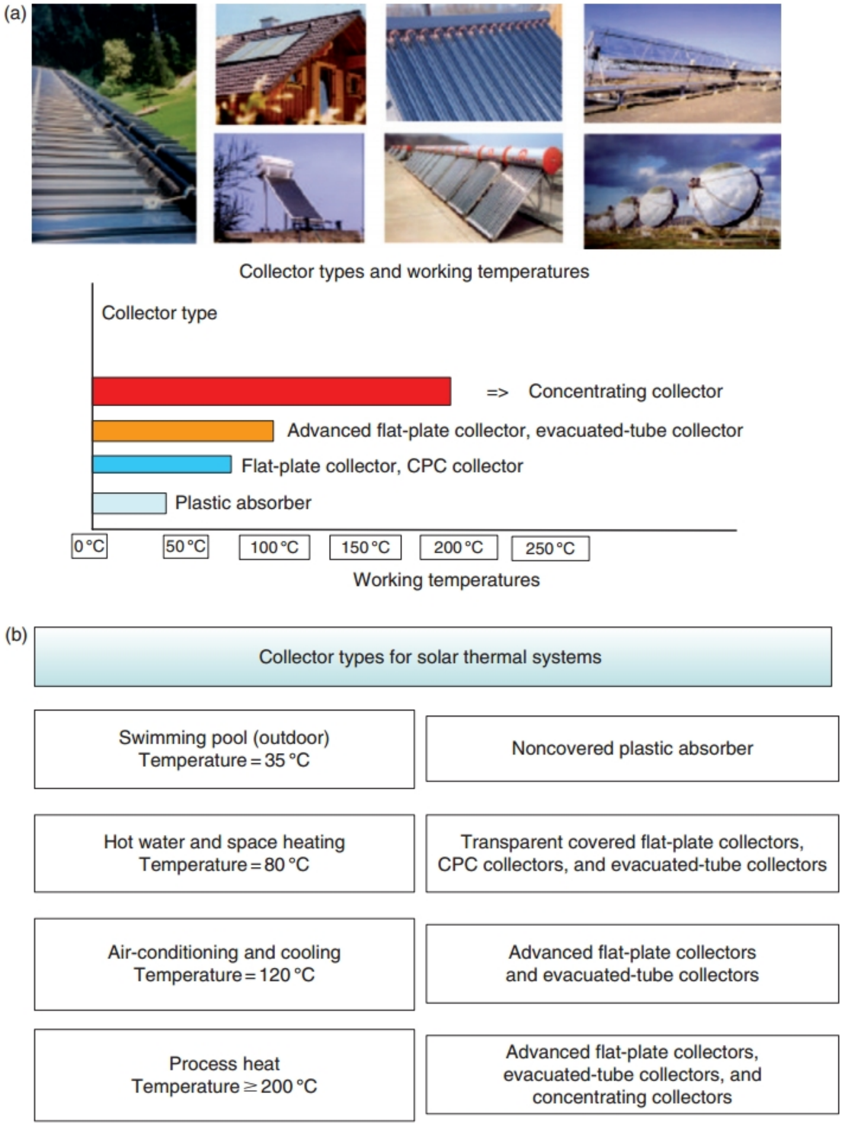


Figure 17. Collector types for low- to medium-temperature applications. (a) Collector types and working temperatures and (b) collector types for solar systems (Faninger, 2012).

Thermal storage is essential when amount of produced thermal energy and energy demand fluctuate. However, the need for thermal storage in solar hot water systems is often temporary. One of the most common and affordable thermal energy storage technologies is the hot water tank (Faninger, 2012).

Layout of a simple solar water heating system is presented in Figure 18.

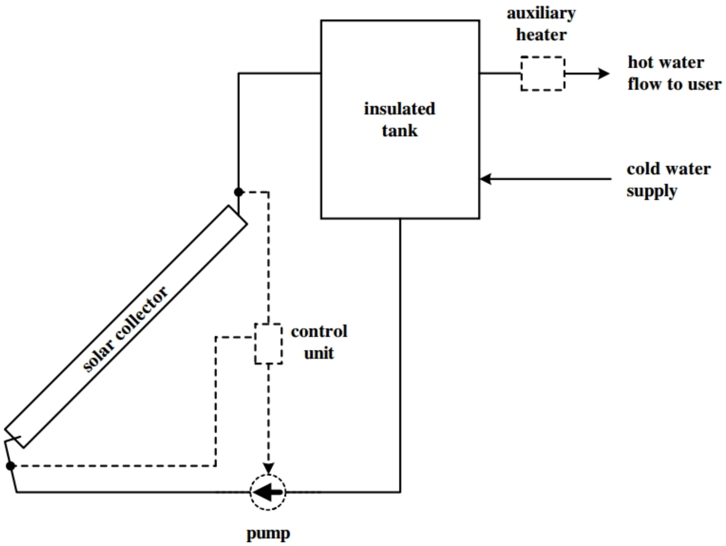


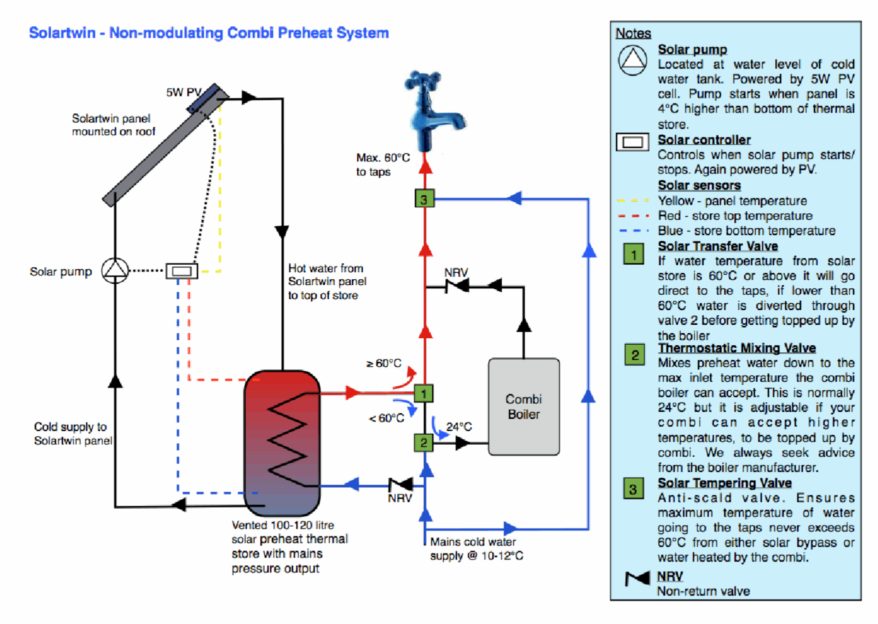
Figure 18. A layout of a simple solar water heating system (Yohanis et al., 2006).

Nowadays Domestic Hot Water (DHW) systems are the most common type of solar heating systems. DHW system consists of collector, storage, collector cycle, heat exchanger, auxiliary heat source and regulation. Auxiliary heater is not always present in the system but especially in regions where solar irradiation levels are not high it is often included. In DHW systems for households mainly electricity is chosen as the auxiliary heat source, whereas other options are for instance biomass boiler, oil, gas and heat pump. (Faninger, 2012; Ma et al. 2011.)

DHW systems are operated with two main principles which are natural circulation and forced circulation. Forced circulation technology is common in areas with moderate and cold climates. Forced circulation and natural circulation systems can also be referred as active and passive circulation systems (note: this has nothing to do with passive solar heating which is explained in introduction). DHW systems can also be classified into direct and indirect systems. In the direct system water is heated directly in the collector and the indirect system has independent heat transfer circuit which then heats the water in heat exchanger. Different types of heat transfer fluids such as water, refrigerants, and anti-freeze mixtures can be used in the closed-collector loop of indirect system. (Faninger, 2012; Ma et al. 2011.)

3.3.1 **Effective solution in Nordic regions**

In Nordic conditions, the following system (Figure 19) including “preheater” or pre-storage could be the most feasible solution. By the presented system, also low temperature heat (any temperature over the temperature in feed water network) can be utilised. For example in Finland, this could increase the annual production of solar collectors significantly as there are a lot of hours when some energy would be available but temperature does not exceed the temperature of water tank.



Notes

Solar pump
Located at water level of cold water tank. Powered by 5W PV cell. Pump starts when panel is 4°C higher than bottom of thermal store.

Solar controller
Controls when solar pump starts/stops. Again powered by PV.

Solar sensors
Yellow - panel temperature
Red - store top temperature
Blue - store bottom temperature

1 **Solar Transfer Valve**
If water temperature from solar store is 60°C or above it will go direct to the taps, if lower than 60°C water is diverted through valve 2 before getting topped up by the boiler

2 **Thermostatic Mixing Valve**
Mixes preheat water down to the max inlet temperature the combi boiler can accept. This is normally 24°C but it is adjustable if your combi can accept higher temperatures, to be topped up by combi. We always seek advice from the boiler manufacturer.

3 **Solar Tempering Valve**
Anti-scald valve. Ensures maximum temperature of water going to the taps never exceeds 60°C from either solar bypass or water heated by the combi.

NRV
Non-return valve

Figure 19. Example on the preheat system, which could improve annual production of solar collectors significantly in Nordic regions (Solartwin, 2014).The solution is suitable also for systems with hot water tank (water tanks heated by electricity) as "Combi Boiler" can be assumed to present any existing hot water system.

The system including a preheater or two storage tanks may be highly beneficial especially in the case of CHP installations described in Chapter 2.3 where temperature of the available heat is low.

Another option to utilise low temperature heat available from solar collectors around the year might be preheating of air heat pumps. As the heat pump "efficiency", typically measured as Coefficient of Performance (COP), increases significantly as a function of air temperature, even a small increase in feed air temperature may have a significant benefit in annual electricity consumption of the pumps. Preheating could be beneficial especially during the cold and sunny winter days when heat demand is high but solar energy would be available in low temperature levels (at least above outdoor air temperature!). Preheating would also enable some heat pumps operation in low temperatures. Feasible solutions might be simple and cheap wall collectors where air is heated directly and more expensive solutions based on liquid circulation and reasonable control automation directing heat to preheating and DHW heating. The latter requires higher investments but results to better yields on annual level as solar heat can be utilised also during summer. If heat pump is used for cooling during the hot days in summer time, control systems (manual or automatic) should be taken into account when considering preheating solutions.

3.4 Commercial scale systems

There are several potential applications for solar heat also in the commercial scale, for example:

- air heating/preheating
- fuel drying (e.g. biomass)
- district heating

In this report, examples on district heat applications are given in the following chapters. Fuel drying is one potential solution for seasonal variation of solar energy. The solution can be compared to energy storage as heating value of dried fuel is increased. Potential applications for fuel drying will be presented in other reports of Sandwish project.

3.4.1 Solar District Heating (SDH)

The interest to install a connection between solar heating units and district heating network is increasing. If connection to district heating exists spare energy from solar system could be dispatched to district heating network and overall efficiency of solar heat system increased. First solar district heating conference was hold in Sweden in April 2013. Model of the low temperature district heating was suggested (Figure 20). Advantages of low supply temperatures are more effective and stable utilisation of solar energy and lower distribution heat losses due to lower temperature gradient. Also the investment cost of plastic pipes is lower and the installation is easier compared to metal pipes. On the other hand, it is realistic only for new residential areas and new buildings with relatively low energy consumption. In addition, when the distances in district heating network grow it may not be effective to use low temperatures. Distributed solar heat production may help to overcome this challenge (Schmidt & Mangold, 2013).

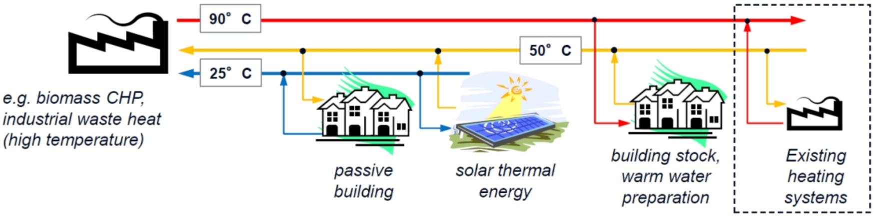


Figure 20. Low temperature district heating network (Schmidt, 2013).

Solar collectors can be connected to district heat network in three different ways which are introduced in Figure 21. RR-assisted connection increases the return temperature and SS-assisted the feed temperature. RS-assisted connection is the traditional connection type of conventional heat source (Hassine, 2013). In any connections to district heating network, the impact on possible CHP production in the network must be taken into account. Potential replacement of CHP and compensation of consequent production losses with condensing production of electricity would probably reduce the benefits of solar in some extends.

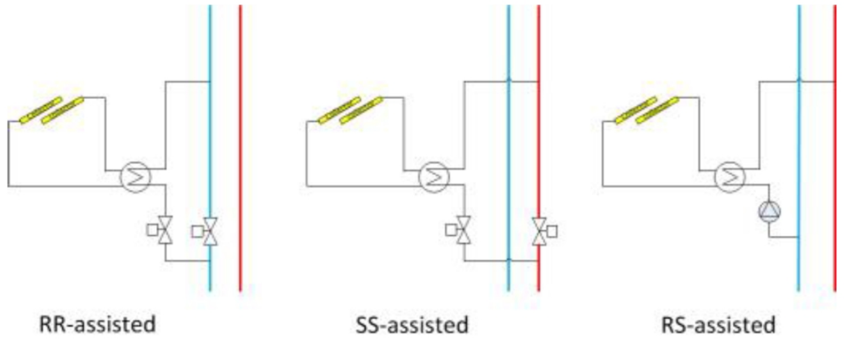


Figure 21. Three different feed-in possibilities for solar district heating systems (Hassine, 2013).

3.4.1.1 Energy storing in SDH systems

Different seasonal thermal energy storage concepts are presented in Figure 22. Detailed pictures of different type of STES are presented in Appendixes.

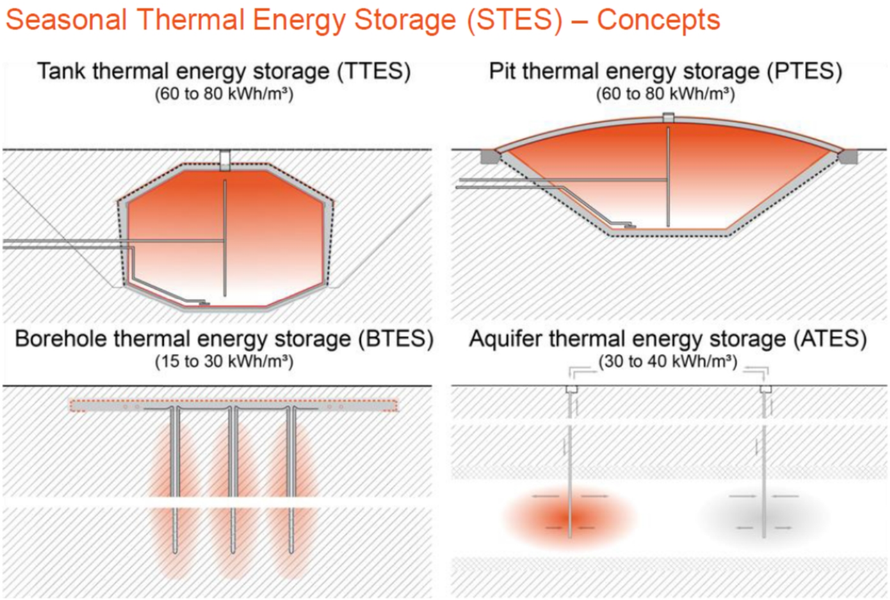


Figure 22. Seasonal thermal energy storage concepts (Schmidt & Mangold, 2013).

3.5 Case examples

3.5.1 Examples of small scale solutions in Nordic circumstances

Ruukki offers roof installation equipped with integrated solar collectors which are manufactured by Savosolar. The roof solution is presented in Figure 23. Ruukki estimates that panel area of 4 m^2 is enough to meet 50% of domestic hot water demand in average size detached house (375–500 kWh/a/m2). Also systems with larger collector areas are available. (Ruukki, 2013)

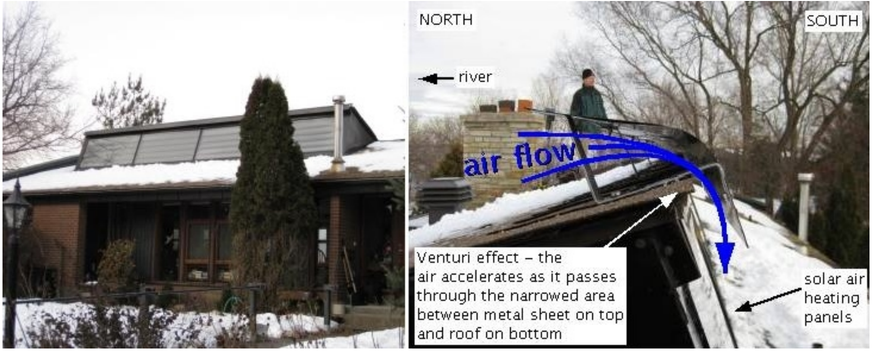
Figure 23. Ruukki's roof installation equipped with integrated solar collectors (Ruukki, 2014).

Especially in the Nordic region snowy conditions during winter time has to be taken into account. Ruukki has also different kind of solutions for vertical installations on wall. In the case of wall installation, the annual irradiation is probably lower than in the case of roof installation. However, the following benefits are possible:

- better absorption during winter (higher electricity price, more valuable from the energy system point of view) due to lower altitude of sun.
- potential to utilise morning and night radiation (often higher hourly electricity prices than during the day)
- utilisation of reflection from snow (can be significant, up to 10%, during the winter)
- in addition, some cost benefits are possible due to avoided façade materials

The benefits are possible in the case of both, heat collectors and PV, as in several CHP systems more electricity can be produced during high prices if heat production is decreased.

Another option is to clean the collectors after snowfalls to enable production. House equipped with self-cleaning solar panel system is presented in Figure 24.



Venturi effect – the air accelerates as it passes through the narrowed area between metal sheet on top and roof on bottom

Figure 24. Self-cleaning solar panel system (Rimstar, 2012).

Example of the installation with room for snow to pile up is presented in Figure 25.

Figure 25. Evacuated tube collector installed with extra space (Rimstar, 2012).

Viessmann offers several solar solutions. In Jyväskylä, six similar new row house apartments (80 m^2 each) were equipped with similar Viessmann Vitotres 434 heating systems in 2007. The system utilises heat pump and solar collectors (flat plate) for heating of water, bathroom floor and ventilation. Collector area for each apartment is 4.6 m^2. The equipment includes data collection and produced solar heat was followed on monthly basis during three years (2008–2010). Monthly variation is illustrated in Figure 26 and annual productions per collector m^2 are presented in Table 4.

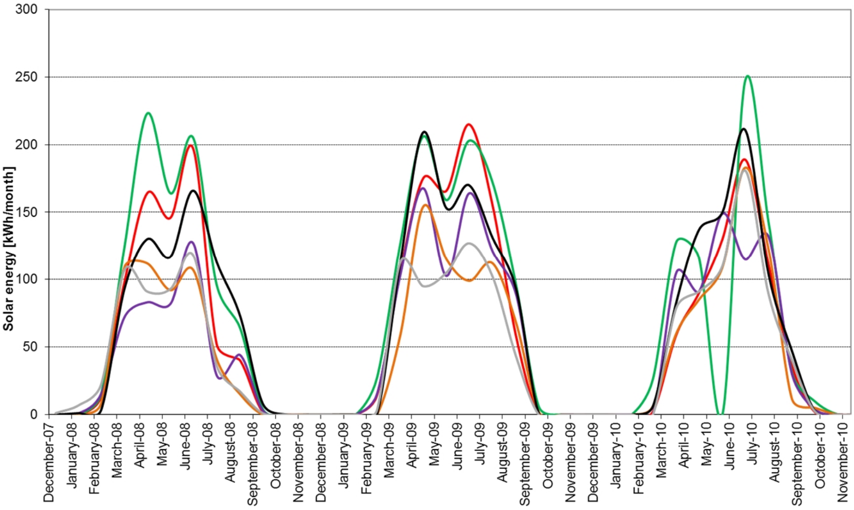


Figure 26. Solar thermal energy from six similar collectors between January 2008 and December 2010. Data was collected manually from six apartments and values are not always exactly from the same dates. Therefore monthly values are not fully comparable but indicative. In June 2010, expansion tank of one system was broken and therefore no solar energy was gained during that month.

Table 4. Annual production of six similar solar systems (4.6 m^2) in Jyväskylä [kWh/m^2/a].

year	case1	case2	case3	case4	case5	case6
2008	155	195	99	105	153	107
2009	193	217	166	132	189	128
2010	135	152	136	127	161	129

From Figure 26 and Table 4 it can be seen that variation between months and years is significant. More surprising is the variation between similar systems. The main reason for that may be the differences in water consumption (amount and timing) between apartments. Another reason may be in different settings (required minimum temperature of hot water tank etc.).

Generally the values presented in Table 4 are lower than often presented for solar heat systems in Finland. The main reason for that may be smaller hot water tank than typically presented for similar size solar systems. In the beginning of this chapter range 375–500 kWh/a/m^2 based on (Ruukki, 2013) was presented. Motiva has published range 250-400 kWh/m^2/a in their information pages for solar collectors (Motiva, 2014a). In the calculations of Pöyry (2013) values between 400 and 500 kWh/a/m^2 were used, depending on the region. In www-pages of Jodat Ympäristöenergia, several production values are presented with extensive information about solar energy including, for instance, possible reasons for large differences (values up to 700 kWh/m^2/a have been presented by some suppliers!). Possible reasons are, for example, different sizing of the components and differences in definitions (e.g. collector area) (Jodat Ympäristöenergia, 2014).

Viessmann has supplied also improved systems to Jyväskylä utilising for example shared collectors and heat storage for all apartments. Measured production data from these solutions are not available. However, this solution should have several benefits due to, for example, dynamics of distributed consumption, larger storage capacity and lower specific investment costs.

There are also several other small scale solar heat installations in Finland. When writing this report, it was possible to follow online operation of two solar heat systems in Lappeenranta and Kolho from the internet address http://www.y-energia.com/aurinkolampo/seuranta/seuranta.html.

3.5.2 Examples of commercial scale SDH and large heat storages

Conventional district heating networks in Europe are presented in Figure 27 and commercial scale solar heating (and solar cooling) plants Figure 28. Extensive database on the European SDH projects, useful information and guidelines for SDH projects etc. can be found from the SDH platform (www.solar-district-heating.eu).

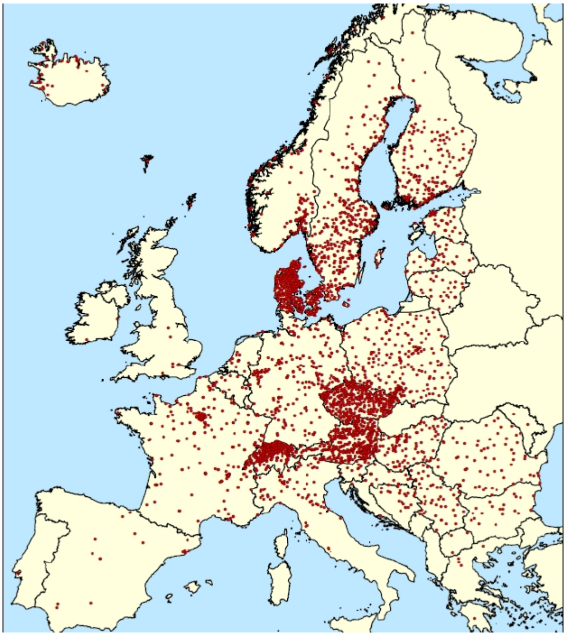


Figure 27. European map with district heating systems identified in various countries (CIT Energy Management, 2012).

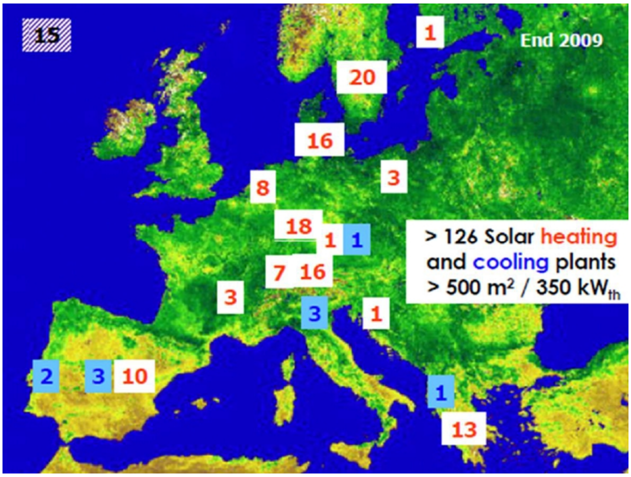


Figure 28. Commercial scale solar heating and cooling plants in Europe (ESTTP, 2010).

For example in Denmark district heating is well utilised, including also district heating by solar. Installed and planned SDH in Denmark is presented in Figure 29.

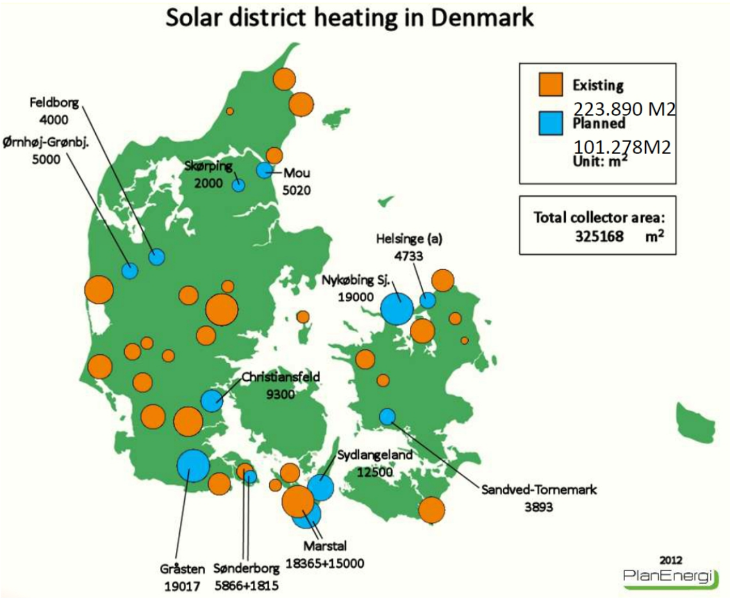


Figure 29. Installed and planned solar district heating in Denmark in 2012 (Holm, 2012).

One of the largest solar district heating plants presented in Figure 30 is located in Brædstrup. The solar plant is operated together with a CHP plant. Brædstrup SDH plant supplies around 1400 homes with 40 GWh of heat annually. The collector area of 8000 m^2 produces 3.0–3.4 GWh heat per year depending on weather. More specific description of the plant is given in Appendix 1. (Bach, 2012; CIT Energy Management, 2010; Rehau, 2011.)

Figure 30. Solar district heating plant located in Brædstrup, Denmark (CIT Energy Management, 2010).

SDH plants in Brædstrup and Marstal have seasonal energy storages. Brædstrup is the largest borehole storage combined with a solar thermal energy system in Europe. At Brædstrup, 48 holes have been drilled to a depth of 45–50 metres. Vertical PE-Xa probes have been installed across an area of approximately 225 m^2. The storage consists of 19 000 m^3 of soil. The SDH plant is equipped with 1.5 MW heat pump and the basic idea is that heat stored (e.g. during the summer) can be used during the winter. Without storage, no more than 10% of the annual heat demand could be produced by solar. After installing the storage, the solar fraction could be increased from 10% to 20% in phase one. Schematic description of the system located in Brædstrup is presented in Figure 31 and measurement results of storage behaviour in Figure 32. (Bach, 2012; Jensen, 2013.)

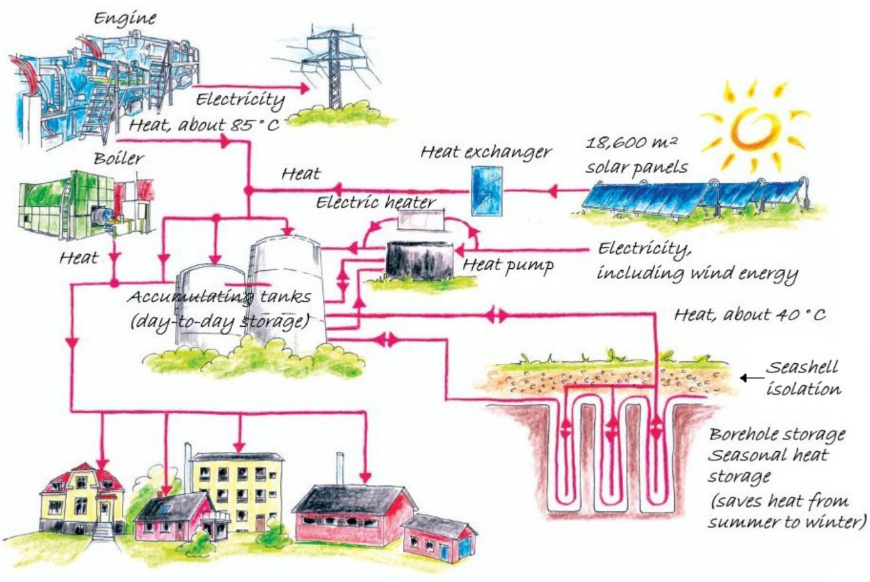


Figure 31. Description of the system located in Brædstrup (Bach, 2012).

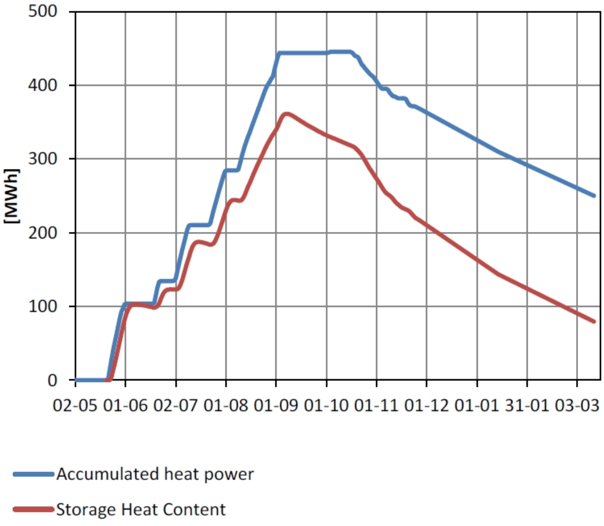


Figure 32. Measuring results for Brædstrup seasonal energy storage from one year (Jensen, 2013). It can be seen that storage was loaded until September and used during the winter.

Structure of the seasonal energy storage located in Marstal is presented in Figure 33 and measuring results in Figure 34.

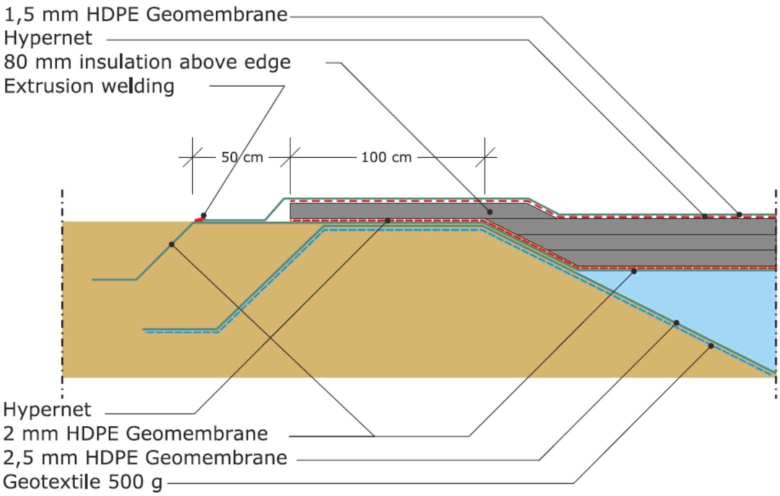


Figure 33. Structure of the seasonal energy storage located in Marstal (Jensen, 2013).

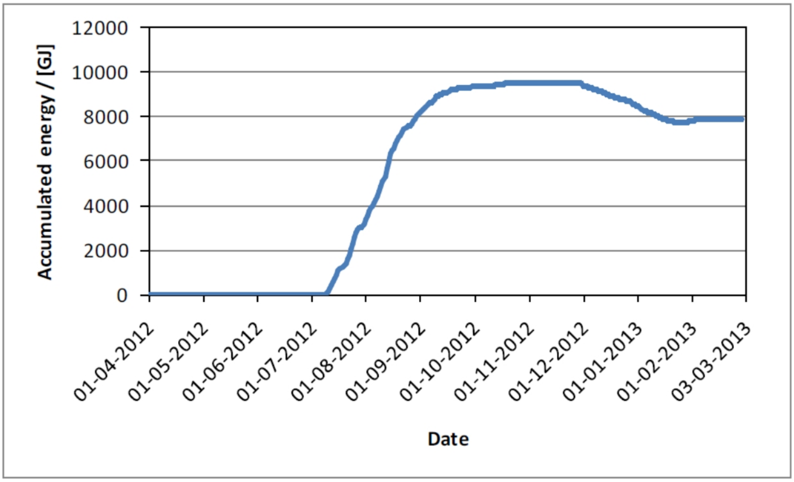
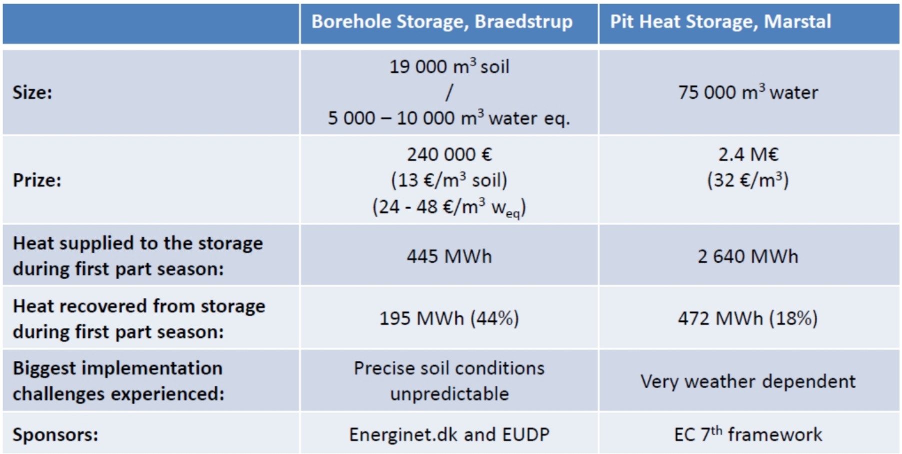


Figure 34. Measuring results for Marstal seasonal energy storage (Jensen, 2013).

Key figures of Brædstrup Borehole storage and Marstal pit heat storage are presented in Figure 35.



	Borehole Storage, Braedstrup	Pit Heat Storage, Marstal
Size:	19 000 m^3 soil / 5 000 – 10 000 m^3 water eq.	75 000 m^3 water
Prize:	240 000 € (13 €/m^3 soil) (24 - 48 €/m^3 w$_{eq}$)	2.4 M€ (32 €/m^3)
Heat supplied to the storage during first part season:	445 MWh	2 640 MWh
Heat recovered from storage during first part season:	195 MWh (44%)	472 MWh (18%)
Biggest implementation challenges experienced:	Precise soil conditions unpredictable	Very weather dependent
Sponsors:	Energinet.dk and EUDP	EC 7th framework

Figure 35. Key figures of Brædstrup Borehole storage and Marstal pit heat storage (Jensen, 2013).

Most of the existing seasonal heat storages are located in Denmark. List with details is provided in Table 5. Investment cost of large-scale thermal energy storages are presented in Figure 36.

Table 5. List of some existing seasonal heat storages (Schmidt & Mangold, 2013).

Type/Location		
Tank thermal energy storage (TTES)	**Water volume [m^3]**	**Year of construction**
Friedrichshafe, DE	12 000	1996
Hamburg, DE	4 500 / 4 100	1996 / 2010* reconstruction
Hanover, DE	2 750	2000
Munich, DE	5 700	2007
Pit thermal energy storage (PTES)	**Storage volume [m^3]**	
Chemnitz, DE	8 000 (gravel/water)	1997
Augsburg, DE	6 500 (gravel/water)	1997
Steinfurt, DE	1 500 (gravel/water)	1999
Eggenstein, DE	4 500 (sand/gravel/water)	2008
Ottrupgaard, DK	1 500 (water)	1995
Marstal-1, DK	10 000 (water)	2003
Marstal-2, DK	75 000 (water)	2012
Borehole thermal energy storage (BTES)	**Ground volume [m^3]**	
Neckarsulm, DE	63 400	1997, 1998, 2001
Attenkirchen	9 850*	2002
Crailsheim, DE	37 500	2008
Okotoks, CA	34 000	2007
Braedstrup, DK	17 000	2011
* 500 m^3 water + 9350 m^3 ground volume		

Annual yields of energy produced in 22 SDH plants in Sweden are presented in Figure 37. For SDH plant to be profitable it is recommended to achieve annual yield of 300 kWh/m^2 or greater (Dalenbäck, 2013). Monthly yields gained in Malmö, Sweden, between 2011–2012 are presented in Figure 38.

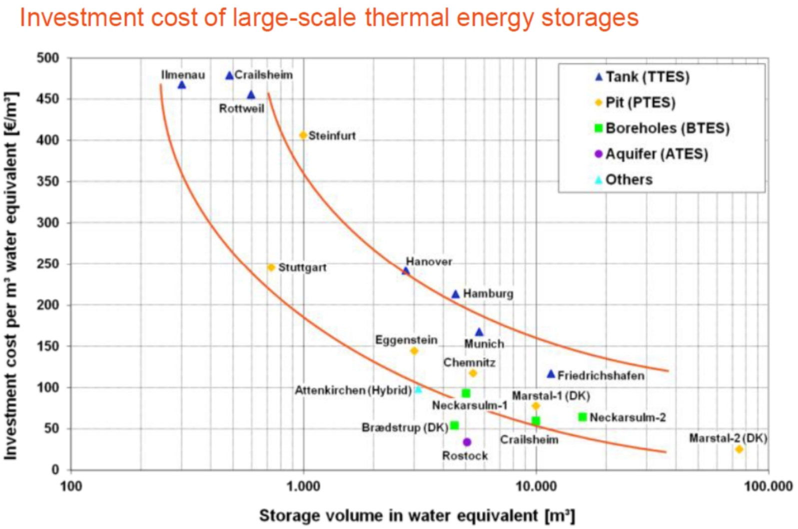


Figure 36. Investment cost of large-scale thermal energy storages (Schmidt & Mangold, 2013). Water equivalent is used as a unit to enable comparison of different types of heat storages (e.g. water and soil).

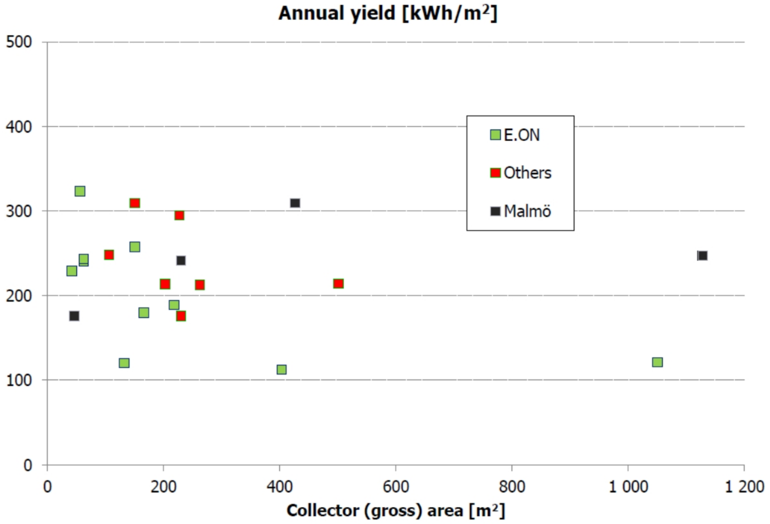


Figure 37. Annual yields of energy produced in 22 SDH plants in Sweden (Dalenbäck, 2013).

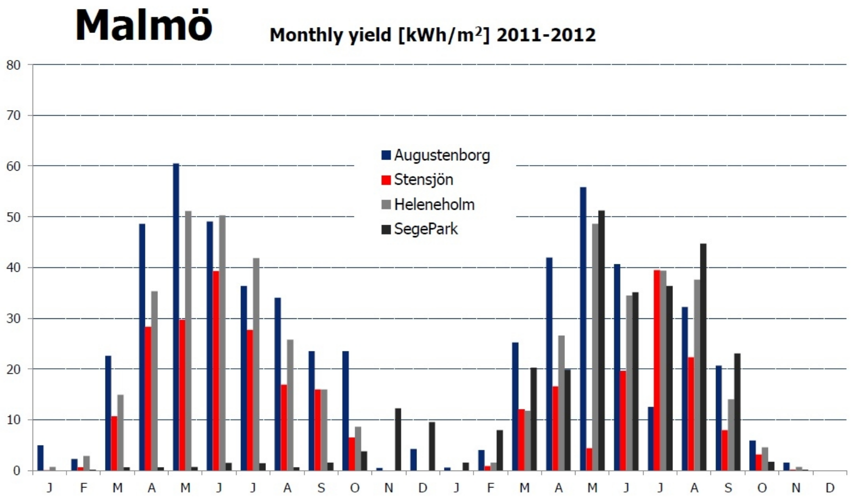


Figure 38. Monthly yields of energy produced in SDH plants in Malmö, Sweden, between 2011–2012 (Dalenbäck, 2013).

3.5.2.1 Commercial scale case examples in Finland

In Finland, one of the few existing installations is located in Lappeenranta summer house fair and is depicted in Figure 39. Heating center combines geothermal and solar thermal energy production while natural gas boiler acts as a backup heater. Heating center has a 40 m^2 collector area and estimated annual solar yield is 30500 kWh. (Savosolar, 2013)

Figure 39. Savosolar collector installation (40 m^2) in Lappeenranta summer house fair (Savosolar, 2013).

Solar collector field connected to district heating network in Myrskylä is presented in Figure 40. Total area of the solar collectors is 60 m^2 and the system utilises also geothermal heating (Savosolar, 2013).

Figure 40. Solar collector field (60 m^2) connected to district heat network in Myrskylä, Finland (Savosolar, 2013).

One of the recent commercial scale installations exist in conjunction with Sakarinmäki school where 160 m^2 collectors are installed simultaneously with the extension of the school. The system is equipped also with other energy sources, for instance geothermal heat but connection to district heat system is not available (Savosolar, 2014).

The largest solar thermal installation for domestic use in Finland is installed to Ekoviikki, Helsinki. Eight building integrated solar heating systems have a total collector area of 1246 m^2 which can produce 15% of the total heating demand of the domestic hot water need of 400 apartments. One of the domestic hot water systems installed was produced by Sonnenkraft. This Sonnenkraft XL system consists of 145 m^2 of collector area and has a 10 m^3 tank for hot water. (Aurinkovoima, 2013; European Urban Knowledge Network, 2010.)

In the city of Lahti, 240 m^2 collector system was installed on the roof of new apartment building in 2014 (Figure 41). There are also some existing commercial scale solar systems in for example Oulu. At present, several commercial scale systems are under evaluation around Finland (Savosolar, 2014).

Figure 41. The 240 m^2 collector system installed on the roof of new apartment building in the city of Lahti (Savosolar, 2014).

A different but interesting example of the existing commercial scale utilisation of solar heat is the combination of district cooling and district heating in Helsinki.

While cooling of apartments and office buildings energy is transferred from buildings to cooling network. This energy can be classified as solar energy, at least by some extend (a share of the heat is also from appliances, people etc.). Helsingin Energia utilises this solar energy by upgrading and transferring it by heat pump to district heat network. At Helsinki, almost 32 GWh of district heat was produced during the summer 2012 from cooling network and about half of that was estimated to be solar energy (Energiauutiset, 2013).

4. Potential for solar energy

4.1 Potential for PV in Europe

Technical potential to utilise PV in Europe and even in Finland is several times more than energy consumption in these regions. For example, if conversion efficiency of 10% and irradiation of 900 kWh/m2/a are assumed for average values in Finnish conditions (Pasonen et al., 2012), electricity production of 81 TWh/a is gained from the PV area of about 30 km x 30 km. This corresponds about the annual electricity consumption of Finland, but of obviously a seasonal storage or significant import and export of electricity would be required.

Economic potential of PV is strongly dependent on international climate policy and national energy policies (sustainability, self-sufficiency, balance of trade etc.). The essential question is the feasibility of PV in comparison with other (domestic) low carbon technologies.

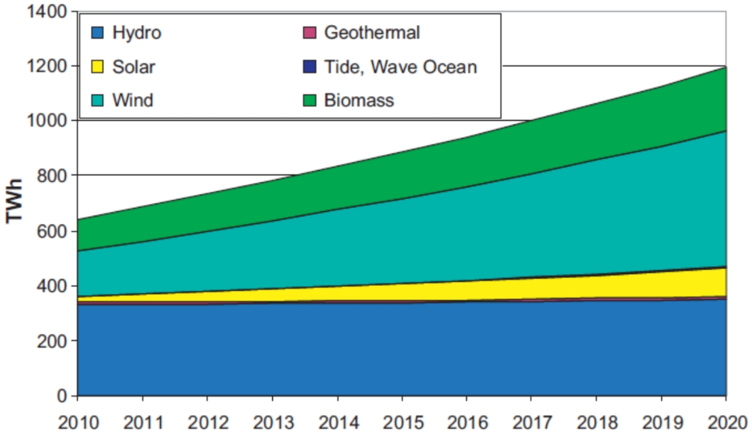
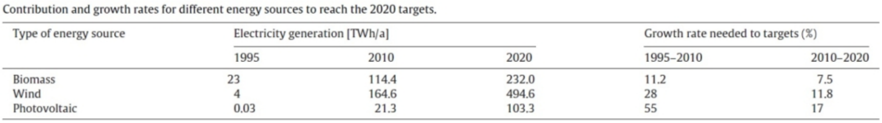


Figure 42. Planned European electricity production according to the National Renewable Energy Action Plans (Jäger-Waldau et al., 2011).

European Union has set a target to reduce greenhouse gas (GHG) emissions to 80–95% below 1990 levels by 2050 (European Commission, 2012). The price for PV technology has decreased faster than any other energy technology since the 1950s and the trend is seen to remain (Stiftung Umweltenergierecht, 2012). As presented before in Figure 5, PV was the most installed power generation type (measured by capacity as MW) in Europe in 2012 which is obviously a consequence of national support mechanisms as well.

EU member states have submitted National Renewable Energy Action Plans to European Commission. According to these plans, European electricity production by renewables is shown in Figure 43. Amount of solar and wind power is clearly growing. However, the share of solar is not increasing as quickly as for example in Figure 5 if measured as annual production (TWh). Even if the share of solar is relatively small, the (annual) growth rate is the greatest for PV, as presented in Figure 44.

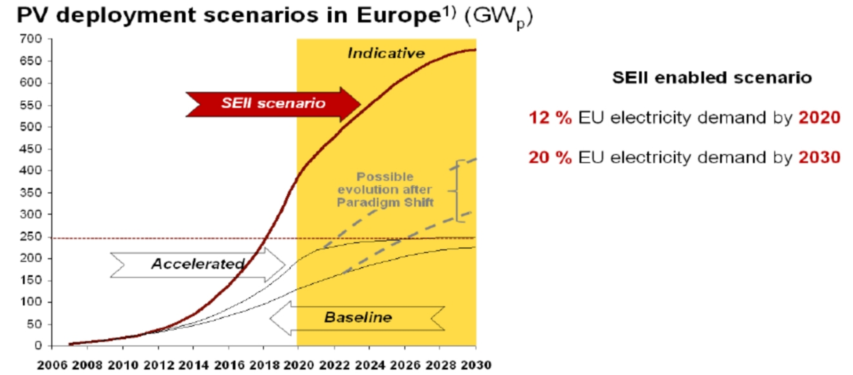


Contribution and growth rates for different energy sources to reach the 2020 targets.

Type of energy source	Electricity generation [TWh/a]			Growth rate needed to targets (%)	
	1995	2010	2020	1995–2010	2010–2020
Biomass	23	114.4	232.0	11.2	7.5
Wind	4	164.6	494.6	28	11.8
Photovoltaic	0.03	21.3	103.3	55	17

Figure 43. Contribution and growth rates for different energy sources to reach the 2020 targets (Jäger-Waldau et al., 2011).

In 2020 installed wind power and photovoltaic power capacities are estimated to be 227 GW and 68 GW, respectively (Heide et al., 2010). European Photovoltaic Industry Association (EPIA) has published a goal to provide up to 12% of the European electricity using PV by 2020, up to 20% in 2030 and 30% in 2050. This optimistic scenario of Solar Europe Industry Initiative (SEII) is shown in Figure 1. (European Photovoltaic Industry Association, 2010.)



1) Europe 27, Croatia, Norway and Turkey
Sources: EPIA, EU DG TREN "European Energy and Transport: trends to 2030, update 2007", Eurostat Data Portal, EU JRC Photovoltaic Geographical Information System, A.T. Kearney analysis

Figure 44. PV deployment scenarios in Europe (European Photovoltaic Industry Association, 2010).

Different scenarios for PV are presented in Figures 45 and 46. It can be seen, that variation between different scenarios is significant, but huge demand for PV is estimated in all of the presented scenarios.

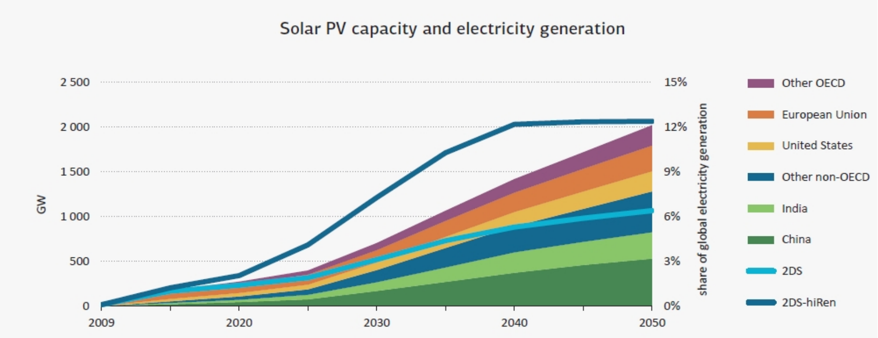


Figure 45. Roadmap for global PV capacity and electricity generation. The growth of PV is estimated to be enormous between 2030 and 2050. (IEA ETP, 2012.)

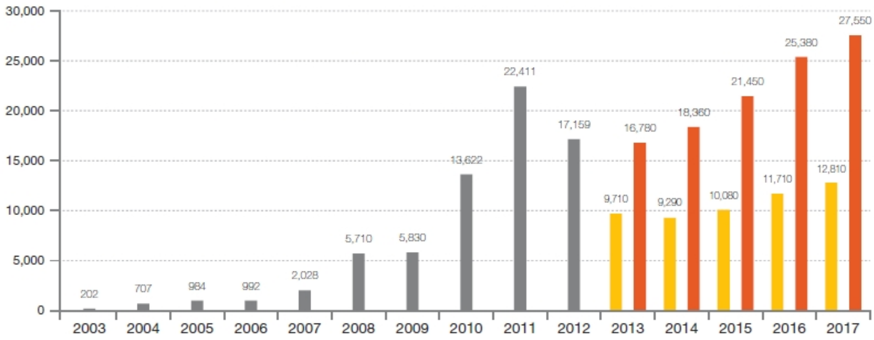
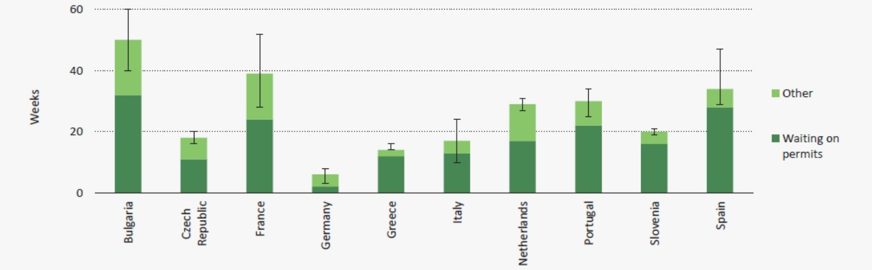


Figure 46. European annual PV market scenarios until 2017 – Business-as-Usual (yellow) and Policy-Driven (red) (MW) (EPIA, 2013).

There has been an intense debate about the need to reduce support tariffs and/or introduce caps to policy support in the regions, where PV installations are focused due to attractive support policies. These uncertainties may reduce future investor confidence in these markets. In the future, it is likely that European market deployment will slow, while new markets will emerge (e.g. China and India) and other OECD markets will increase (e.g. the United States and Japan). (IEA ETP, 2012.)

Delays in project may significantly increase transaction costs for investors. For example, waiting for permits for rooftop solar projects in certain European countries (with the exception of Germany) accounted for over 50% of the total project timeline (Figure 47). It is important to develop clear, streamlined planning and permitting processes so these technologies can be deployed rapidly. (IEA ETP, 2012.)

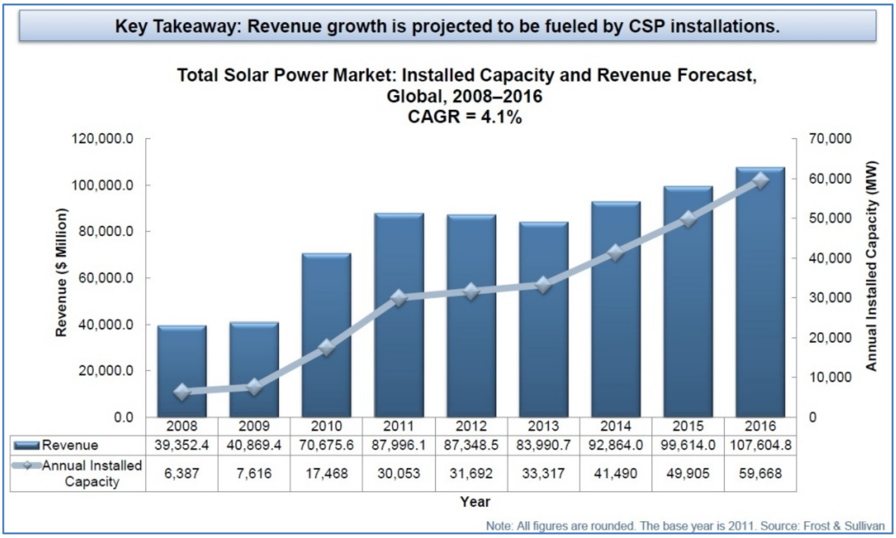


Note: Average values shown; error bars show minimum and maximum total durations.
Source: PV legal, 2010; from IEA, 2011c.

Key point *Overcoming non-economic barriers, such as planning and permitting process delays, is central to reducing project transaction costs and uncertainties.*

Figure 47. Time needed to develop small-scale rooftop photovoltaic projects in selected European Union countries (IEA ETP, 2012).

The revenue of global solar power markets (incl. CSP) is estimated for example by Frost & Sullivan for the near future. The graph is presented in Figure 48.


Key Takeaway: Revenue growth is projected to be fueled by CSP installations.

Total Solar Power Market: Installed Capacity and Revenue Forecast, Global, 2008–2016
CAGR = 4.1%

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Revenue	39,352.4	40,869.4	70,675.6	87,996.1	87,348.5	83,990.7	92,864.0	99,614.0	107,604.8
Annual Installed Capacity	6,387	7,616	17,468	30,053	31,692	33,317	41,490	49,905	59,668

Note: All figures are rounded. The base year is 2011. Source: Frost & Sullivan

Figure 48. Total Solar Power Market in the world (Frost & Sullivan, 2013).

Energy scenarios are highly dependent on parameters given for different technologies in each scenario modelling. The share of solar and wind based electricity has great potential to increase in the future but it is based on the assumption that costs will decrease. Solar PV has already seen massive cost reduction and the same effect is likely to happen for CSP which has potential especially in the heat storage technology. Cost estimates according to Frost & Sullivan for the near future are presented in Figure 49. CAGR stands for Compound Annual Growth Rate which means the year-over-year growth rate of an investment over a specified period of time. (Frost & Sullivan, 2013; Investopedia, 2013.)

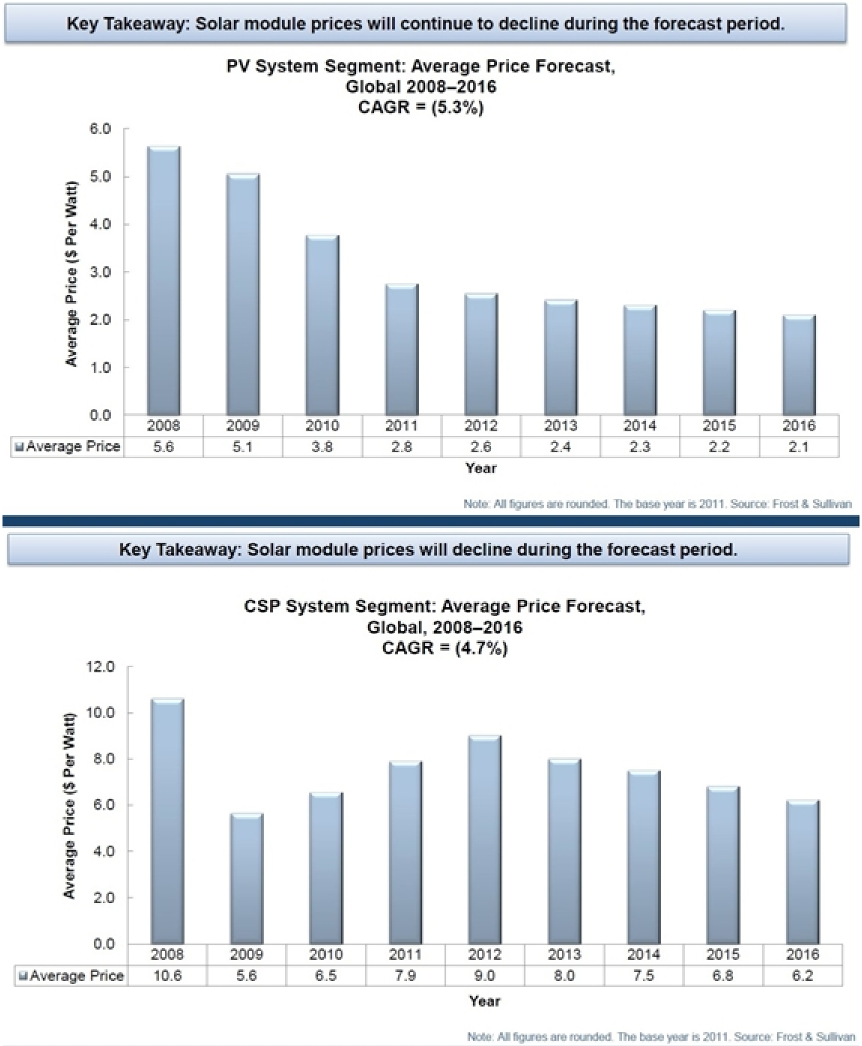
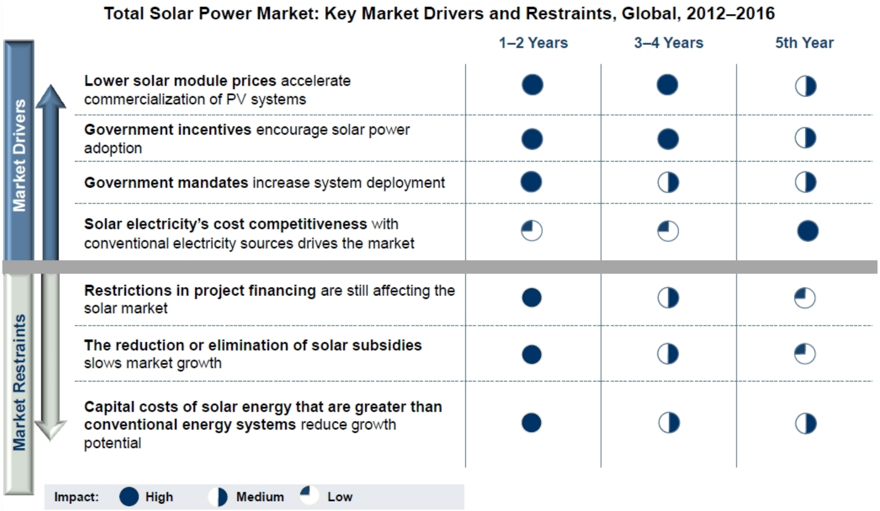


Figure 49. Cost estimates for PV and CSP in the near future (Frost & Sullivan, 2013).

Key market drivers and restrains listed by Frost & Sullivan for solar power market are presented in Figure 50.



Total Solar Power Market: Key Market Drivers and Restraints, Global, 2012–2016

		1–2 Years	3–4 Years	5th Year
Market Drivers	**Lower solar module prices** accelerate commercialization of PV systems	●	●	◑
	Government incentives encourage solar power adoption	●	●	◑
	Government mandates increase system deployment	●	◑	◑
	Solar electricity's cost competitiveness with conventional electricity sources drives the market	◔	◔	●
Market Restraints	**Restrictions in project financing** are still affecting the solar market	●	◑	◔
	The reduction or elimination of solar subsidies slows market growth	●	◑	◔
	Capital costs of solar energy that are greater than conventional energy systems reduce growth potential	●	◑	◑

Impact: ● High ◑ Medium ◔ Low

Figure 50. Key market drivers and restraints in solar power market (Frost & Sullivan, 2013).

One of the most significant factors reducing the market growth is the uncertainty on existing and future support mechanisms, such as reduction or elimination of subsidies for solar power. For example, at 2013 the Spanish government approved measures to limit and tax solar power generation, including ending the feed-in tariff program (PV Magazine, 2014). Future developments of overall energy system, pricing principles of electricity, storage technologies and capacity etc. will also have major impacts on the market potential of solar energy.

4.1.1 Potential of PV in Finland

Typically the proportion of PV is insignificant in energy system scenarios modelled for Finland. Without subsidies and with given development of investment costs and production rates, PV is not a feasible way to reach the short-term greenhouse gas emission targets or renewable energy targets in Finland. Models often do not take into account individual choices to invest on small scale PV even if it would not be the most economic option (with given interest rate, economic lifetime etc.). It is important to keep in mind, that scenario is not a forecast. If for example, high feed-in tariffs would be applied, lower pay-back time would be achievable and more PV installations would be possible. Figure 51 shows the pay-back time of PV installations in Finland as function of the value of the electrical energy produced. (The concept of pay-back time has been extended to the case where time value of money has been taken into account. The pay-back time here is the time when NPV of the investment becomes positive.)

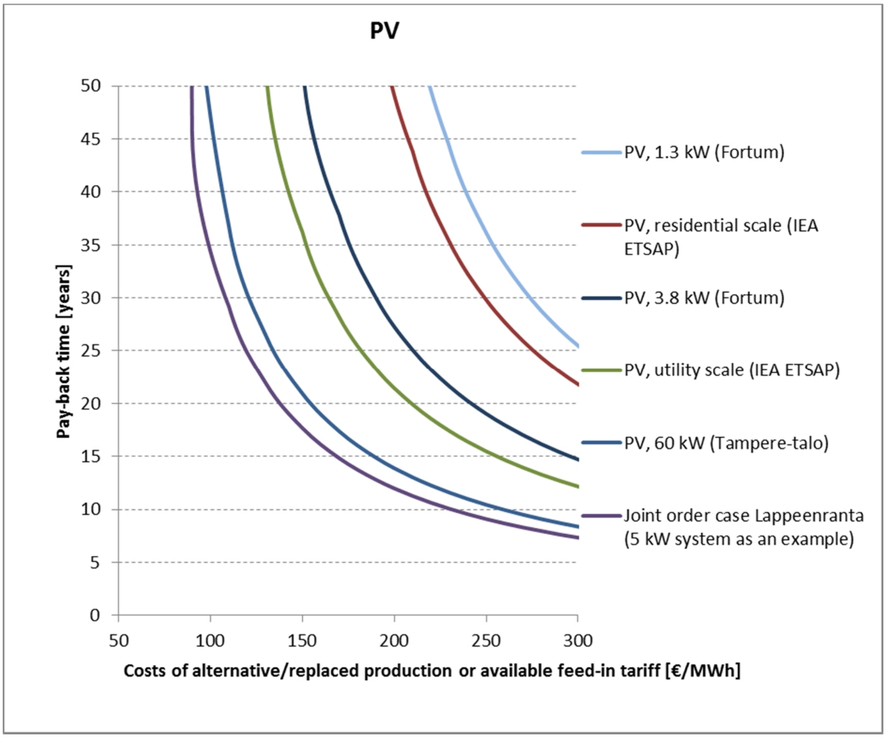


Figure 51. Pay-back time of PV as a function of electricity price (or cost of alternative energy source or feed-in tariff). The data for cost curves is from sources Fortum (2013), Resca (2013) and Grönberg (2014). General interest rate 4% was used. In addition, investment costs presented by (IEA ETSAP, 2011) for PV system were used with Finnish production rates (Fortum, 2013).

If for example feed-in tariff leading to target price of 83.5 €/MWh (as for wind energy in Finland) (Motiva, 2014b) would be available, the pay-back time for PV investments would be very high with 4% interest rate. For comparison, in Germany significantly higher feed-in tariffs are available but the system is quite complicated. The value of tariff depends on the size and type of the PV installations as well as year commissioned. For example, the plants commissioned in July 2013 receive between 10.44 and 15.07 Euro cents / kWh (104–151 €/MWh) for a period of 20 years. During previous years, the tariffs have been higher as average tariff for PV power in Germany in 2013 was 290 €/MWh (Fraunhofer ISE, 2013). If similar system would be applied for PV in Finland, the pay-back time presented in Figure 51 for, for example, 60 kW system would be about 8 years if average feed-in tariff is used (and all production is sold). This would be attractive as the risk for the investment is low due to long lifetime of PV and guaranteed level of income for 20 years. It should be noted, that after this 20 years, PV would still produce electricity even if the efficiency would be slightly decreased. The pay-back time is very sensitive for used interest rate in the case of low costs for replaced production.

It should be noted, that presented investment costs are based on all inclusive turn-key deliveries without any subsidies. Subsidies, joint orders and decreased installation costs would obviously decrease pay-back times as presented for example by (Grönberg, 2014).

If PV markets in Finland would develop and similar prices than presented for example in Pasonen et al. (2012) would be available here, the pay-back times would decrease significantly. This could probably be created by similar feed-in tariff system than applied in Germany.

During the previous years, the average market price of electricity in Nordpool has been typically between 30–50 €/MWh (Figure 52). According to Figure 51, PV is not feasible at all if all the electricity is sold at market price.

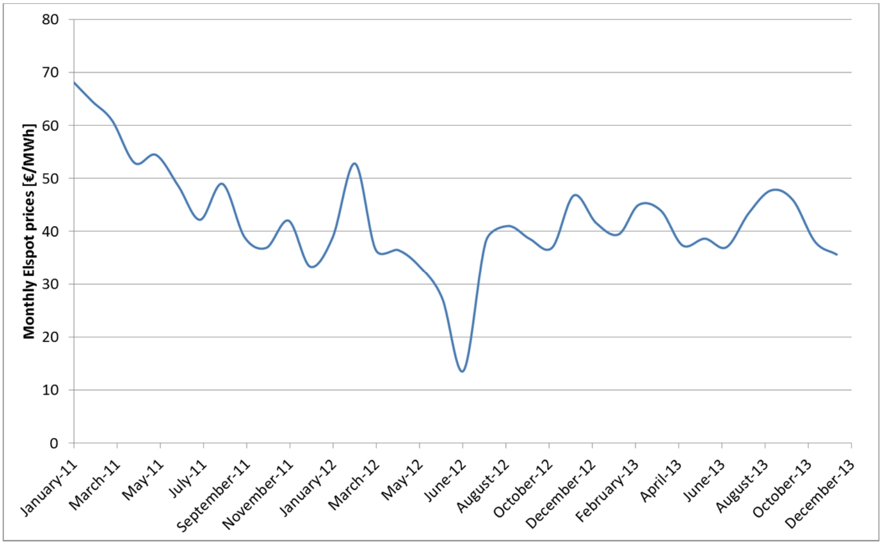


Figure 52. Market price of electricity in Nordpool (Finnish bidding area) (Nordpool, 2014).

If all the produced electricity is consumed by producer, the PV investment can be compared to overall price of purchased electricity, including also variable part of transmission price (Figure 53) and electricity tax, currently 2.36 c/kWh (incl. VAT 24%). Typical variable cost of purchased electricity in Finland for small consumer has been about 11 c/kWh (110 €/MWh) in recent years. According to Figure 51, the pay-back time would be too high for PV investments also in this case.

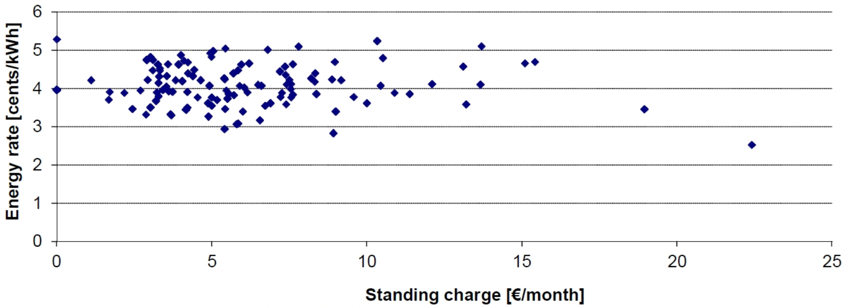


Figure 53. Flat rate distribution tariffs of Finnish distribution system operators for a main fuse of 3x25 A (based on statistics of the Energy Market Authority) (LUT, 2012).

If strict climate policy will be applied, the overall cost of electricity is likely to increase. In that case, feasibility of PV installations would obviously be better.

In some cases, for example summer houses outside of electricity grid, PV may be the most feasible option already as costs of alternative electricity supply can be much higher than presented in previous figure. In addition, in summer houses the consumption of energy fits perfectly on the production of solar energy. This potential is also recognised in the background report of the national energy strategy of Finland (National Energy and Climate Strategy of Finland, 2013a). However, in the strategy PV is considered insignificant in Finland at least until 2025 if additional subsidies will not be introduced. At present, large PV projects could apply “energy support” for the investment but the support is not allowed for households. PV is also excluded from the Finnish feed-in tariff system (National Energy and Climate Strategy of Finland, 2013b).

Most of the scenarios regarding Finnish energy system and national energy and climate strategy are strongly based on increased biomass combustion and nuclear power. Solar energy is not visible in the figures of the strategy. According to national energy and climate strategy, utilisation of woodchips as energy should be increased from 14 TWh/a (as 2010) to 25 TWh/a at 2020 (National Energy and Climate Strategy of Finland, 2013b). However, there are some uncertainties regarding such a large increase in biomass utilisation.

- biomass availability, longer transportation distances, more difficult harvesting sites
- possibility to utilise CHP as heat consumption is not increasing
- sustainability of increased harvesting, new areas and limited resources
- possible competition for raw material with forest industry
- lower quality of feedstocks and increased biomass shares in power plants (increased O&M costs)

The factors listed above may significantly increase costs related to bioenergy. In addition, the discussion regarding carbon debt resulted by biomass harvesting and combustion has been active in recent years. If for example some kind of CO_2 emission factor will be applied for bioenergy, the costs will further increase. Due to reasons presented above, the costs of PV are compared also to costs of bio-electricity production (excluding CHP) in the following figure.

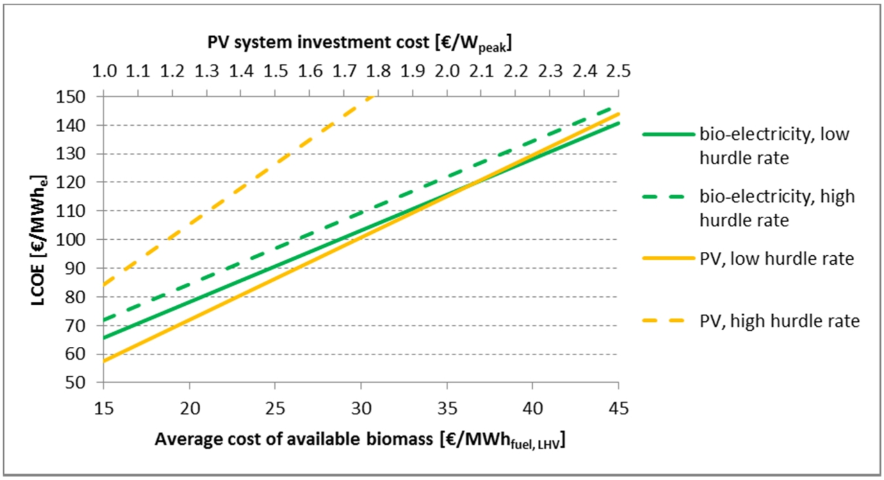


Figure 54. Electricity production costs by PV and biomass as a function of biomass price (lower horizontal axis) and specific investment of PV system (upper horizontal axis). Assumed hurdle rates and other economy variables are presented in Table 6. For PV, annual peak production hours of 833 was used based on 60 kW PV system presented in Resca (2013). For bio-electricity, utilisation rate of 5000 h/a was assumed. In practice, utilisation rate of bio-electricity would probably decrease with increasing biomass price whereas utilisation rate of PV is not dependent on (positive) market prices.

According to Figure 54, for example, if specific investment cost of 1.75 €/W$_{peak}$ is assumed (as estimated for the example system in Resca [2013]) and with variables presented in Table 6, the cost of electricity production would be about 145 €/MWh if higher hurdle rate is used. With lower hurdle rate the cost would be significantly smaller, about 100 €/MWh. Similar production costs would be achieved with biomass costs of 44 €/MWh$_{fuel}$ if higher hurdle rate is used and 28 €/MWh$_{fuel}$ if lower hurdle rate is used.

Table 6. Economy variables used in the calculations of Figure 54.

Economic timespan	20	a
Technical lifetime	40	a
Hurdle rate, low	5%	
Hurdle rate, high	10%	
General discount rate	2%	
Investment on bioenergy plant	1.4	M€/MW$_e$
Efficiency of bioenergy plant	40%	net
Fixed O&M costs for bioenergy plant	15.9	€/kW$_{fuel}$ (year)
Variable O&M costs for bioenergy plant	2.7	€/MWh$_{fuel}$

Feasibility of PV investment is very sensitive for the required hurdle rate. Based on Figure 54 it can be concluded, that even if biomass price would double in the future to about 40 €/MWh (corresponding also, for example, fuel price increase to 30 €/MWh + about 50% carbon accounting in EU ETS with allowance price about 40 €/t) bioenergy would still be more competitive than PV if higher hurdle rate is required for the investment and specific investment for PV systems would remain on the level presented in Resca (2013). On the contrary, PV would be more feasible already with the biomass price of 30 €/MWh (corresponding also, for example, the biomass price level at present 20 €/MWh$_{fuel}$ + about 50% carbon accounting with CO_2 price 40 €/t) if lower hurdle rate is used. From PV point of view, optimistic scenario could be, for example, the specific investment level of 1.2 €/W, which would make PV more feasible than bioelectricity already with the existing biomass prices and CO_2 emission regulation (100% carbon neutral in EU ETS) if lower hurdle rate is used.

From the energy system point of view, the grid connected PV is of interest. Based on the previous figures, it seems that PV might be feasible also in Finland in the replacement of electricity purchase (including transmission fees) only if required investments would decrease significantly and/or cost of electricity purchase would increase. For reasonable pay-back times in commercial operation, similar feed-in tariffs than in Germany would be needed. If similar progress than in Germany at present is assumed per capita, the amount of PV would be 398 W/habitant (EPIA, 2013). With population of 5.45 Million in Finland, this would result in PV capacity 2169 MW.

4.2 Potential for solar heat collectors in Europe

The main challenge of solar energy, intermittency is emphasized in the case of solar heating. When most solar energy is available, there is no demand for it. If heat would be stored, significantly higher shares of heat demand could be produced by solar. Example system is illustrated in Figure 55.

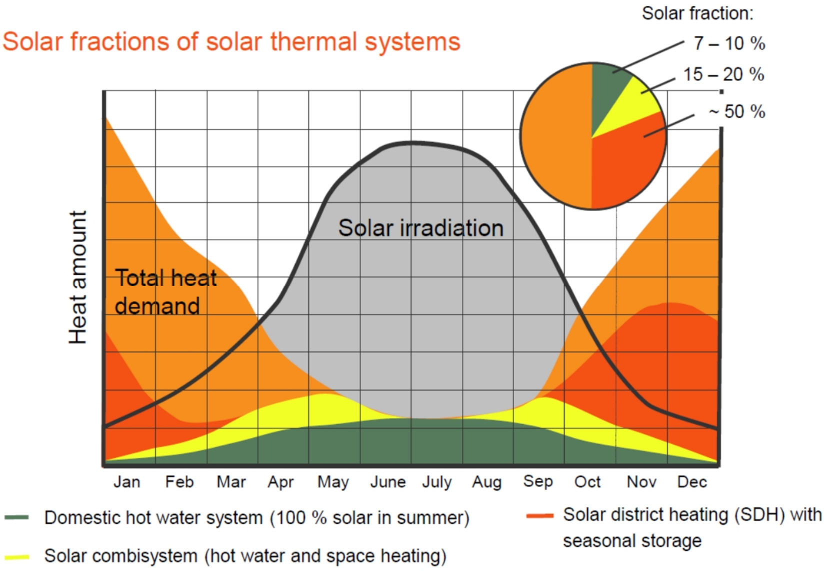
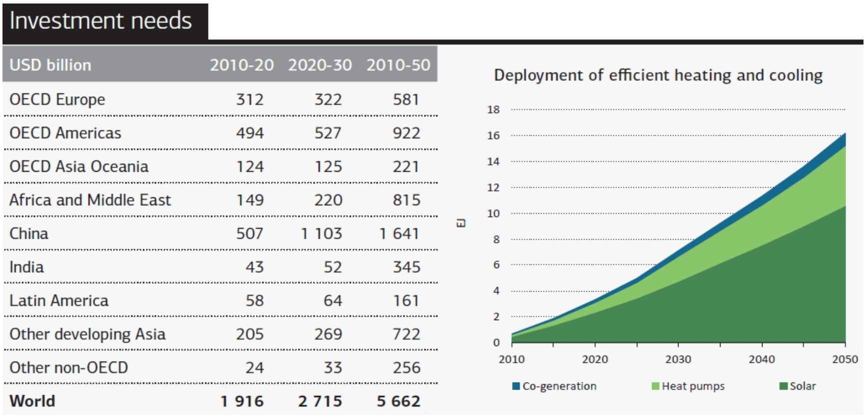


Figure 55. Solar fractions of solar thermal systems (Schmidt & Mangold, 2013).

According to IEA ETP, the costs of small scale solar thermal systems range from USD 1100/kW to USD 2140/kW for new constructions and USD 1300/kW to USD 2200/kW for existing houses. For multifamily dwellings, unit costs are slightly lower, at USD 950–1050/kW for new, and USD 1140/kW – 2050/kW for existing (IEA ETP, 2012). In general, significantly higher potential is estimated for solar heating in IEA ETP 2DS than would be achieved by current pace. The investment needs and deployment roadmap of efficient heating and cooling technologies are presented in Figure 56. From the figure, it can be concluded, that massive deployment of solar technologies is given before 2050 led by China but investment needs are significant also in Europe.



Investment needs

USD billion	2010-20	2020-30	2010-50
OECD Europe	312	322	581
OECD Americas	494	527	922
OECD Asia Oceania	124	125	221
Africa and Middle East	149	220	815
China	507	1 103	1 641
India	43	52	345
Latin America	58	64	161
Other developing Asia	205	269	722
Other non-OECD	24	33	256
World	**1 916**	**2 715**	**5 662**

Figure 56. Deployment roadmap of efficient heating and cooling technologies presented in IEA ETP 2012 (IEA ETP, 2012).

4.2.1 Example studies regarding the small scale applications in Europe

There is a study concerning water heating throughout the summer in northern climates. Study also aimed to find out how often the solar water heating can provide adequate water temperatures for domestic use without auxiliary heating system. In northern Europe domestic hot water is often provided by the house's central heating boiler. (Rogers et al., 2013.)

Water storage temperatures with no auxiliary heating are presented in Figure 57.

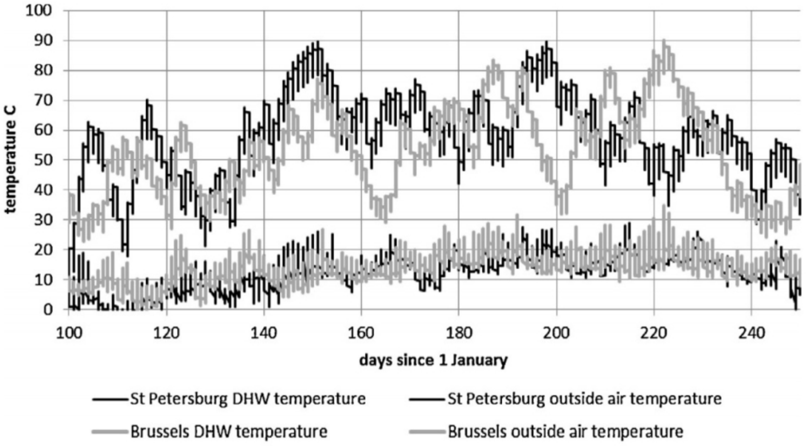


Figure 57. Water storage temperatures with no auxiliary heating throughout the summer (Rogers et al., 2013).

What comes to sizing DHW systems the larger is the water storage the larger the collector area can be. When larger water storage is in use there are more days in a year when auxiliary heating is not needed. For example, electrical immersion heater can be used to maintain sufficient water storage temperature. Capital costs for this kind of electrical heater are relatively low. (Rogers et al., 2013.)

If auxiliary heating is not used, number of days the temperature of water in the storage tank exceed certain temperatures are presented in Figure 58. The study was done using commercial software package TRNSYS which is graphically based software environment made to simulate transient systems. Typical meteorological year (TMY) weather data was used and it was generated using TRNSYS and monthly average NASA data. (TRNSYS, 2013; Yohanis et al., 2006.)

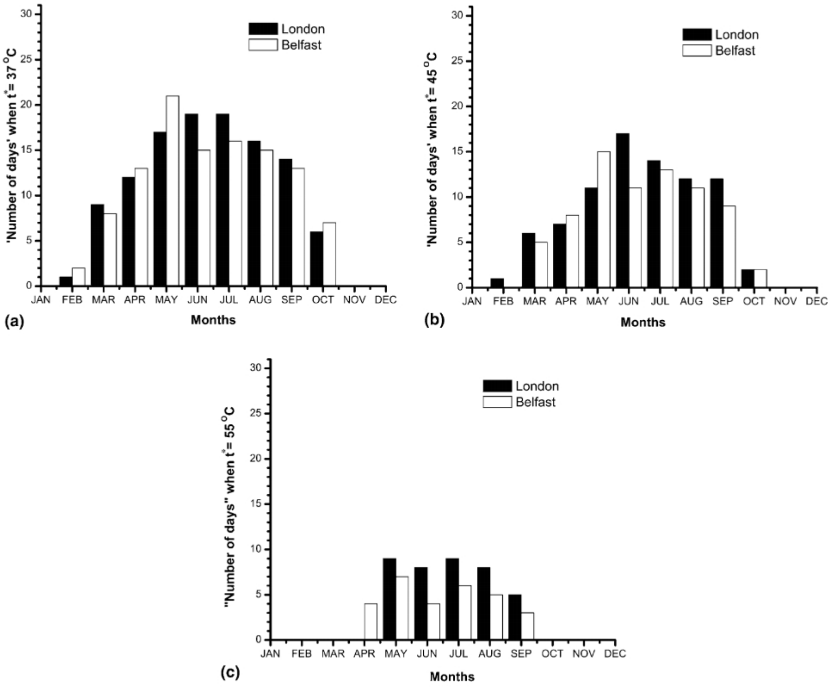


Figure 58. Number of days the temperature of water in the storage tank exceeds (a) 37 °C, (b) 45 °C and (c) 55 °C in London and Northern Ireland (Yohanis et al., 2006).

The fluctuation of the solar energy covering energy demand of the detached house is presented in Figure 59. The data is from Austria.

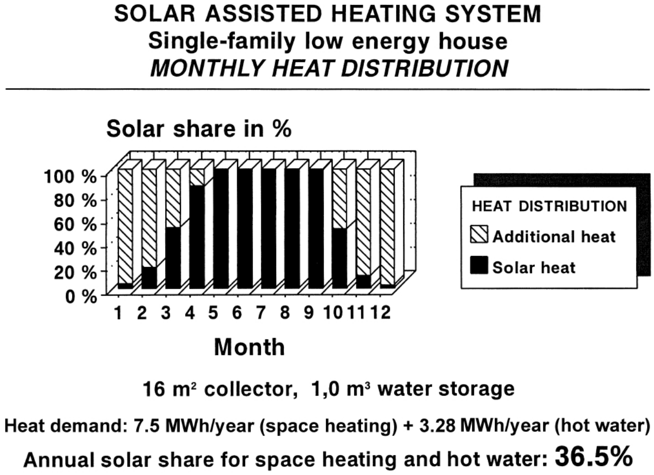


Figure 59. Monthly heat distribution of a solar assisted heating system in Austria (Faninger, 2000).

4.2.2 **Studies about commercial scale systems in Europe**

Annual solar heat production rates have been simulated in Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems. Simulations were performed using TRNSYS based models and the results are presented in Figure 60. Calculations were carried out for Barcelona, Milan, Würzburg and Stockholm. Greatest production is gained with CPC which means collector type called evacuated tube with compound parabolic concentrator. Second highest solar heat is produced by vacuum tube and third highest production is gained by flat-plate HT which is high temperature flat-plate collector. (Deschaintre, 2013.)

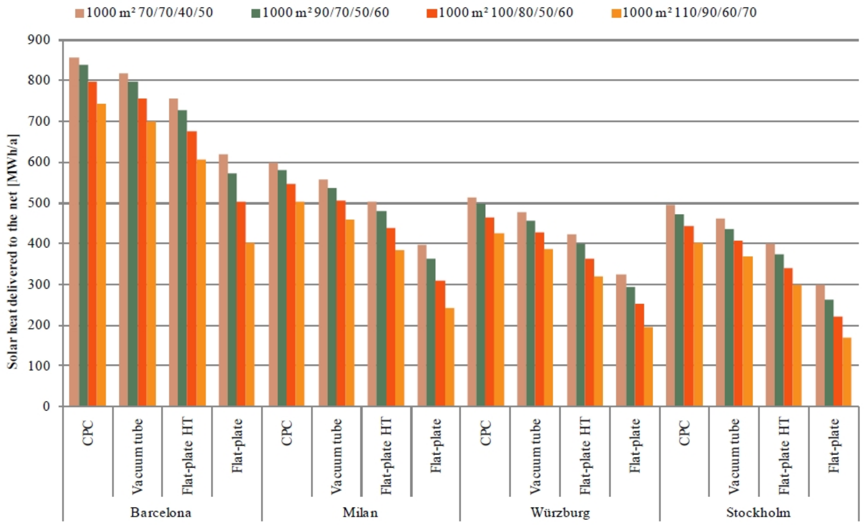


Figure 60. Annual solar heat production rates in four different locations as a result of simulation (Deschaintre, 2013).

Study has been done for the future Ecodistrict Villeneuve in Chambery. Influence of the DH return temperature on the performance is presented in Figure 61. Simulation results are for flat plate collectors and the total collector area is 180 m^2 being 4.5 m^2 per apartment as there are 40 apartments.

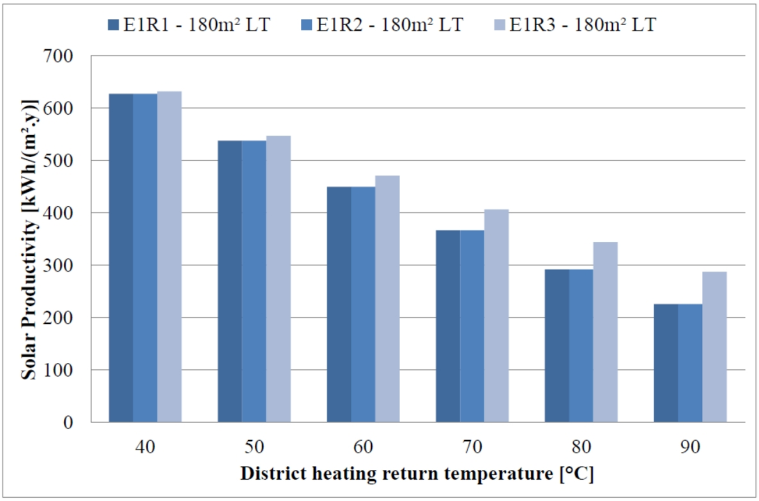


Figure 61. Influence of the DH return temperature on the annual heat produced (Paulus, 2013).

In Austria has been conducted a survey which states that solar plants would act together with communal small-scale biomass district heating plants. During the summer time boilers are typically oversized and they are operated with a low load which leads to low efficiency. The combination would have the advantage that heat outside the heating period could be produced mainly by solar heating plant. Data from this combined solar-biomass district heating is presented in Figure 62. (Faninger, 2000.)

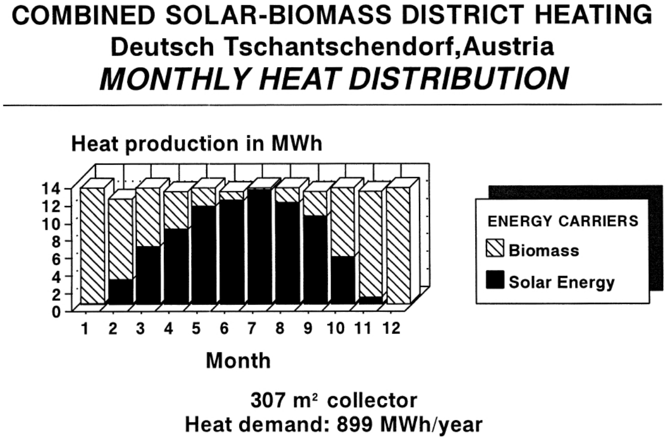


Figure 62. Monthly heat production in district heating plant in Austria (Faninger, 2000).

4.2.3 **Potential of solar thermal energy in Finland**

4.2.3.1 Small scale solar thermal energy systems

When comparing the costs of solar heating systems, it is important to take into account the following major cost categories:

- collectors,
- hot water storage (tank) or additional coil to existing tank,
- control unit and pipelines,
- installation work,
- cost of auxiliary system,
- taxes and subsidies.

In this report, the focus is in addition of solar heating on existing buildings. Therefore investments on auxiliary systems are not taken into account (assumed that there is existing heating system which use is replaced by solar heating when available). Generic all-inclusive costs are difficult to achieve from the equipment suppliers as these are case specific. According to Motiva, the investment cost (as installed, including VAT) for the example system (8–12 m^2) is typically between 4000–5000 € and heat production between 250-400 kWh/m^2/a (Motiva, 2014a). Higher estimates have been obtained from suppliers. For example, Oilon offered 6 and 8 m^2 all-inclusive collector systems with heat storage tanks at prices about 5000 € and 7000 €, respectively, excluding installation work (Oilon, 2013). Ympäristöenergia presents 7 and 9 m^2 all-inclusive systems at about 4700 to 5700 €, respectively, excluding installation (Ympäristöenergia, 2014). Ultimatemarket offers 8 m^2 collector systems at price 2119 € (Ultimatemarket, 2014a) and relatively small storage tank, 1590 € (Ultimatemarket, 2014b) at overall price about 3700 €, excluding installation. Despite of several inquiries, estimation for installation costs was received from only one supplier, LVI Pirttinen Oy (LVI Pirttinen, 2014). The installation cost is about 1800 € for residential scale collector system (7 m^2). Investment cost for the equipment offered by LVI Pirttinen (based on Viessmann Vitosol 200-F collectors) was 6000–6500 € including storage tank and 5300–5700 € if existing storage tank can be utilised (equipped with solar coil). The overall turnkey supply would therefore be about 7000–8000 €. The estimated annual production by presented system is 440 kWh/m^2.

Fortum has announced a calculator for solar heat applications (Fortum, 2014), including estimates for installation costs. Based on the calculator, for example the following table can be conducted for a detached house in central Finland (Table 7).

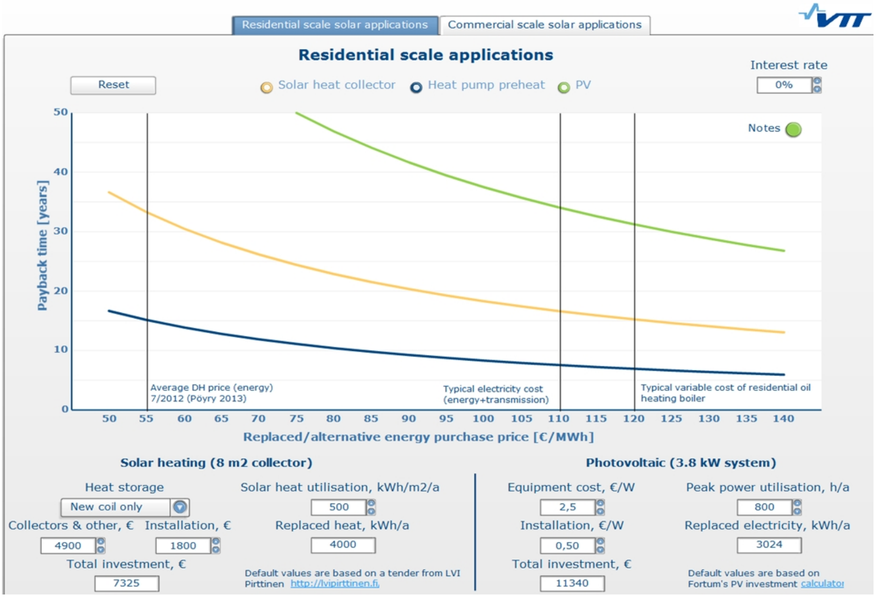
Table 7. Investment costs and annual productions for solar heat systems based on the Fortum's calculator (Fortum, 2014).

Number of collectors	**1**	**2**	**3**
Investment [€]	3692	5082	6462
• Price of collectors and auxiliaries	1650	2400	3452
• Installation	1672	2272	2560
• Additional coil + installation	370	410	450
Production [kWh/a]	734	1467	1944

It should be highlighted that significant share of the investment is possible to gain back as tax relief. Neither tax reliefs nor other incentives are taken into account in the values presented for residential applications in this report. However, potential incentives have significant impact on feasibility of solar collectors from consumer's point of view.

Operational expenditures of solar heating are typically very small. Important factor affecting on payback time of the investment is the price of replaced/alternative energy, heat consumption (typically hot water) and its distribution over the year. If heat is consumed typically on sunny days (summer) investment on collector is more feasible than in the case that heat consumption in summer is small. If for example hot water is not consumed during some sunny week in July, the benefit from solar collector is practically zero from that week. In addition, the required temperature of the heat is essential in terms of annual production of heat collectors in Finland. If also low temperature heat can be utilised, utilisation hours of the collectors are significantly higher, especially during spring and autumn.

Detailed cost and feasibility analysis of different solar applications were executed in WP7 of the SANDWISH project including also dynamic toolkit for sensitivity analysis with varying economic parameters. The toolkit will be available at http://www.vtt.fi/img/research/ene/combustion/ after the SANDWISH project. However, for potential analysis, the costs are presented in this report by rough estimates. The purpose is to enable comparison of costs between solar heat and other technologies and thus map economic potential for solar heat in Finland. Based on the values received from LVI Pirttinen the following graph (*Figure 63*) can be drawn for the pay-back time for solar heat investment. Similar interface as presented in Figure 63 will be available also under the public domain after the project.



Interest rate: 0%

Solar heating (8 m2 collector)

Heat storage: New coil only
Collectors & other, €: 4900
Installation, €: 1800
Total investment, €: 7325
Solar heat utilisation, kWh/m2/a: 500
Replaced heat, kWh/a: 4000

Default values are based on a tender from LVI Pirttinen http://lvipirttinen.fi

Photovoltaic (3.8 kW system)

Equipment cost, €/W: 2,5
Installation, €/W: 0,50
Total investment, €: 11340
Peak power utilisation, h/a: 800
Replaced electricity, kWh/a: 3024

Default values are based on Fortum's PV investment calculator

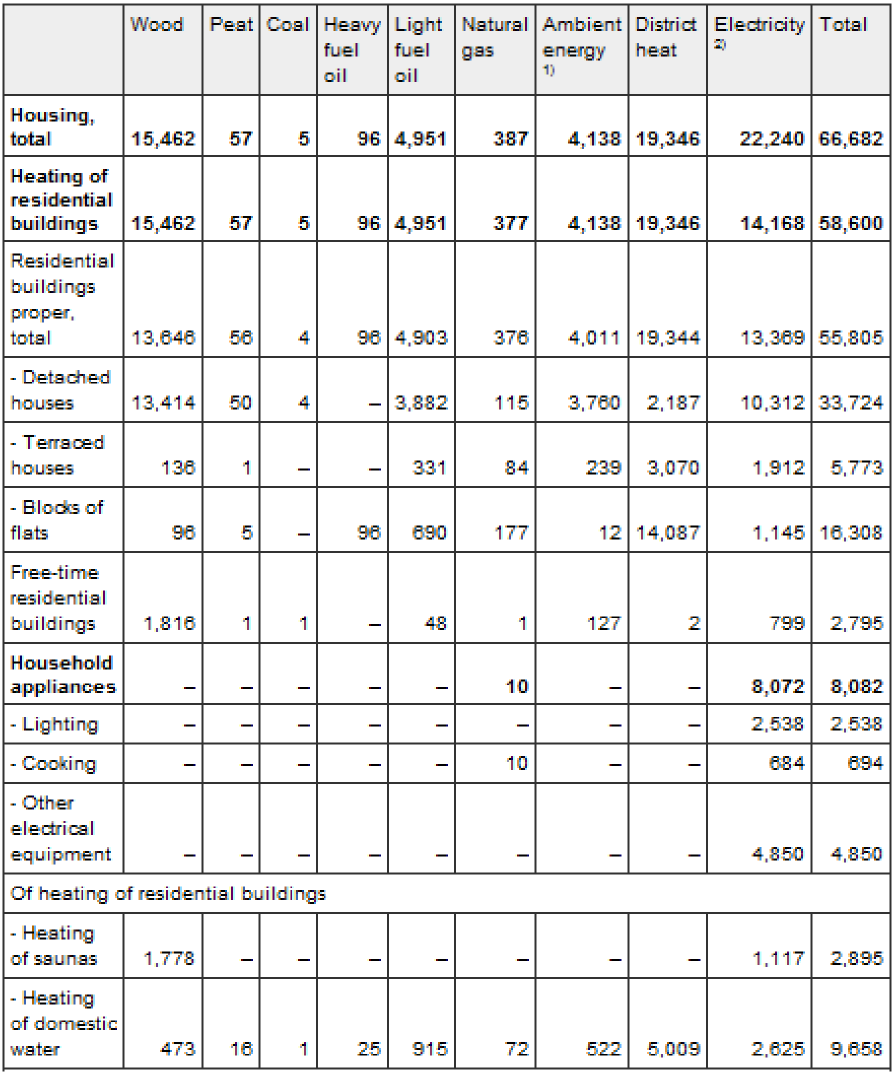
Figure 63. The pay-back time for small scale solar heat collectors and comparison with PV and fictional air pump preheating. Neither potential tax reliefs nor other subsidies are taken into account in this graph but can be estimated by the toolkit at http://www.vtt.fi/img/research/ene/combustion/ for example by reducing the impact of tax relief from the installation cost. The scale represents collectors sized for detached house, i.e. the feasibility for apartment buildings might be significantly better.

If compared to the variable costs of existing heating systems the pay-back time can be estimated based on Figure 63. In this report, comparison to three largest water heating systems in Finnish residential sector (Table 8) is presented. Variable costs of electricity for households is about 110 €/MWh, depending on e.g. grid operator. When replacing electricity in water heating, the consequent pay-back time of solar heat system investment is about 20 years, depending also on the required interest rate. If hot water heating by oil (variable costs about 120 €/MWh) is replaced, the pay-back time of about 15 years is achievable. In addition, it is probable that oil price will increase in future, making the investment more feasible. Average variable cost of district heat in Finland is about 55 €/MWh and prices over 80 €/MWh are rare (Pöyry Management Consulting Oy, 2013). Replacing district heat by solar heat is therefore not seen as feasible in this scale as the replacement of electricity and light fuel oil. However, utilisation of the scale of district heat network could bring some benefits, different business models etc. as discussed earlier in Chapter 3.5.2. This may offer feasible solar solutions in some cases, especially if fuel availability, taxes or subsidies will change and/or price of CO_2 allowances increases.

Pöyry (2013) presented the costs of solar heating also for apartment buildings and office buildings. At 2012, the variable cost of district heat for apartment buildings was higher than the production costs of solar heating in less than 10 district heat systems. For office buildings, the cost of solar heating was smaller in about 20 district heat systems. These district heat networks, where variable costs are high, utilise typically relatively high share of oil in production (Pöyry, 2013). The conclusion is similar than in the case of detached buildings: replacement of oil by solar heating is economically feasible if relatively long pay-back time can be justified.

In Finland, there exists significant potential to replace purchase of electricity and light fuel oil by solar especially in domestic water heating. If existing heating system is based on the water circulation, some benefits are achievable in heating of building as well but the additional investment required may not be that feasible. In addition, integration of solar collectors with heat pumps seems to be promising as well, but more research is needed to evaluate the economic feasibility. The statistics of energy consumption in residential sector during 2012 are presented in Table 8.

Table 8. Energy consumption in households by energy source in 2012, GWh (Tilastokeskus, 2013).



	Wood	Peat	Coal	Heavy fuel oil	Light fuel oil	Natural gas	Ambient energy [1)]	District heat	Electricity [2)]	Total
Housing, total	**15,462**	**57**	**5**	**96**	**4,951**	**387**	**4,138**	**19,346**	**22,240**	**66,682**
Heating of residential buildings	**15,462**	**57**	**5**	**96**	**4,951**	**377**	**4,138**	**19,346**	**14,168**	**58,600**
Residential buildings proper, total	13,646	56	4	96	4,903	376	4,011	19,344	13,369	55,805
- Detached houses	13,414	50	4	–	3,882	115	3,760	2,187	10,312	33,724
- Terraced houses	136	1	–	–	331	84	239	3,070	1,912	5,773
- Blocks of flats	96	5	–	96	690	177	12	14,087	1,145	16,308
Free-time residential buildings	1,816	1	1	–	48	1	127	2	799	2,795
Household appliances	–	–	–	–	–	**10**	–	–	**8,072**	**8,082**
- Lighting	–	–	–	–	–	–	–	–	2,538	2,538
- Cooking	–	–	–	–	–	10	–	–	684	694
- Other electrical equipment	–	–	–	–	–	–	–	–	4,850	4,850
Of heating of residential buildings										
- Heating of saunas	1,778	–	–	–	–	–	–	–	1,117	2,895
- Heating of domestic water	473	16	1	25	915	72	522	5,009	2,625	9,658

During 2012 the total domestic water heating with electricity and light fuel oil was 3 540 GWh in Finland. Based on the estimate presented by Ruukki in Chapter 3.5.1 (50% of domestic hot water demand) about 1770 GWh of electricity and oil could be replaced relatively economically. In addition, a proportion of other water heating systems and fuels and electricity consumed to heating of buildings could be replaced by solar. However, these solutions are estimated to be less feasible than replacement of light fuel oil and electricity in hot water heating and therefore not included to this estimation about economic potential. Other fuels for hot water heating are typically less expensive than electricity or light fuel oil increasing the pay-back time of replacing solar investment. Heating of buildings is not as feasible due to weak matching of irradiation and heat demand. In the case of new buildings, potential solutions for active and passive solar heating are less limited but the amount of new constructions is limiting the potential to utilise solar heating. In addition, hybrid solutions for both, existing and new houses are possible and may be more economical than solar solely. These solutions are not included in this report.

Based on the values presented above, the estimated impact of small scale solar heating in Finland in "high solar" scenario could be:

- replacement of electricity use in water heating 1313 GWh/a
- replacement of light fuel oil use in water heating 458 GWh/a (389 GWh/a heat assuming 85% boiler efficiency)

In the case of new constructions (excluded from this report), the order of economic feasibility of different heating systems may be different with and without integration with solar heating. In new buildings, the share of solar heating is typically larger than in older buildings because the share of hot water consumption of overall heat consumption is higher due to lower heat demand (better insulation, windows, etc.). In new apartment building, the share of water heating of overall heat demand can be over 60% (Pöyry, 2013).

4.2.3.2 Commercial scale solar heating

As discussed earlier, there are different business models and technical solutions to produce district heat by solar. Despite small scale replacement of district heat is not seen as feasible as replacement of electricity and light fuel oil, some benefits would be achievable with larger solar collector systems enabled by district heat network. Pöyry Management Consulting published a study at 2013 regarding business opportunities for solar heating in district heat systems (Pöyry Management Consulting Oy, 2013). The study includes for example case studies and monthly variation of solar production in Finland and it is not repeated in this report. At present, the replacement of existing CHP production seems unfeasible but replacement of heat production by oil seems to be feasible already (Pöyry Management Consulting Oy, 2013). According to Statistics Finland, 1 720 GWh of oil was used for district heating in 2012 (Statistics Finland, 2014). However, majority of the consumption occurs during winters, because the heat consumption is obviously largest then and especially because oil fired boilers are used for peak load production in many networks. Therefore also the amount of oil consumption during sunny periods in Finland is difficult to estimate.

According to Pöyry (2013) there are only few district heating networks utilising oil as main fuel in Finland and typically the size of these networks is relatively small. The potential for solar heat would be about 20 GWh/a (Pöyry, 2013). On the other hand, this is only 1% of the oil consumed for district heating and might be underestimated.

The pay-back times for commercial scale solar heat installations are presented in Figure as a function of the cost of replaced heat and with different interest rates and installation sizes. Values are based on the estimated costs and production values (Table 9) presented by Pöyry (2013).

Table 9. Estimated investment costs and production volumes of commercial scale solar collector systems (Pöyry, 2013).

Collector area [m^2]	**5 000**	**50 000**
Investment [M€]	1.5	10
€/m^2	*300*	*200*
MWh/a	2000	20000
kWh/m^2/a	*400*	*400*

It should be noted, that no costs are assumed for required installation area, i.e. the land or large roof area is available free of charge. Fixed annual operational expenditure of 1.2% of the investment is used based on Pöyry (2013).

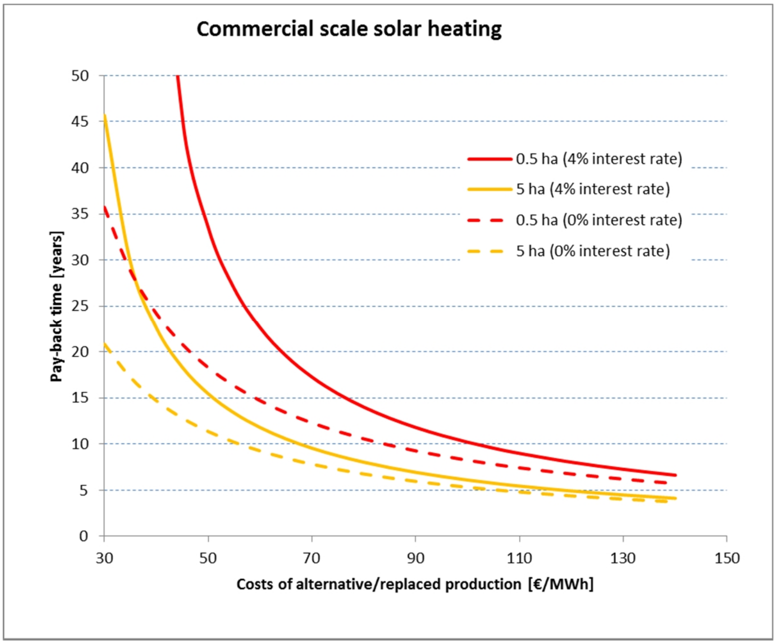


Figure 64. The pay-back time of commercial scale solar heat investments as a function of the costs of replaced heat. The concept of pay-back time has been extended to the case where time value of money has been taken into account. The pay-back time here is the time when NPV of the investment becomes positive. Calculation is based on the values presented by Pöyry (2013).

In practice, the costs of replaced production changes over the time in several district heat networks if large amount (e.g. 20 GWh/a) of solar heat is introduced to the system. The horizontal axis of Figure 64 presents the weighted average of replaced production costs over the considered time frame. If solely oil could be replaced, pay-back time below 10 years could be possible. In the case of CHP, heat production costs are typically too low to rationalize investment on solar heating. However, in CHP system, the cost of replaced production is dependent on the fuel prices, support policies and electricity price (and allocation method used). In addition, network specific future requirements regarding additional/replacing production capacity have significant impact on the feasibility of solar heating.

Solar district heating may be feasible especially in new suburbs, where new buildings are built but connection to main district heat network is not feasible due to low heat consumption of the buildings and too long distance to main network. In addition, the importance of domestic water heating is highlighted in the case of new buildings due to reduced demand for room heating. This favours solar heating.

As visible in the previous figures, commercial scale solar heating is more feasible than small scale solar heating. This was also concluded by Pöyry (2013) but calculations included the assumption that required area is available free of charge. However, in larger scale, there are some major benefits, namely inherent storage capacity of the network, other potentially existing heat storages, distributed consumption resulting guaranteed utilisation for solar heat and economy of scale in terms of investment.

4.2.3.3 Detailed analysis of CHP district heating system with solar thermal installation

Whether heat is generated by utility-scale solar district heating or small-scale solar thermal collectors, it should be taken into account in the operational scheduling the existing district heat system. This includes possible CHP plants, district heating plants, heat storages and the DH. After the operational changes have been accounted for, we can compare the economic figures before and after the inclusion of solar thermal collectors.

As part of WP6 of the Sandwish project we calculated the example case of Jyväskylä district heating network with solar thermal input. The thermal input was assumed to originate from 12 MW_{th} flat-plate collectors which could be installed in the Kangas district. The simulation of these solar collectors has been described in a separate report (Hoang et al., 2014) based on irradiation measurements of the Finnish Meteorological Institute. Table 10 shows the main district heat generating and storage units in the Jyväskylä main DH network.

The effect of solar heating on the operational scheduling of the conversion units and storages can be studied with the help of a scheduling optimization system. This system optimizes the scheduling of heat and electricity generating plants and energy storages within the district heating system with respect to given heat demand and additional heat generation by solar thermal collectors, i.e. performs unit commitment and economic dispatch calculations. Figure 65 below shows the schematic illustration of the district heat scheduling optimization tool with its inputs and outputs.

Table 10. The main electricity and district heat generating and storage units in the Jyväskylä main network.

Unit	**Capacity**	**Fuels**
Keljonlahti CFB plant	electricity 213 MW, heat 260 MW	wood, peat, coal
Rauhalahti BFB plant	electricity 87 MW, heat 180 MW	wood, peat, coal
district heating plants	heat ca. 400 MW	heavy fuel oil
heat storage	volume 10,000 m^3 (unpressurized)	
main DH network	volume ca. 20,000 m^3	

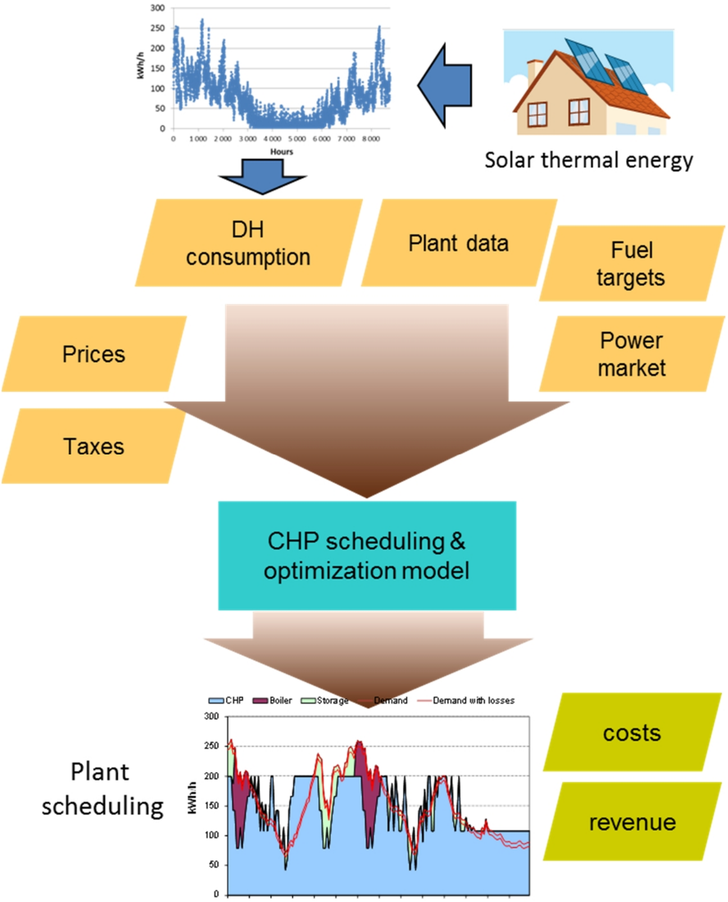


Figure 65. Schematic illustration of the inputs and outputs of the district heat system optimization tool.

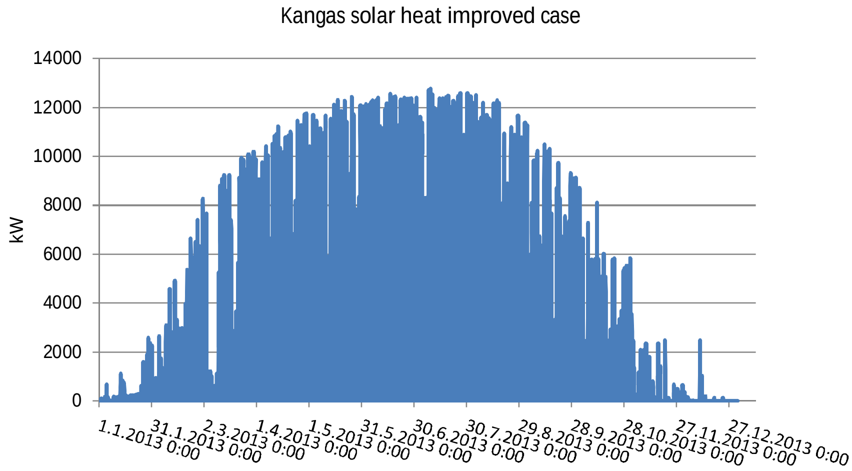


Figure 66. Solar heat output of the collectors in Jyväskylä as function of time during one year (Hoang et al., 2014).

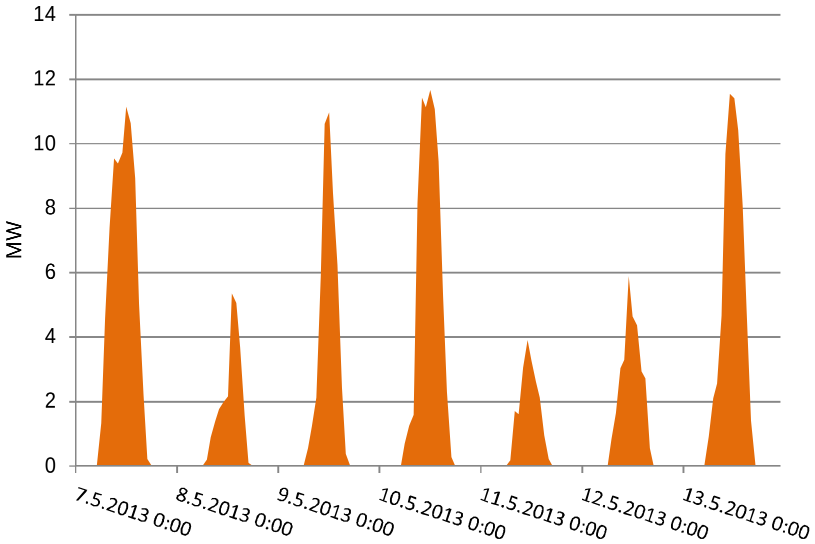


Figure 67. Solar heat output hourly averages in Jyväskylä as function of time during one week in May (Hoang et al., 2014).

Figure 66 shows the simulated heat output of the collectors in Jyväskylä during a whole year and Figure 67 shows the heat output during one week. The working temperature of the collectors was kept at 65 °C, which is suitable for space heating and DHW production. The assumption was that the produced heat can mostly be used to reduce the DH consumption of the customers without feeding heat into the supply side of the DH network. This requires that the collectors are distributed to a significant number of customers in different parts of the city. If the installation is more concentrated, heat must at times be fed back into the network. In this case a higher working temperature such as 75 °C in summer is desired. Increasing the working temperature somewhat decreases the heat output especially when the irradiation level is low. Feeding heat on the return side of the network was not studied.

Detailed results of the effects of solar thermal energy in the Jyväskylä system are kept confidential. However, about the 12 MW_{th} solar thermal installation we can conclude the following:

- Solar thermal installation can reduce the fuel cost and fuel tax cost of the CHP plants;
- Effects on annual electricity generation of the CHP plants are quite small;
- The cost savings are not large enough to make the investment profitable at current prices (cf. Section 4.2.3.2).

5. Production forecast for solar power and wind power and the accuracy of forecasting

Renewable power production, particularly PV systems, solar thermal power plants and wind turbines produce fluctuating energy, which in turn causes new challenges for electricity companies and transmission system operators. While electricity demand and power production from conventional sources can be predicted with fairly high accuracy, predicting solar and wind power production is more challenging. Solar and wind energy availability and the amount of production from these sources are largely determined by existing weather conditions, and are consequently more challenging to be forecasted. This causes a challenge when integrating intermittent renewable production into the energy supply system. Today the balancing of production and demand is mainly done by adapting the conventional production to the fluctuating renewable production. Also shifting the loads (demand response) and utilizing storage technologies are potential tools to response the challenge of balancing intermittent renewable production and demand in the future. However, all these methods benefit from prediction of renewable production as an input value for scheduling the production of other technologies and matching it to demand (Lorenz & Heinemann, 2012).

The accuracy of forecasts is emphasized when the penetration of solar and wind production increases. With accurate prediction of future solar and wind production it is possible to integrate renewable energy sources into energy source mix more cost-effective and increase the value of produced renewable energy. Prediction of generation is required as input value for management and operation strategies of balancing production including increasing share of fluctuating renewable generation and demand with before mentioned concepts (adaption of conventional production, shifting loads, energy storage). (Lorenz & Heinemann, 2012.)

5.1 Solar irradiance and solar and wind production forecasting

As PV installations are increasing rapidly, various PV prediction systems have been introduced. Wind power prediction systems are already widely used in the countries having large shares of wind power. Systems have already shown their economic impact on the wind power integration into the electricity grid; they are highly cost-effective compared to situation where forecast system is not used. Though, current forecasting technology must still be improved. Improvements will be based on better models and better use of them, and more observational data. (Lorenz & Heinemann, 2012; Brower, 2011.)

5.1.1 **Practical issues of solar irradiance and power forecasting**

Most references discussing forecasting of solar production are concentrated on electricity production forecasts for PV systems, which is therefore in focus also in this report. In this chapter solar forecasting technology is discussed in general, as in Finland forecasting technology is not widely used because the production level remains low and is focused in households. In Finland, Finnish Meteorological Institute provides solar irradiance forecasts for customers, as solar power production forecasts are not yet done. Irradiance forecasts are done for global horizontal irradiance (GHI), and also cloudiness forecasts can be done when needed (Rauhala, 2014). When predicting solar power production with PV technology, also prediction for solar irradiance is needed (Lorenz & Heinemann, 2012).

A typical solar power forecasting system is presented in Figure 68. As can be seen, power forecasting includes site specific prediction of horizontal irradiance utilizing satellite images, NWP (Numerical Weather Prediction) forecasts and/or irradiance measurements. Based on site-specific prediction of horizontal irradiance, forecast of irradiance on the module plane and forecast of PV power can be done. The time horizon to be predicted highly affects the input data and models to be used. PV system output is mainly determined by the incoming solar irradiance, so the irradiance forecasting and its accuracy are essential for power prediction. Input data determines the forecast horizon, which can vary from minutes to hours or days. For very short term horizon forecasts ranging from minutes to few hours on-site measured data is usually suitable for input data. The temporal development of clouds is used as input data for short term forecasts up to 6 hours. From 4–6 hours onwards NWP models usually offer the best accuracy for the forecasts. (Lorenz & Heinemann, 2012.) NWP models work on the basis of dynamical equations. Dynamical equations use initial weather conditions and predict the evaluation of the atmosphere up to several days ahead. Their initial conditions are gathered and derived from satellite, radar, radiosonde and ground station measurements. In

Table *11* presented is a comparison between some existing NWP based models. NWP models get higher accuracy if they are derived to mesoscale models covering only a limited area of the normal NWP model area, having higher resolution and thus attempting to take better into account local conditions. (IEA, 2013.)

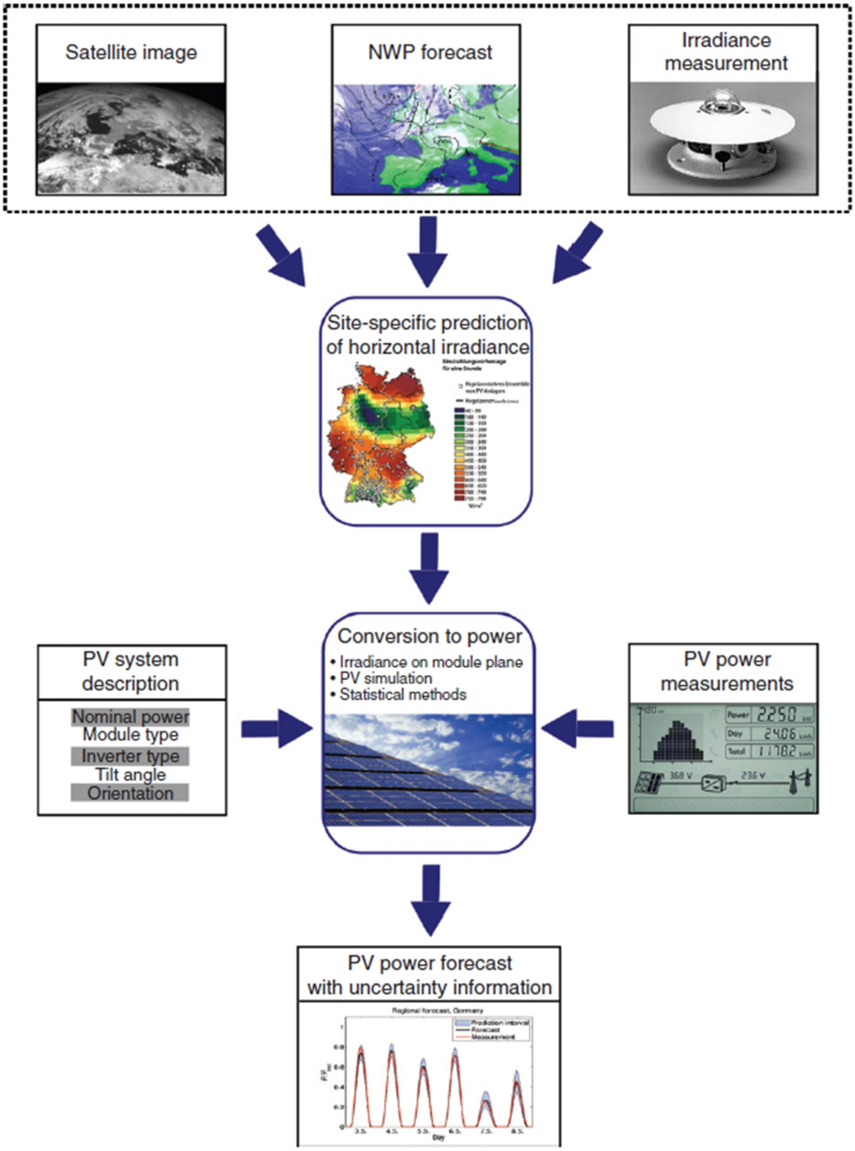


Figure 68. Typical PV solar power forecasting system with different kind of input data options (Lorenz & Heinemann, 2012).

Table 11. Comparison of some NWP based models (Inman et al., 2013).

Name	Resolution	Layers	Update period	Time horizon	Time step
GFS	28 km	64	6 h	180 h	6 h
–	–	–	–	384 h	12 h
RUC/RAP	13 km	50	1 h	18 h	1 h
NAM	12 km	60	6 h	96 h	6 h
HRRR	3 km	50	1 h	15 h	15 min
WRF	≥1 km	User Specific	User specific	User specific	User specific

Evaluation of performance and production values of concentrated solar power (CSP) plant is a complex task and there are many tools to enable it. For example NREL has a publicly available model “System Advisor Model” (SAM). It produces output profile for the investigated plant with detailed weather data. Advanced prediction of CSP plant production is challenging because the output is sensitive to direct normal irradiance (DNI), ambient temperature, wind speed, humidity and other weather phenomena. Accurate production forecast for a certain plant at a certain site requires weather data from many years at the site. Because this data is generally not available extrapolated data and for example satellite data is used. (CSPA, 2012.)

5.1.2 Practical issues of wind power forecasting

In 2012 only 0.6% of the total electricity consumption in Finland was covered by wind power. That is the reason why wind power forecasting applications are still not so widely in use in Finland. However, there is a goal to increase wind power capacity to 2500 MW responding 6% of electricity consumption. This requires wider usage of short term forecasting tools and developing of more accurate tools as the forecast errors increase the balancing costs of wind power producer. (Holttinen et al., 2013.) At the moment Finnish Meteorological Institute provides forecasts for wind and wind power in certain power plant sites in Finland. These forecasts are partly based on customers’ power production history and wind measurements. (Ilmatieteen laitos, 2013.)

Wind power can be forecasted with physical or statistical model or with a combination of these. Forecasting horizon can be very short term, short term or medium term, when the time horizon ranges from minutes to one week. Wind power forecasting errors can be divided in level and phase errors. Level errors are caused by erroneous prediction, usually due to badly configured forecast model, whereas phase errors are caused by failing the prediction of timing of production changes (Holttinen et al., 2013). In Figure 69 is presented basic steps of wind power production forecasting system. Weather observations produce the initial data for the NWP models, which predicts the changes in the weather conditions. Statistical models are used to convert predicted wind to expected power output including error correction. By comparing expected production to real power production can be achieved feedback to improve the statistical models. (Brower, 2011.)

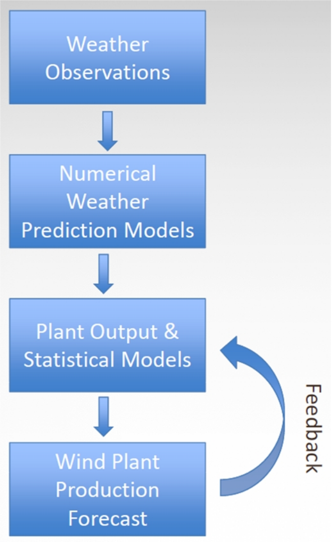


Figure 69. Basic steps of forecasting wind power production (Brower, 2011).

5.2 Accuracy of forecasting the production

The accuracy of solar and wind production forecasts directly affects the cost-efficiency of integrating large shares of fluctuating renewable energy into the electricity supply system (Brower, 2011). The accuracy of the production forecast can be indicated by using statistical error measures. There are several metrics to evaluate the prediction error; mainly used are bias, mean absolute error (MAE) and root mean square error (RMSE) (Lorenz & Heinemann, 2012; Holttinen et al., 2013). When discussing forecast accuracy it is important to specify which metric is used (RMSE, MAE etc.). In addition it is essential to clarify the time horizon and whether also the night hours are taken into account or not. Often forecast errors are normalised; in these cases it should be clarified by the mean of which value this is done. Normalisation is typically done by the mean produced power or installed capacity (IEA, 2013).

5.2.1 Accuracy of solar power production forecasts

The accuracy of the forecast for solar power depends on the accuracy of the used forecast model, climate conditions at the selected site and the forecast horizon. Mainly the forecast accuracy is influenced by the variability of the meteorological and climatological conditions. The cloud situation affects strongly the forecast accuracy as variable cloud situation is more difficult to forecast than clear sky situation, and consequently leads to lower forecast accuracy. Of course the forecast accuracy of solar power production is highly determined by the forecast accuracy of solar irradiance. When cosine of the solar zenith angle is known the maximum possible irradiance during the day can be calculated, and that information determines the magnitude level of forecast error. Uncertainties related to the different modelling steps that are needed to derive power forecasts from irradiance forecasts have also a minor influence on the forecast accuracy. Figure 70 demonstrates five different predictions for the daily irradiances made with different forecast methods and the measured data. The forecasts are provided by German companies. As can be seen in the figure, all the algorithms provide good agreement with the real measured data. The days with worse correlation between forecasts and measurements probably represent cloudy days. (Lorenz & Heinemann, 2012; IEA, 2013.)

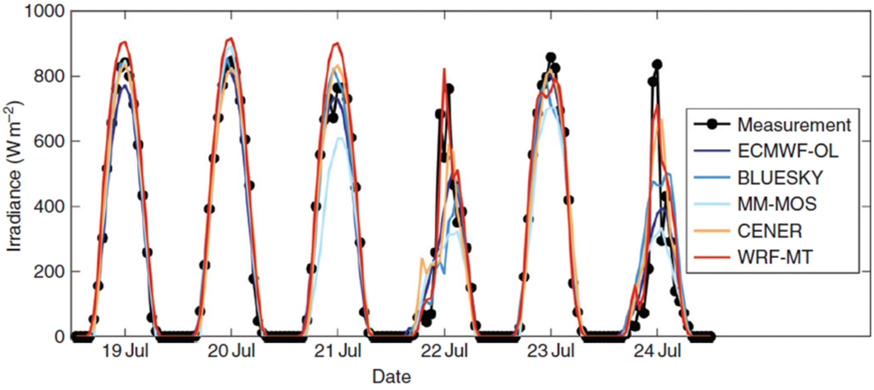


Figure 70. Predicted irradiances for six days with five different methods and the real measured irradiance (Lorenz & Heinemann, 2012).

As mentioned before, forecast horizon partly determines the forecast accuracy of irradiance and consequently affects the forecast accuracy of power production. The suitable forecast model is chosen partly in terms of forecast horizon. The best day-ahead irradiance and power production forecasts are based on NWP model forecasts combined with post-processing of those forecasts to improve them. Statistical models using data from local ground measurements are useful for short forecast horizon prediction, six hours or less. Ground measurements can be furthermore complemented with satellite or sky imager data of cloud movements. It is typical that there is higher reduction in forecast accuracy with increasing forecast horizon for prediction methods using the past data compared to for example NWP based models. (Lorenz & Heinemann, 2012; IEA, 2013.) In Figure 71 is demonstrated an example case about differences between different forecasting method accuracies both for short term and day-ahead time horizons. Red line represents satellite nowcast as a reference value. It can be seen that Numerical Weather Prediction (NDFD in Figure 71) based forecast starts to have better performance than the other methods from five hours forecast horizon onwards, as especially the cloud motion forecasts have better performance up to five hours ahead. (IEA, 2013.)

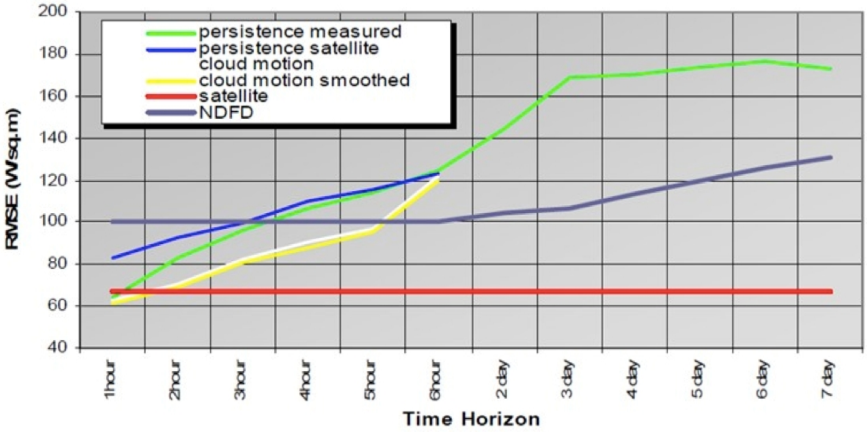


Figure 71. Comparison of forecast accuracies of different forecasting methods (IEA, 2013).

All in all, NWP models provide many benefits over other forecasting methods. It has been shown that for forecast horizons exceeding four hours they provide more accurate predictions than satellite based methods. As a result, NWP based forecasting is the most suitable option for medium-term and long-term forecasting as it provides forecasts for time horizons up to 240 hours (Inman et al., 2013). More about different irradiance forecasting methods and their accuracies can be found from Inman et al. (2013).

In Figure 72 is shown relative root-mean-square error for all the forecasts introduced in Figure 70. The errors marked with different blue colours represent errors for different NWP model based forecasts with post-processing as the other two models are based on mesoscale. It can be clearly noted, that forecasts based on global model with post-processing show better forecasting results. The figure shows how the forecast accuracy decreases when forecast horizon increases. NWP based models show smaller increase in errors than mesoscale models when moving from intraday forecasts to day-ahead forecasts. (Lorenz & Heinemann, 2012.)

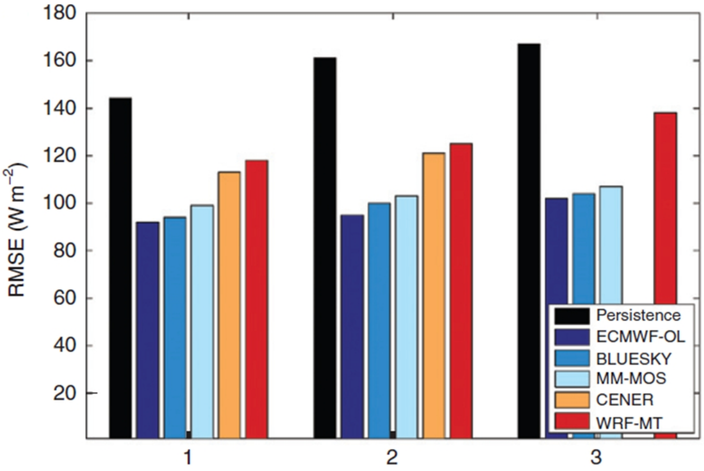


Figure 72. RMSE for different forecast horizons in Germany with five different forecast models (Lorenz & Heinemann, 2012). Horizon 1 was the same day forecast, 2 the day-ahead forecast and 3 forecast 2 days ahead. The mean measured irradiance for the time period was 227 W/m^2

It can also be seen that there is a high dependency between solar irradiance forecast accuracy and cloudiness. For example in sunny Spain the absolute forecast errors are smaller than in Central Europe. This is because the forecast errors are shown to be lower in areas with sunnier weather conditions. According to one study relative root mean square error ranges between 20% and 35% in Spain as in central Europe it ranges from 40% to 60%. (Lorenz & Heinemann, 2012; IEA, 2013). Figure 73 presents an example of the relation between cloud situation and forecast accuracy. The figure also shows how the solar elevation affects the forecast accuracy. This correlation causes not only regional, but also seasonal and daily differences in the forecasting accuracy. (Lorenz & Heinemann, 2012; IEA, 2013.)

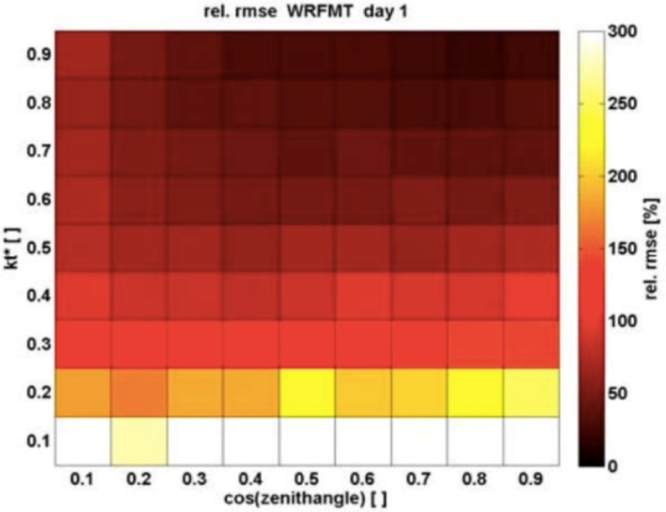


Figure 73. The relation between forecast accuracy (dark red representing the highest accuracy), cloud situation, which is described by clear sky index k_t^*, and solar elevation (IEA, 2013). k_t^* is close to 1 for clear sky and approaches 0 when the cloud cover is thick.

Forecasting larger aggregated solar power production, as well as wind production as explained later, is beneficial from the forecast accuracy`s point of view. It is shown that there is substantial increase in forecast accuracy when the size of the geographic area increases. For example a reduction of 64% in RMSE was gained when forecasting over an area the size of Germany compared to a forecast of only one point. (IEA, 2013.)

5.2.2 **Accuracy of wind power production forecasts**

The level of prediction errors is influenced by many factors. The location of wind power plant affects the prediction system performance. When the prediction is based on NWP, it causes the main uncertainty in forecast accuracy. In Figure 74 is presented forecast error in the form of mean absolute error of capacity as a function of forecast horizon for one wind power plant representing close to average forecast error and the range of errors with data of all 25 investigated wind power plants in Finland. The figure shows how the error increases when forecast horizon is increased, especially during the first hours. First 6 hours have significantly lower errors than the forecast horizon hours onwards. The range of error also increases when the horizon is increased especially during the first hours. After 6 hours forecast horizon the error range increases pretty linearly. The range of the average absolute error of installed capacity at a certain time horizon forecast is significant. The difference is caused by several factors changing between the sites; site orography and roughness, input data for the NWP model and wind resource. Low wind speed sites have less error than high wind speed sites as production during low wind speed is easier to predict. (Holttinen et al., 2013)

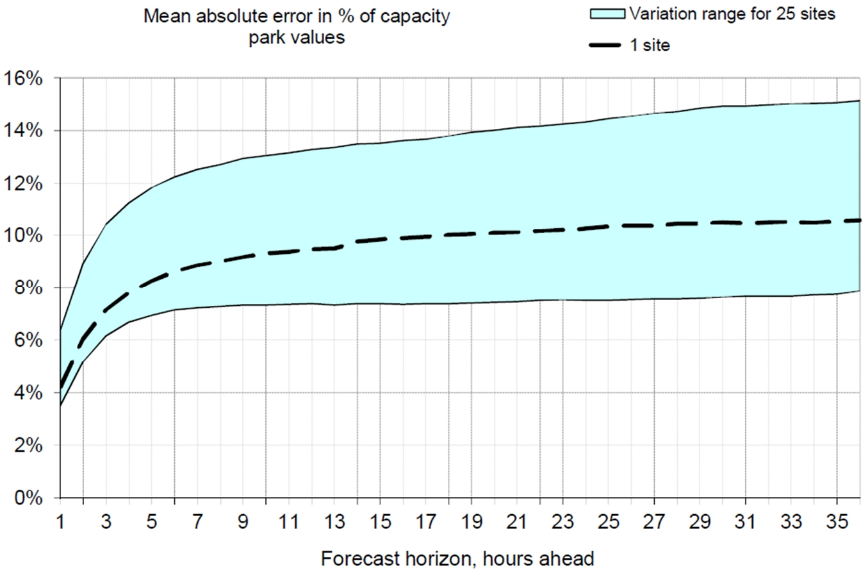


Figure 74. Forecast error as a function of forecast horizon. On investigated wind power plant shows close to average forecast error as the others show the range of errors. Data is given in VTT's publication in the given reference (Holttinen et al., 2013).

It is common for forecast error of wind power production that the errors in larger geographical area tend to be unrelated and due to that smooth out when the investigated area of wind power plants is raised. So when the number of investigated power plants is increased, the total relative forecast error smooths out. When single sites are aggregated and investigated together, the mean absolute error relative to yearly produced energy can decrease substantially. This decrease in forecast error has a huge impact on balancing costs from producer's point of view. (Holttinen et al., 2013.)

The accuracy of the wind power production forecast can be improved by combining several input weather forecasts from several providers instead of using only one forecast as an input for the prediction (Holttinen et al., 2013).

6. Discussion and conclusions

Renewable energy has become increasingly important due to several drivers. However, in national energy strategy of Finland, solar heating and PV have a minor role. Some potential, and remarkable irradiation also in Finland, are recognised but concrete actions to utilise the potential are not taken. On the other hand, reduction in heat demand of buildings is assumed in background report of energy strategy, which may be partly due to solar heating. Upcoming regulations regarding energy consumption of the buildings, especially new constructions, may be significant drivers increasing utilisation of solar energy in Finland.

Solar water heating (SWH) is effective technology to convert solar energy into thermal energy even though most of the solar heat is produced during summer time especially in northern Europe. In Finland, typical range of annually utilised solar energy in water heating is about 200–400 kWh/m^2 (collector area). This value is very sensitive for consumption dynamics of the application, system sizing etc. and some suppliers present higher values as well. There are potential solutions under development, by which utilisation per collector are could be doubled in some applications but more research is needed.

Flat plate collector is the most common solar collector type in Europe. The other commonly used collector type is evacuated type collector which is predominant in Asia. Economically the production cost of solar heat is still quite high even if the cost per produced energy is very sensitive for several parameters, especially for considered timespan in calculations. On the current price levels solar heating can be seen as a potential replacement for oil and direct electrical heating what comes to heating of domestic water. There exist already several companies who offer solar heating installations and turnkey options.

There is a possibility to install a connection between solar heating units and district heating network. Connection is useful because during the summer time solar collectors tend to produce excess heat which can be then fed to the district heating network. Solar energy can be utilised also as centralized district heat production as done in several cases in, for example Denmark. One option is to use a combination of small-scale biomass heating units and solar heating units as a district heating plant. Also seasonal heat storages act important role in SDH systems because with the help of heat storage significant share of heat produced during summer season can be utilized during winter season. So far, there are very few district heat systems utilising solar heat in Finland. However, several plans exist and if economic feasibility would be good enough, readiness to utilise solar district heat exists also in Finland.

Basically, the share of solar and also wind based electricity has great potential to increase in the future. For instance, solar PV has already seen massive cost reduction and similar effect may happen for solar collectors. Some market segments are not included in the values presented in this report for the potential of solar energy, such as new constructions utilising solar heating (passive or active, as it does not directly replace existing energy consumption), agriculture applications, fuel drying, large gas and service stations and supermarkets outside of district heating network area.

The operational environment may also change, for example due to strict climate policy. The possible impacts of increased biomass combustion were discussed in Chapter 4.1.1 and those impacts would have consequences on the solar heat feasibility as well. Solar energy could be utilised for example in district heat network during summertime and limited (sustainable) biomass resources could be saved for usage when solar heat is not achievable. In addition, if electricity price will be high, utilisation of condensing production is possible in several CHP plants in Finland. In that case, it could be temporarily feasible to utilise solar heat in district heat network. However, in the case of that high electricity prices, PV may be more feasible option. Due to seasonal matching, combining district cooling with solar heat utilising absorption may be feasible option. Further analysis of this is not included in this report.

On the contrary, mushrooming of PV in Europe and heat pumps in Finland, as well as developing electricity markets and transmission opportunities, may lead to low electricity prices during summer time. This will decrease the feasibility of CHP production and therefore improve the feasibility of solar collectors in district heat area.

It would be possible to replace electricity consumption by solar heat also by small modifications on existing systems and thereby improve the feasibility of solar heating. For example, washing machines could be equipped with mixing valves, enabling utilisation of solar heat and replacing electricity consumption. Also for example bathroom floor heating by solar is beneficial also during summer time and it can be used for adjustment between varying production and demand as well.

References

Abernethy, T.L. & Raichle, B.W. 2012. *An empirically derived model regarding the performance of flat plate solar thermal collectors based on varying ratios of direct to diffuse solar radiation*. Department of Technology and Environmental Design. Appalachian State University. http://ases.conference-services.net/resources/252/2859/pdf/SOLAR2012_0260_full%20 paper.pdf

Aurinkovoima. 2013. Webpage. http://www.aurinkovoima.fi/fi/sivut/referenssit

Bach, P.-F. 2012. *An Energy System with Seasonal Storage*. http://www.pfbach.dk/firma_pfb/pfb_energy_system_with_seasonal_storage_2012.pdf

Brower, M. 2011. *Wind Energy Forecasting.* AWS Truepower.

Brunold, S., Frey, R. & Frei, U. 1994. *Comparison of three different collectors for process heat applications*. Proc. SPIE 2255, Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII, 107 (September 9, 1994). http://www.solarenergy.ch/fileadmin/daten/publ/procheat.pdf

CIT Energy Management. 2010. *Success Factors in Solar District Heating*. Solar District Heating._http://www.solar-district-heating.eu/Portals/0/SDH-WP2-D2-1-SuccessFactors-Jan2011.pdf

CIT Energy Management. 2012. *Market for Solar District Heating*. http://www.solar-district-heating.eu/Portals/0/SDH-WP2-D2-3-Market-Aug2012.pdf

CSPA (Concentrating Solar Power Alliance). 2012. *The Economic and Reliability Benefits of CSP with Thermal Energy Storage: Recent Studies and Research Needs.* CSP Alliance Report.

Dalenbäck, J.-O. 2013. *Decentralised SDH Systems – Swedish Experience.* First Solar District Heating conference. April 9, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0W Sc5Pk%3d&portalid=0

Deschaintre, L. 2013. *Development of a solar district heating online calculation tool*. First Solar District Heating conference. April 10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4Ve N0WSc5Pk%3d&portalid=0

Energiauutiset. 2013. Number 6/2013, Energiateollisuus Ry (in Finnish)

EPIA. 2013. European Photovoltaic Industry Association (EPIA), Global Market Outlook For Photovoltaics 2013–2017. http://www.epia.org/fileadmin/user_upload/Publications/GMO_2013_-_Final_PDF.pdf

ESTIF. 2013. European Solar Thermal Industry Federation. 2013. *Solar Thermal Markets in Europe*. http://www.estif.org/fileadmin/estif/content/market_data/downloads/Solar_Thermal_M%20arkets%202012.pdf

ESTTP. 2010. Dalenbäck, J. Solar Heating plants presentation slide. (cited 9.2.2014). Available at: http://www.solarthermalworld.org/node/2880

European Commission. 2012. *Energy roadmap 2050*. ISBN 978-92-79-21798-2. http://www.energy.eu/publications/Energy-Roadmap-2050.pdf

European Photovoltaic Industry Association. 2010. *Solar Europe Industry Initiative Implementation Plan 2010–2012*. http://setis.ec.europa.eu/system/files/Solar_EII_PV_Implementation_Plan_final.pdf

European Urban Knowledge Network. 2010. *Ekoviikki – Sustainable City Projects in Helsinki*. http://www.eukn.org/E_library/Housing/Housing_Quality/Energy_Efficiency/Ekoviikki_Sustainable_City_Projects_in_Helsinki

Faninger, G. 2000. *Combined solar–biomass district heating in Austria*. Solar Energy, Volume 69, Issue 6, 2000, Pages 425–435, ISSN 0038-092X, http://dx.doi.org/10.1016/S0038-092X(00)00117-1

Faninger, G. 2012. *3.12 – Solar Hot Water Heating Systems*. In: Editor-in-Chief: Ali Sayigh, Editor(s)-in-Chief, Comprehensive Renewable Energy, Elsevier, Oxford, 2012. Pp. 419–447. ISBN 9780080878737, http://dx.doi.org/10.1016/B978-0-08-087872-0.00312-7

Fraunhofer ISE. 2013. Recent facts about photovoltaics in Germany. http://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/recent-facts-about-photovoltaics-in-germany.pdf (cited at 17.2.2014)

Fortum. 2013. Aurinkopaneelien tuotto- ja investointilaskuri https://www.fortum.fi/countries/fi/yksityisasiakkaat/energiansaasto/aurinkoenergiaratkaisut/aurinkopaneeli/tilaaminen/pages/default.aspxFrost & Sullivan. 2013. *Analysis of the Global Solar Power Market*. http://www.frost.com/c/10077/sublib/display-report.do?id=NBB2-01-00-00-00

Fortum. 2014. Solar heat calculator and price examples. https://www.fortum.fi/countries/fi/yksityisasiakkaat/energiansaasto/aurinkoenergiaratkaisut/aurinkolampojarjestelma/aurinkolampolaskuri/pages/default.aspx (cited at 18.6.2014, in Finnish)

Grönberg, I. 2014. Passiivisesta sähkönkuluttajasta aktiiviseksi energiakansalaiseksi? Aurinkopaneelien yhteistilaus ja -rakentaminen Etelä-Karjalassa. Lappeenrannan teknillinen yliopisto, LUT Scientific and Expertise Publications, Tutkimusraportit – Research Reports, 21. ISBN 978-952-265-567-7 (PDF). Yliopistopaino, Lappeenranta 2014. http://www.doria.fi/bitstream/handle/10024/95741/abb0c9f6-1a29-4313-9337-6295ac6e3d27.pdf?sequence=2

Hakkarainen, E. 2013. Concentrated Solar Power: State-of-the-Art. VTT Research report VTT-R-1706-13.

Hassine, I.B. 2013. *Decentralised solar heat supply in DH networks: Theoretical and practical aspects*. First Solar District Heating conference. April 9-10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0WSc5Pk%3d&portalid=0

Heide, D., von Bremen, L., Greiner, M., Hoffmann, C., Speckmann, M. & Bofinger, S. 2010. *Seasonal optimal mix of wind and solar power in a future*. Highly renewable Europe, Renewable Energy, Volume 35, Issue 11, November 2010, Pages 2483–2489, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2010.03.012. http://www.sciencedirect.com/science/article/pii/S0960148110001291

Hoang, H., Pasonen, R., Kannari, L., Weiss, R. & Rämä M. 2014. *Energy production and demand of Kangas core area*. Espoo: VTT Technical Research Centre of Finland.

Holm, L. 2012. Long Term Experiences with Solar District Heating in Denmark. European Sustainable Energy Week, Brussels. 18–22 June 2012. Powerpoint. http://www.euroheat.org/Admin/Public/DWSDownload.aspx?File=%2fFiles%2fFiler%2fPresentations%2f20120618-22_EUSEW%2f120619_EUSEW_3+-+Holm+brussel+juni+2012.pdf

Holttinen, H., Miettinen, J. & Sillanpää, S. 2013. *Wind power forecasting accuracy and uncertainty in Finland.* VTT Technology 95. Espoo: VTT. www.vtt.fi/inf/pdf/technology/2013/T95.pdf.

IEA (International Energy Agency). 2013. *Photovoltaic and Solar Forecasting. State of the Art.* PVPS. Photovoltaic Power Systems Programme. Report IEA PVPS T14-01:2013.

IEA ETP. 2012. IEA Energy Technology Perspectives 2012 - Pathways to a Clean Energy System. OECD/IEA, 2012

IEA ETSAP. 2011. Technology Brief E11, Photovoltaic Solar Power, Highlights. http://iea-etsap.org/web/Highlights%20PDF/E11_PV_gs_am_gb_gs EPIA2011_FINALDRAFT%201.pdf (cited at 18.2.2014)

Ilmatieteen laitos. 2013. *Tuulivoimalan tuuli- ja tuotantoennusteet*. http://ilmatieteenlaitos.fi/tuulivoiman-tuotantoennusteet

Inman, R.H., Pedro, H.T.C. & Coimbra, C.F.M. 2013. *Solar forecasting methods for renewable energy integration.* Progress in Energy and Combustion Science 39 (2013) 535-576.

Investopedia. 2013. *Compound Annual Growth Rate*. http://www.investopedia.com/terms/c/cagr.asp

Jäger-Waldau, A., Szabó, M., Scarlat, N. & Monforti-Ferrario, F. 2011. Renewable electricity in Europe. Renewable and Sustainable Energy Reviews, Volume 15, Issue 8, October 2011, Pages 3703–3716, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2011.07.015. http://www.sciencedirect.com/science/article/pii/S1364032111002516

Jensen, M.V. 2013. *Two Approaches of Seasonal Heat Storing: Pit Heat Storage and Borehole Thermal Energy Storage*. PlanEnergi. First Solar District Heating conference. April 9-10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0WSc5Pk%3d& portalid=0

Jodat Ympäristöenergia. 2014. www-pages of Jodat Ympäristöenergia Oy, http://www.y-energia.com/aurinkolampo/teho_ja_tuotto/ teho_ja_tuotto.html (in Finnish, cited 2.2.2014)

JRC. 2014. European Commission Joint Research Centre, Institute for Energy and Transport (IET). Solar radiation and photovoltaic electricity potential country and regional maps for Europe. http://re.jrc.ec.europa.eu/pvgis/cmaps/eu_cmsaf_opt/PVGIS_EU_201204 _publication.png (cited 7.2.2014)

Kalogirou, S.A. 2004. *Solar thermal collectors and applications*. Progress in Energy and Combustion Science, Volume 30, Issue 3, 2004, Pages 231-295, ISSN 0360-1285, http://dx.doi.org/10.1016/j.pecs.2004.02.001

Kardonar. 2013. Kardonar Bioenergy Solutions Oy Ab. *Effecta aurinkokeräin*. http://www.kardonar.com/aurinko.html

Lorenz, E. & Heinemann, D. 2012. *Prediction of Solar Irradiance and Photovoltaic Power*. Comprehensive Renewable Energy, Elsevier, Oxford, 2012, Pages 239-292, ISBN 9780080878737, http://dx.doi.org/10.1016/B978-0-08-087872-0.00114-1

LUT. 2012. Tariff scheme options for distribution system operators. LUT Energy, Report 4 May 2012.

LVI Pirttinen. 2014. Personal communication by e-mail from Jaani Pirttinen to Eemeli Tsupari 5.3.2014

Ma, J., Sun, W., Ji, J., Zhang, Y., Zhang, A. & Fan, W. 2011. *Experimental and theoretical study of the efficiency of a dual-function solar collector*. Applied Thermal Engineering, Volume 31, Issue 10, July 2011, Pages 1751-1756, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2011.02.019.

Mauthner, Fr. & Weiss, W. 2013. *Solar Heat Worldwide: Markets and Contribution to the Energy Supply 2011*. International Energy Agency: Solar Heating & Cooling Programme. http://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2013.pdf

Mehnert, S., Kramer, K., Kovacs, P., Dias, P., Fischer, S., Mateu, E., Navarro, P. & Helminger F. 2012. *Towards a new global standard for solar thermal collectors*. International Solar Energy Society -ISES-: 30th ISES Biennial Solar World Congress 2011. Vol. 6: Kassel, Germany, 28 August – 2 September 2011. Red Hook, NY: Curran, 2012. ISBN: 978-1-618-39364-7. Pp. 4623–4634.

Motiva. 2014a. Information pages for solar collectors. http://www.motiva.fi/toimialueet/uusiutuva_energia/aurinkoenergia/aurinkolampo/aurinkokeraimet (cited 31.1.2014).

Motiva. 2014b. Feed-in tariff, http://www.motiva.fi/toimialueet/uusiutuva_energia/uusiutuvan_energian_tuet/syottotariffi (cited at 16.2.2014, in Finnish)

National Energy and Climate Strategy of Finland. 2013a. Background report. https://www.tem.fi/files/36279/Kansallinen_energia-_ja_ilmastostrategia_taustaraportti.pdf (cited at 16.2.2014, in Finnish)

National Energy and Climate Strategy of Finland. 2013b. Government Report to Parliament on 20 March 2013. Ministry of Employment and the Economy, Energy Department. MEE Publications, Energy and the climate 8/2013.

Nordpool. 2014. Electricity price in Nordpool. http://www.nordpoolspot.com/Market-data1/Downloads/Historical-Elspot-prices/Monthly-Elspot-prices/ cited at 16.2.2014

Oilon. 2013. TARJOUS SP2013085, 12.9.2013 VTT/Timo Hakkarainen.

Pasonen R., Mäki K., Alanen R. & Sipilä K. 2012. *Arctic solar energy solutions*. VTT. ISBN 978-951-38-7825-2. http://www.vtt.fi/inf/pdf/technology/2012/T15.pdf

Paulus, C. 2013. *Comparison of different architectures of substations for Decentralised Solar District Heating System*. First Solar District Heating conference. April 9–10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0WSc5Pk%3d&portalid=0

Pöyry Management Consulting Oy. 2013. *Aurinkolämmön liiketoimintamahdollisuudet kaukolämmön yhteydessä Suomessa*. Työ- ja elinkeinoministeriö, Energiateollisuus Ry. http://www.tem.fi/files/37133/TEMrap_28_2013_05072013.pdf

PV Magazine. 2014. Spanish solar industry demands national referendum on energy policy. http://www.pv-magazine.com/news/details/beitrag/spanish-solar-industry-demands-national-referendum-on-energy-policy_100014097/#axzz2tPQGPttj (cited at 15.2.2014).Rehau. 2011. *Borehole Seasonal Thermal Energy Storage*. http://www.rehau.com/linkableblob/GB_en/1026454/data/Braedstrup_project_Case_Study-data.pdf

Rauhala, H. 2014. Teollisuuden sääpalvelut. Ilmatieteen laitos. Personal communication by phone from Rauhala to Hakkarainen. 6/2014.

Resca. 2013. Tampere-Talon Laajennusosan Aurinkoenergiaselvitys / Resca. Loppuraportti 18.12.2013. Ramboll. http://www.tampere-talo.fi/uploads/Aurinkoenergia_loppuraportti_Tampere-talo.pdf (cited at 1.3.2014)

Rimstar. 2012. *Solar in winter issues*._http://rimstar.org/renewnrg/solar_in_cold_climate_and_winter_snow.htm

Rogers, J.G., McManus, M.C. & Cooper, S.J.G. 2013. *Potential for reliance on solar water heating throughout the summer in northern cloudy climates*. Energy and Buildings, Volume 66, November 2013, Pages 128-135, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2013.07.031

Rommel, M., Kovács, P. & Kramer, K. 2010. *Solar thermal technology update*. Renewable Energy Focus, Volume 11, Issue 5, September–October 2010, Pages 36-38, ISSN 1755-0084, http://dx.doi.org/10.1016/S1755-0084(10)70114-9.

Ruukki. 2013. *Ruukki lämpökatto -esite*. http://www.ruukki.fi/~/media/Finland/Files/Katot/Asennusohjeet/Ruukki_Classic_lampokatto_A4_4s_251013_web.ashx

Ruukki. 2014. Ruukki Classic solar-lämpökatto. http://www.ruukki.fi/Tuotteet-ja-ratkaisut/Rakentamisen-ratkaisut/Omakotitalojen-teraskatot/Ruukki-Classic-solar-lampokatto (cited 7.2.2014, in Finnish)

Savosolar. 2013. Brochures and simulation results from the company. Personal communication by e-mail. 9-10/2013 and company webpage http://www.savosolar.fi/.

Savosolar. 2014. Personal communication between Miika Kilgast (Savosolar) and Eemeli Tsupari (VTT) March 2014 and September 2014.

Schmidt, R.R. 2013. *The Smart Cities concept and challenges for heat networks*. First Solar District Heating conference. April 9-10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0WSc5Pk%3d&portalid=0

Schmidt, T. & Mangold, D. 2013. *Large-scale thermal energy storage – status quo and perspectives.* First Solar District Heating conference. April 9–10, 2013, Malmö, Sweden. http://www.solar-district-heating.eu/LinkClick.aspx?fileticket=4VeN0WSc5Pk%3d&portalid=0

Solartwin 2014. Solartwin Combi Preheat System. http://www.solartwin.com/wp-content/uploads/2011/08/Combi-prefeed-NONmodulating-giff.gif, cited 7.2.2014.

Statistics Finland. 2014. Production of electricity and heat [e-publication]. ISSN=1798-5099. 2012, Appendix table 1. Electricity and heat production by production mode and fuel in 2012. Helsinki: Statistics Finland [referred: 25.2.2014]. Access method: http://tilastokeskus.fi/til/salatuo/2012/salatuo_2012_2013-11-05_tau_001_en.html.

Stiftung Umweltenergierecht. 2012. PV support schemes and regulations for all target countries. http://www.pvparity.eu/index.php?eID=tx_nawsecuredl&u=0&file=fileadmin/PVPARITY_docs/documents/SUER_D3.1_Version_2.pdf

Tilastokeskus. 2013. *Energy consumption in households by energy source in 2012*. https://tilastokeskus.fi/til/asen/2012/asen_2012_2013-11-13_tau_002_en.html (cited at 16.2.2014)

TRNSYS. 2013. *Transient System Simulation Tool.* http://www.trnsys.com

Tyagi, V.V., Kaushik, S.C. & Tyagi, S.K. 2012. *Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology.* Renewable and Sustainable Energy Reviews, Volume 16, Issue 3, April 2012, Pages 1383-1398, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2011.12.013

Ultimatemarket. 2014a. Ultimate Ultra Flat aurinkokeräinpaketti 2. http://www.ultimatemarket.com/PublishedService?file=page&pageID=9&itemcode=airsolar_ultra2 (cited at 26.3.2014)

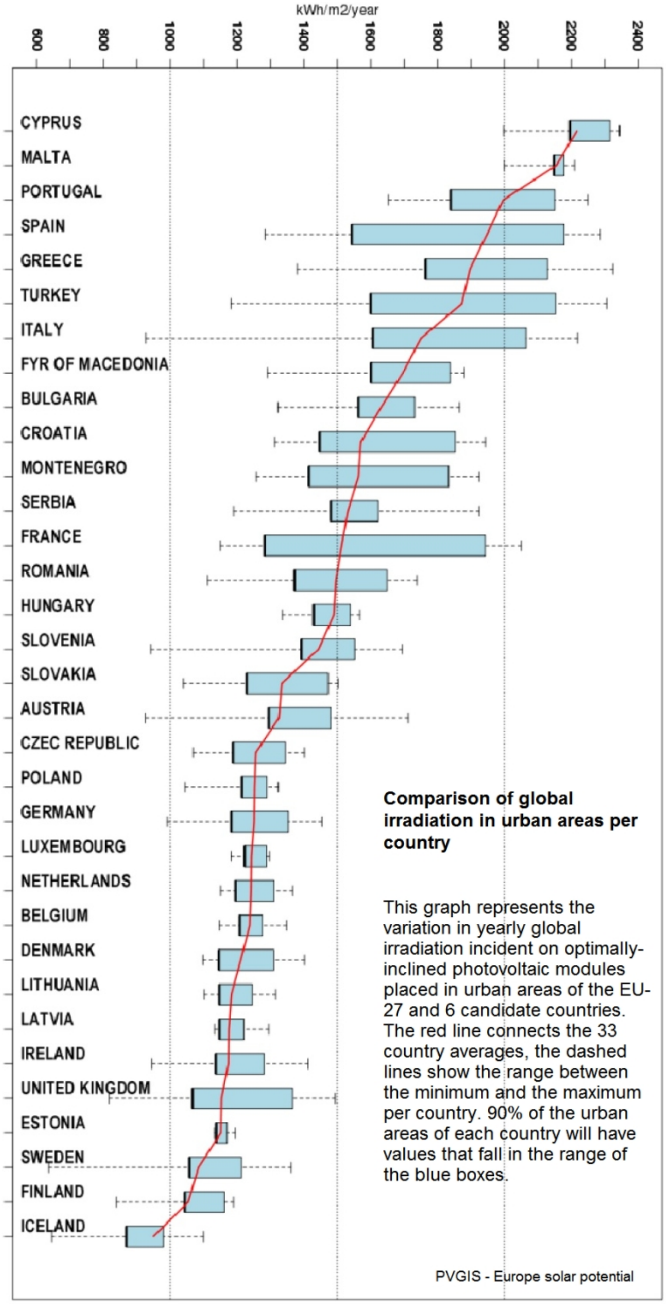
Ultimatemarket. 2014b. Ultitherm Energiavaraaja 600 Air Solar. http://www.ultimatemarket.com/PublishedService?file=page&pageID=9&itemcode=EV600tempaus (cited at 26.3.2014)

Ympäristöenergia. 2014. Commerce pages of Ympäristöenergia Oy. http://www.energiakauppa.com/shop/catalog/search?shop_param= (cited at 26.3.2014)

Yohanis, Y.G., Popel, O., Frid, S.E. & Norton, B. 2006. *The annual number of days that solar heated water satisfies a specified demand temperature*. Solar Energy, Volume 80, Issue 8, August 2006. Pp. 1021–1030. ISSN 0038-092X, http://dx.doi.org/10.1016/j.solener.2005.06.018

Zambolin, E. & Del Col, D. 2010. *Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions*. Solar Energy, Volume 84, Issue 8, August 2010, Pages 1382–1396, ISSN 0038-092X, http://dx.doi.org/10.1016/j.solener.2010.04.020

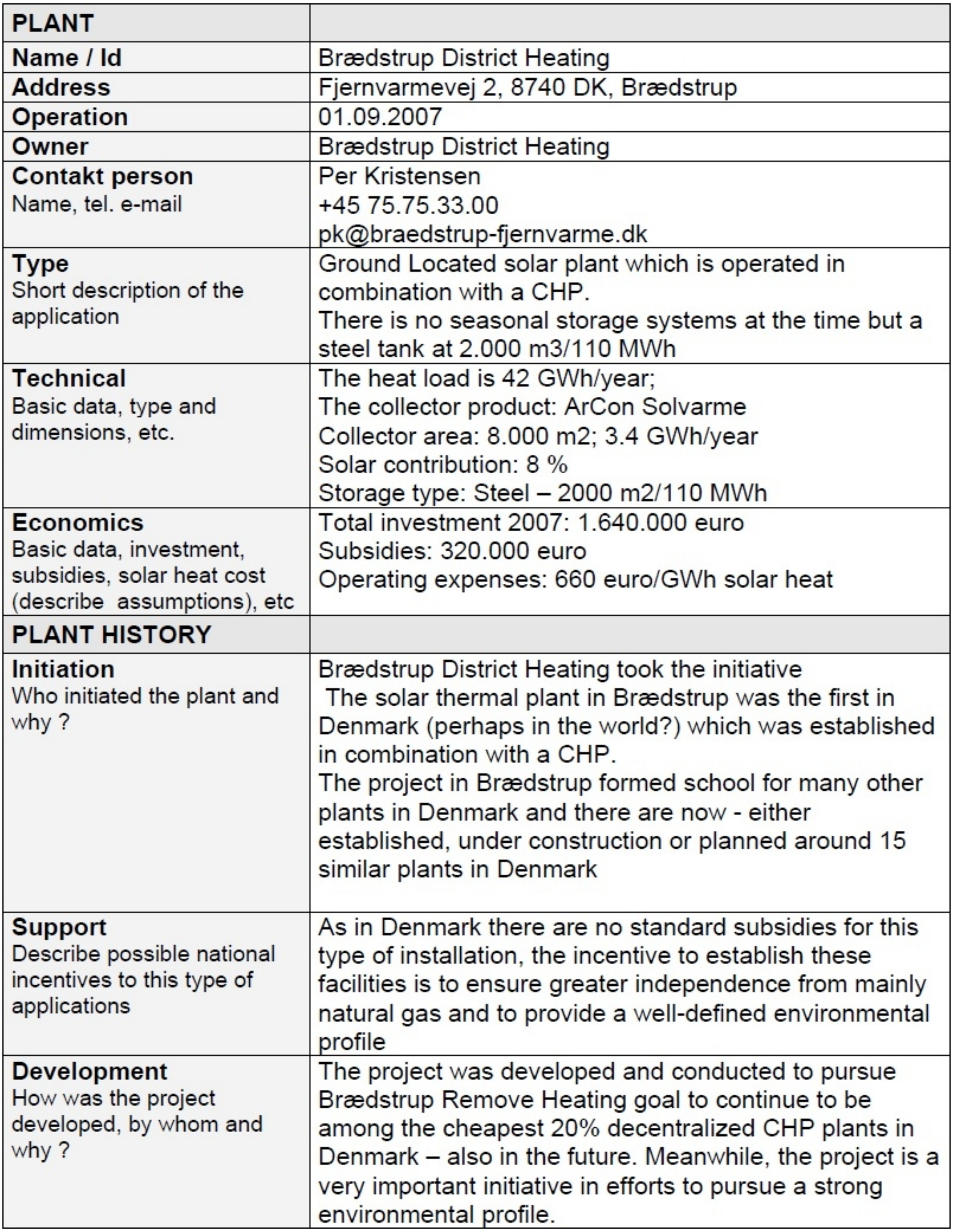
Appendix A: Comparison of global irradiation per country



Comparison of global irradiation in urban areas per country

This graph represents the variation in yearly global irradiation incident on optimally-inclined photovoltaic modules placed in urban areas of the EU-27 and 6 candidate countries. The red line connects the 33 country averages, the dashed lines show the range between the minimum and the maximum per country. 90% of the urban areas of each country will have values that fall in the range of the blue boxes.

Appendix B: Description of Brædstrup district heating plant



PLANT	
Name / Id	Brædstrup District Heating
Address	Fjernvarmevej 2, 8740 DK, Brædstrup
Operation	01.09.2007
Owner	Brædstrup District Heating
Contakt person Name, tel. e-mail	Per Kristensen +45 75.75.33.00 pk@braedstrup-fjernvarme.dk
Type Short description of the application	Ground Located solar plant which is operated in combination with a CHP. There is no seasonal storage systems at the time but a steel tank at 2.000 m3/110 MWh
Technical Basic data, type and dimensions, etc.	The heat load is 42 GWh/year; The collector product: ArCon Solvarme Collector area: 8.000 m2; 3.4 GWh/year Solar contribution: 8 % Storage type: Steel – 2000 m2/110 MWh
Economics Basic data, investment, subsidies, solar heat cost (describe assumptions), etc	Total investment 2007: 1.640.000 euro Subsidies: 320.000 euro Operating expenses: 660 euro/GWh solar heat
PLANT HISTORY	
Initiation Who initiated the plant and why ?	Brædstrup District Heating took the initiative The solar thermal plant in Brædstrup was the first in Denmark (perhaps in the world?) which was established in combination with a CHP. The project in Brædstrup formed school for many other plants in Denmark and there are now - either established, under construction or planned around 15 similar plants in Denmark
Support Describe possible national incentives to this type of applications	As in Denmark there are no standard subsidies for this type of installation, the incentive to establish these facilities is to ensure greater independence from mainly natural gas and to provide a well-defined environmental profile
Development How was the project developed, by whom and why ?	The project was developed and conducted to pursue Brædstrup Remove Heating goal to continue to be among the cheapest 20% decentralized CHP plants in Denmark – also in the future. Meanwhile, the project is a very important initiative in efforts to pursue a strong environmental profile.

Appendix C: Example of solar district heating and water tank in Munich

Solar district heating with concrete water tank in Munich

Start of operation: 2007

24.800 m² heated area (2.300 MWh/a)

2.900 m² solar collectors

5.700 m³ tank

Solar fraction: 47 %*

*simulation results ZAE

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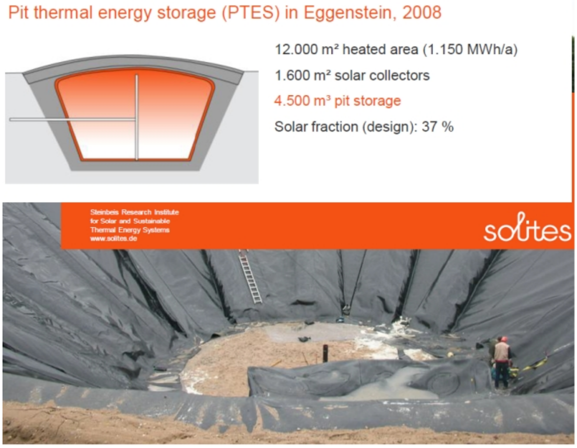

Pit thermal energy storage (PTES) in Eggenstein, 2008

12.000 m² heated area (1.150 MWh/a)

1.600 m² solar collectors

4.500 m³ pit storage

Solar fraction (design): 37 %

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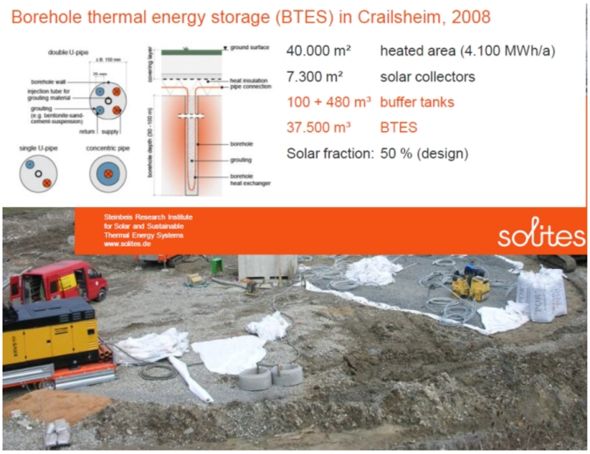

Borehole thermal energy storage (BTES) in Crailsheim, 2008

40.000 m² heated area (4.100 MWh/a)

7.300 m² solar collectors

100 + 480 m³ buffer tanks

37.500 m³ BTES

Solar fraction: 50 % (design)

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Title	**The role and opportunities for solar energy in Finland and Europe**
Author(s)	Timo Hakkarainen, Eemeli Tsupari, Elina Hakkarainen & Jussi Ikäheimo
Abstract	Solar energy provides multiple opportunities for renewable energy production. Technical potential to utilise solar energy in Europe and even in Finland is several times more than energy consumption in these regions. Economic potential is significantly smaller. However, the cost of solar energy is decreasing rapidly. In addition, when considering national economy or balance of trade, potential often increases in comparison to market potential without subsidies. In addition, people's willingness for self-sufficiency, new regulation regarding energy consumption of buildings and different dimensions of sustainability are important drivers for solar energy. In Europe, various subsidies for solar energy exist. Consequently, the amount of solar heating and photovoltaic electricity generation has increased. In the Nordic region, solar heating is often more economical than PV but the potential is limited by heat or hot water consumption, which is very case specific. If connection to district heating exists, potential is increased. On the other hand, Finnish CHP system is efficient and variable cost of district heat is therefore low in most regions. Demand for electricity is less regionally limited. In this report, PV and heat collector markets and scenarios are presented. In addition, different solar heating systems and applications are described, including costs of example systems with sensitivity analysis.
ISBN, ISSN	ISBN 978-951-38-8235-8 (Soft back ed.) ISBN 978-951-38-8236-5 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-1211 ISSN 2242-1211 (Print) ISSN 2242-122X (Online)
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Keywords	Solar energy, solar collector, photovoltaic, PV, flat plate, evacuated tube, water heating, solar district heating
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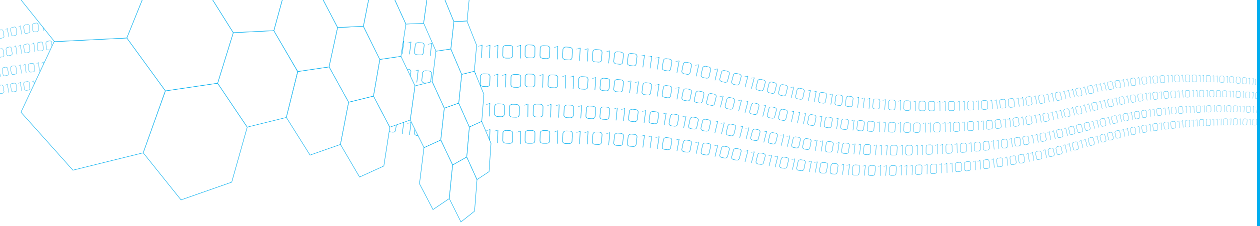

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