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Economic and energy analysis of three solar assisted heat pump systems in near zero energy buildings

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ABSTRACT

The European Union's directive of the energy performance of buildings makes energy systems with local energy generation interesting.

To support local energy generation the government has appointed a commission to investigate the possibility to implement net metering for grid connected PV-systems.

In this paper three different systems are simulated and analyzed with regards to economics and energy: a PV-system and a heat pump (alternative 1), a heat pump and a solar thermal system (alternative 2) and a heat pump, a PV-system and a solar thermal system (alternative 3).

System alternative 1 is profitable with daily net metering and monthly net metering and unprofitable with instantaneous net metering.

The solar electrical fraction of the system is 21.5%, 43.5% and 50%, respectively.

System alternative 2 is unprofitable and has a solar electricity fraction of 5.7%.

System alternative 3 is unprofitable and has a solar electricity fraction of just below 50.

The conclusion is that a PV system in combination with a heat pump is a superior alternative to a solar thermal system in combination with a heat pump.

1. Introduction

In the Europe union (EU-27) the household sector accounts for almost 27% of the total European final energy consumption [1]. This is an important reason for the European commission to adopt the directive on the energy performance of buildings [2] as one of several measures to reach its 20–20–20 goal.

The European Union's directive on the energy performance of buildings will lead to more local energy generation in the future and more energy efficient buildings. Solar energy is regarded as one of the most promising ways for local energy generation. Partly because of this the Swedish government has appointed a commission which will produce proposals on how to facilitate the use of net metering for locally produced electricity in buildings.

In Sweden today one common way of reducing the amount of purchased energy in new buildings is to install a ground source heat pump in combination with a well-insulated building envelope and mechanical ventilation with heat recovery. In Sweden approximately 340,000 ground source heat pumps has been installed the last decade according to the Swedish Heat Pump Association [3].

Because of this it will be more common with energy systems that combine solar energy with ground source heat pumps and heat recovery ventilation.

Earlier studies with solar assisted heat pumps have mainly focused on complex systems with PV/T hybrids or solar thermal collectors acting as the source for the heat pump evaporator [4–6]. Other studies have focused on standard heat pumps and solar thermal systems [7].

In this paper three less complex solar assisted heat pump systems will be simulated in the program Trnsys [8] and analyzed with regards to economics and energy consumption. The different systems are PV-system, solar thermal system and a combination of a PV-system and a solar thermal collector system.

The aim of the work presented in this article is to find the system which is most cost effective and has the highest solar energy fraction.

2. Methodology

The energy simulations are performed in the transient simulation program Trnsys. The simulation interval is set to 3 min and two years, 17,520 h, are simulated.

The Trnsys models are built up with so called decks in Simulation studio which is the graphical user interface of Trnsys.

Each Trnsys model consists of identical decks with exception of the different solar energy systems analyzed. A short description

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Table 1
Main Trnsys type in the simulation deck.

Trnsys type	Description	Comment
Type 56	Multi zone building	
Type 927	Ground source heat pump	Based on external data file for Premiumline EQ C6
Type 534	Heat storage tank	Heat pump internal tank
Type 557a	Borehole	
Type 194	PV-module	5 parameter model
Type 539	Flat plate solar collector	
Type 760	Air–air heat recovery	

of the most important types used in this work is summarized in Table 1.

All results from the energy simulations are exported and further processed and used in the economic calculations.

The analysis is based on the annuity method because of its ability to compare systems with different economic lifespans.

The revenues from the different system alternatives are converted to net present values by multiplying the revenues with the discount factor (DF) defined by:

$$DF = \frac{1}{(1+i)^t} \quad (1)$$

The accumulated net present value (NPV) revenues are then converted to an annuity defined by:

$$(NPV - C_i) \times \frac{i \times (1+i)^z}{(1+i)^z - 1} \quad (2)$$

where i is the interest rate, t is the economical lifespan and C_i is the investment cost.

In the economic calculations the investment cost only includes the solar energy systems and not the ventilation heat recovery and ground source heat pump systems.

A sensitivity analysis is done in order to evaluate the impact of different electricity price changes on systems profitability.

3. The simulated building and technical installations

3.1. The building

The simulated building consists of one zone and one story with a living space of 138 m^2 which is maintained at 21 °C. The building has floor heating embedded in the building foundation which consists of a concrete slab on grade with a total insulation thickness of 300 mm.

In the building walls the insulation is 350 mm thick and the roof has an insulation thickness of 370 mm.

The U-values of the different building elements can be seen in Table 2.

Four inhabitants, two children and two adults, live in the building.

The energy system of the building consists of three main parts: household electricity, the production of domestic hot water and space heating and heat recovery ventilation. The part of the three systems investigated that are identical to each other will be described in this section. Another important factor is how different measuring schemes influence the size and the economics of the PV-system. The different schemes will be explained in detail in Section 4.

The total energy demand for the building with household electricity included is 19,880 kWh/year. The same building with a ventilation heat recovery unit installed has a demand of 16,920 kWh/year purchased energy and with ventilation heat recovery and ground source heat pump the purchased energy demand is 10,157 kWh/year. In Fig. 1 the energy demands per month is shown and in Table 5 the building total energy demand for the different combinations of technical installations are summarized.

Table 2
U-values for the different building components used in the simulation.

Building component	U-value (W/(m^2, K))
Ceiling	0.106
Outer walls	0.102
Ground floor	0.103
Windows	0.81

3.2. Heat pump

The heat pump used in the simulations is based on a commercial available model made in Sweden by Bosch Termotechnik AB. The model used is an IVT Premiumline EQ C6 which has a heating capacity of 5.8 kW.

It has a 225 L internal double jacketed storage tank with an inner domestic hot water tank of 185 L.

The domestic hot water production is prioritized which means that no heat is supplied to the building when the temperature in the tank is below 47 °C which is the set point temperature minus a 3 °C hysteresis. The temperature probe which is measuring the domestic hot water is located approximately 20 mm from the bottom of the tank and on the outside of the tank. A zone valve switches the heated media to either the outer compartment of the domestic hot water tank or to the floor heating system.

Once every week the domestic hot water temperature is raised to 65 °C to avoid growth of the Legionella bacteria. This is partly done with the heat pumps internal electric heater. The heat pump heater is limited to 3 kW which is one-third of the heater potential and will only be active when the domestic hot water is raised to 65 °C.

The domestic hot water consumption in the building is 66 L per day and person and the annual energy amount needed for production of domestic hot water is 4675 kWh.

The tapping cycle is based on EN 16147:2011 [9] tapping cycle M which is a cycle with 23 draw offs a day. Previous studies have shown that the number of tapings and the time of occurrence are of importance for the storages performance as shown by Fiala [10]. An evaluation of different tapping cycles will be done in the future to improve the domestic hot water part of the model.

The required temperature lift of the main water varies with the season, in summer the minimum lift is 42 °C and in winter the maximum lift needed is 49 °C. The variations can be seen in Fig. 2.

The heat pump is connected to a 150 m deep borehole on the heat pump cold side and to the building floor heating system on the hot side. It is dimensioned for monovalent operation which means that it is able to cover 100% of the building heat load. The borehole is dimensioned so the exiting fluid temperature never is below 0 °C.

The heating is regulated by a linear temperature curve based on the heating system forward flow temperature and outdoor temperature. Maximum forward flow temperature to the floor heating system is 33.5 °C.

The temperature differences are within the manufacturers recommended 2–5 °C for the cold side fluid and 7–10 °C for the hot side fluid.

Two circulation pumps are integrated in the heat pump. On the hot side the circulation pump is frequency controlled and the speed is regulated to keep the temperature difference over the heating

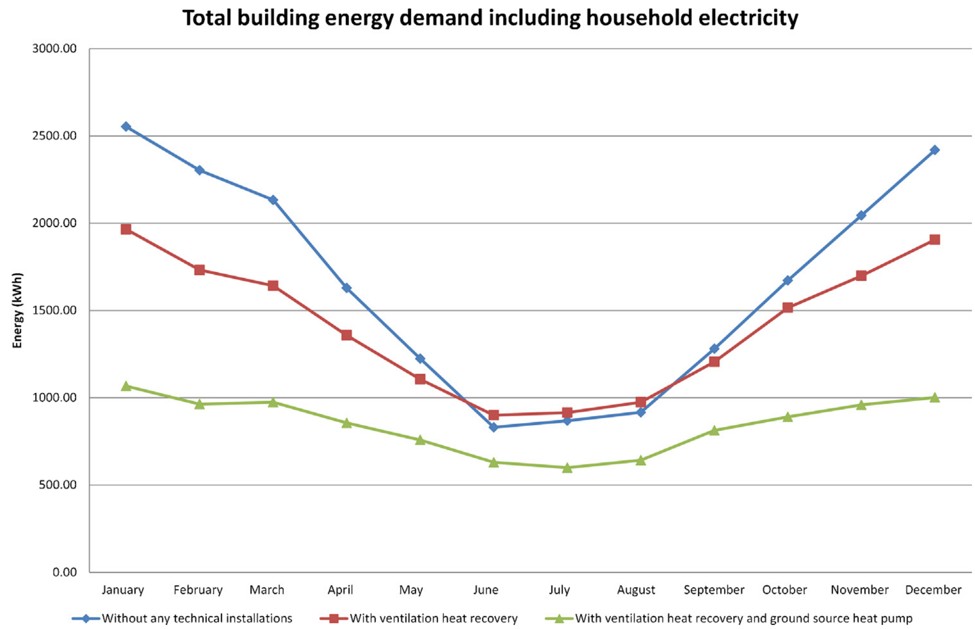

Fig. 1. Total building energy demands without technical installations, with ventilation heat recovery and with ventilation heat recovery in combination with a ground source heat pump.

system at a constant 7 °C. On the cold side the circulation pump is set to a fixed speed.

The reason for having a frequency controlled pump on the hot side is because it is in constant operation during the heating season. The circulation pump on the cold side is only active when the compressor is active.

When the ambient temperature rises above 12 °C the heat pump is switched to summer mode and the circulation pump is only in operation when domestic hot water is produced. This means that no heating is provided to the building until the ambient temperature is below 12 °C.

3.3. Heat recovery ventilation

The system contains two fans, with an installed power of 170 W each, and a rotating heat exchanger with an efficiency of 80%. No electrical anti freezing system is installed in the ventilation system. The supply air is maintained at 17 °C when possible. The ventilation flow rate is set to 0.35 l/s, m^2 living area which is the minimum requirements according to the Swedish building regulations [11]. During summer no heat exchange will occur even though the ambient temperature drops below 17 °C.

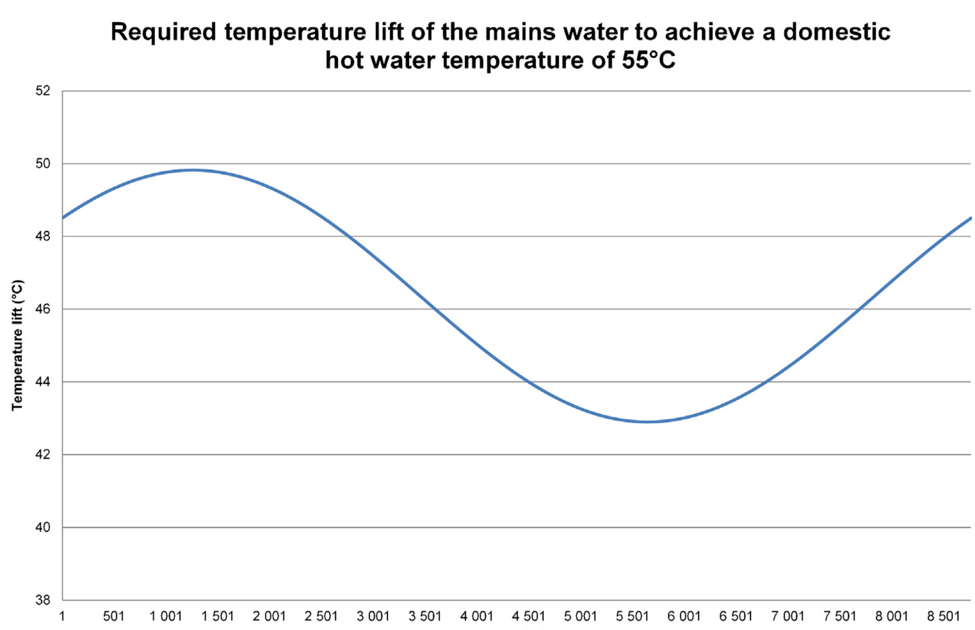

Fig. 2. Annual variations of the required temperature lift of the main water to achieve a domestic hot water temperature of 55 °C.

Table 3
Data for from CNBM Solar's polycrystalline 230 W module at standard test conditions.

Maximum power per module	230 W
Tilt angle of modules	70°
Open circuit voltage	36.9 V
Voltage at maximum power point	30.2 V
Short-circuit current	8.31 A
Current at maximum power point	7.62 A

Table 4
Data taken from Solar Keymark certificate for the aquasol flat plare collector.

Collector efficiency related to aperture area	0.78
a1	3.14 W/(m^2, K)
a2	0.019 W/(m^2, K^2)
Effective thermal capacity	7470 kJ/(m^2, K)

Table 5
Building total energy demand with different combinations of technical installations.

Building	Total building energy demand incl. household electricity (kWh)
Without any technical installations	19,880
With heat recovery ventilation	16,920
With heat recovery ventilation and ground source heat pump	10,157

3.4. PV-system

The system is based on 21 pieces 230 W polycrystalline modules manufactured by CNBM solar and has an installed peak power of 5190 kW.

The modules are tilted 70° from the ground and are facing south. No objects that can shade the modules are present around the building.

The system is grid connected via an inverter to one of the buildings incoming electrical phases. No battery storage is used. Table 3 summarizes the most important data of the PV-system.

3.5. Solar thermal system

The solar thermal system is based on two flat plate solar collectors manufactured by the Swedish company Aquasol. The aperture area is 2.1 m^2 per flat plate collector. The total area of the solar thermal system is dimensioned for a storage volume of 225 L.

The system is connected to the tank via a coiled tube heat exchanger placed in the bottom of the tank.

It is regulated so that the circulation pump starts when the temperature difference between the water in the solar collector and in the bottom of the tank is 3 °C and it stops when the difference is 1 °C. If the temperature in the tank reaches 95 °C the circulation pump stops.

In Table 4 the most important data taken from the Solar Keymark certificate are summarized.

3.6. Household electricity

The annual electricity consumption is based on measured values taken from a one family building with four inhabitants where two are adults and two are children. The annual consumption is 5155 kWh with a small monthly variation [12], see Fig. 3.

4. Metering schemes

The consumer price of electricity consists of the cost for energy, energy tax, sales tax and grid cost. The energy cost is around 40% of the total cost. When the PV-system delivers less energy than the total load it will lower the need for purchased electricity. This means that all these four components are saved. When the PV system delivers more energy than is used in the building the surplus is exported to the grid. The price of exported electricity is determined by market price for electric energy. This means that it is much more favorable to save energy than to export energy. However, if a kWh is defined as saved or exported depends on the metering scheme.

Three different schemes will be investigated in this article: instantaneous metering, daily net metering and monthly net metering. The length of the net metering period affects the amount of PV-electricity regards as saved or exported. The saved electricity fraction is increasing with the length of the metering period, so a larger PV-system can be installed without the need to export and sell electricity to the grid. Technically daily and monthly net metering means that the grid is used as storage.

With instantaneous metering the generated PV electricity has to be used at once in the building. If the PV electricity generation is greater than the building electricity demand the surplus will be exported to the electricity grid and sold.

Daily net metering is a more attractive option for the building owner where the generated PV electricity for a whole day is settled against the building electricity demand for the same day, i.e. the consumer only pays for the net. With this scheme the PV-system surplus is exported to the electricity grid but not sold. The surplus accumulated at daytime is settled against the electricity demand later the same day when no or little PV electricity is generated. If the PV-electricity generation is larger than the building electricity demand over the whole day, i.e. there is a positive daily net, the net surplus is sold to an electricity company.

The same principle as for daily net metering also applies for monthly net metering but the PV electricity generation and the electricity demand are settled monthly.

Fig. 4 shows the saved electricity in the building energy system with heat pump and heat recovery according to Fig. 1 in relations to installed PV-system size and different metering schemes. As can be seen in Fig. 4 the slope of the curve for saved electricity in the building with instantaneous net metering is starting to decline at 400 W and this is because a larger PV-system gives a surplus that have to be exported to the grid. For daily and monthly net metering a larger peak power can be installed before a surplus is exported to the grid and this also gives a larger fraction of saved electricity in the building.

The performance of an energy system for a single family building consisting of a heat pump supported by PV-modules and solar collectors are analyzed for the different metering periods.

5. Differences between solar thermal systems and PV-systems in combination with ground source heat pumps

A PV-system in combination with a heat pump has a better match between heat demand and output from the PV-system than a solar thermal system. The heat pump has a higher monthly coefficient of performance during the winter months because the heat supplied to the building floor heating system has a lower temperature and is a larger portion of the total heat supplied to the building than in summer. The heat supplied in summer is almost only for domestic hot water production. Fig. 5 shows the monthly coefficient of performance.

This means that the PV-electricity supplied to the heat pump during winter is utilized more efficiently than during summer, i.e.

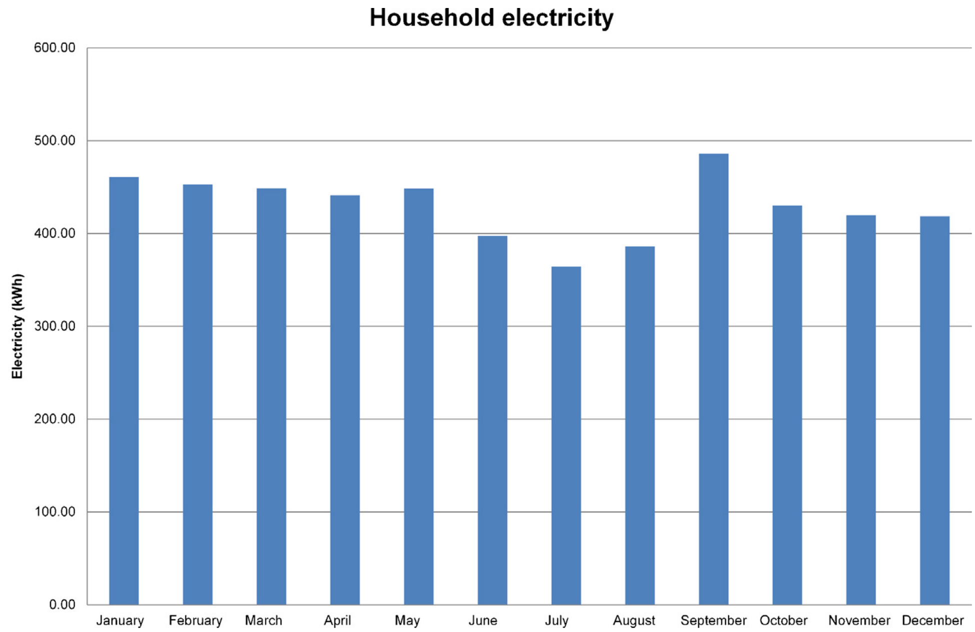

Fig. 3. Monthly variation of the household electricity consumption.

the same amount of electricity to the heat pump gives a larger heat output in winter than in summer, see Fig. 6.

Another advantage for the PV-module is that it is not negatively affected by low ambient temperatures and has the same efficiency independent of the radiation intensity. A flat plate solar collector output depends on the absorbed radiation to be larger than the collector heat losses. The radiation level where the collector heat losses are equal to the absorbed radiation is called the critical radiation level as shown in [13].

6. Energy analysis of solar assisted heat pump systems

The three systems will be described in detail in this section. All general parts of the building energy system in Section 3 are identical for all three systems. The main parts of the different systems can be seen in Fig. 7.

6.1. Alternative 1: ground source heat pump system in combination with 5.19 kWp PV-system

Three different metering schemes will be investigated in this alternative: instantaneous metering, daily net metering and monthly net metering.

The PV-system is dimensioned so that surplus of PV-electricity is avoided. Fig. 8 demonstrates how this principle is used for designing the system with monthly net metering. The chosen PV-power to 5.19 kWp will give balance between load and production during June. During all other months electric energy has to be supplied.

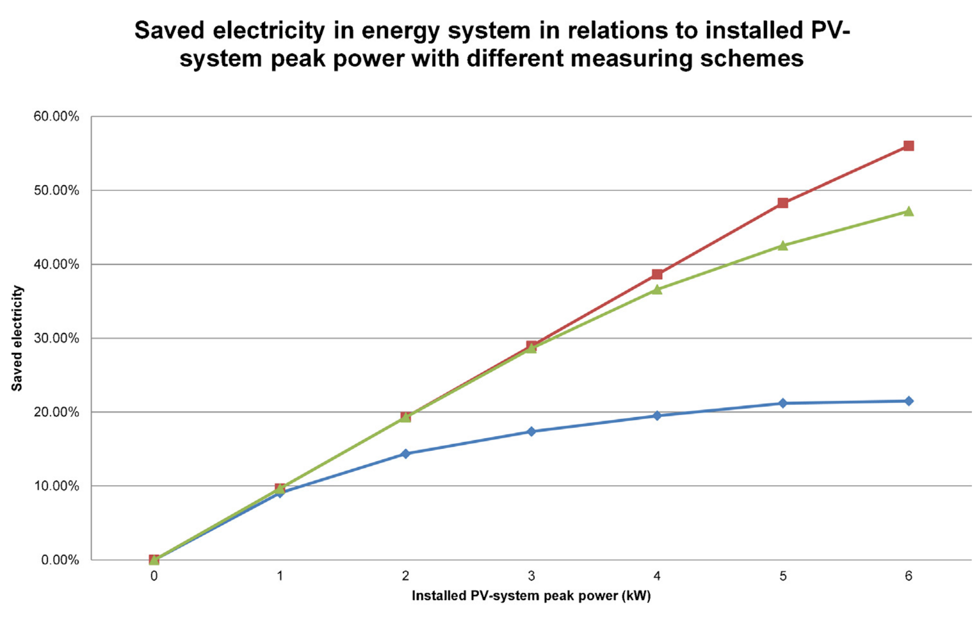

Fig. 4. Saved electricity in the building energy system in relation to installed PV peak power with different periods for net metering. The PV-modules are tilted 70°.

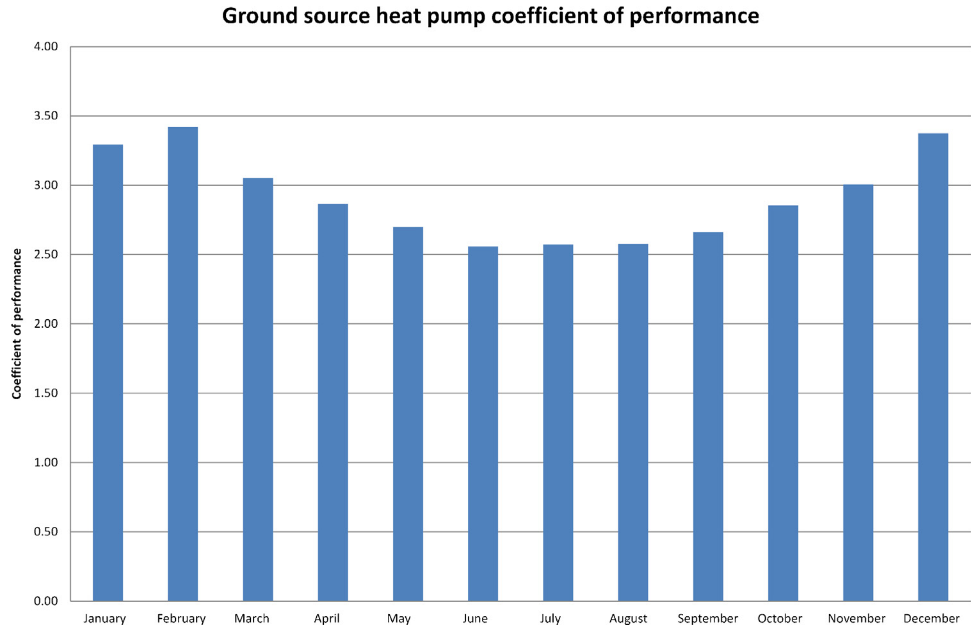

Fig. 5. Ground source heat pump monthly coefficient of performance.

Monthly net metering is expected to be introduced in Sweden during 2013. Therefore this alternative is used as the reference in the overall analysis. It will generate and save 5093 kWh of electricity per year without overproduction which means that the building energy demand is reduced to 5064 kWh or 36.7 kWh/year and m^2.

The solar electricity fraction in this alternative is 50%.

6.1.1. Alternative 1: GSHP in combination with 5.19 kWp PV-system with instantaneous metering

In this metering alternative it is possible to use 2182 kWh of PV generated electricity in the building and 2908 kWh is exported and sold to an electricity company.

When the PV generation used in the building is deducted the building electricity demand is reduced to 7975 or 58 kWh/year and m^2 living area. Fig. 9 shows the monthly building electricity with and without the PV generation deducted.

The fraction of solar electricity in the building energy system is 21.5%.

6.1.2. Alternative 1: GSHP in combination with 5.19 kWp PV-system with daily net metering

In this metering alternative it is possible to use 4418 kWh in the building and 672 kWh is exported and sold to an electricity company.

When the PV generation, possible to use in the building to limit the electricity demand, is deducted the building electricity demand is reduced to 5739 or 41.6 kWh/year and m^2 living area. Fig. 9 shows the monthly building electricity with and without the PV generation deducted.

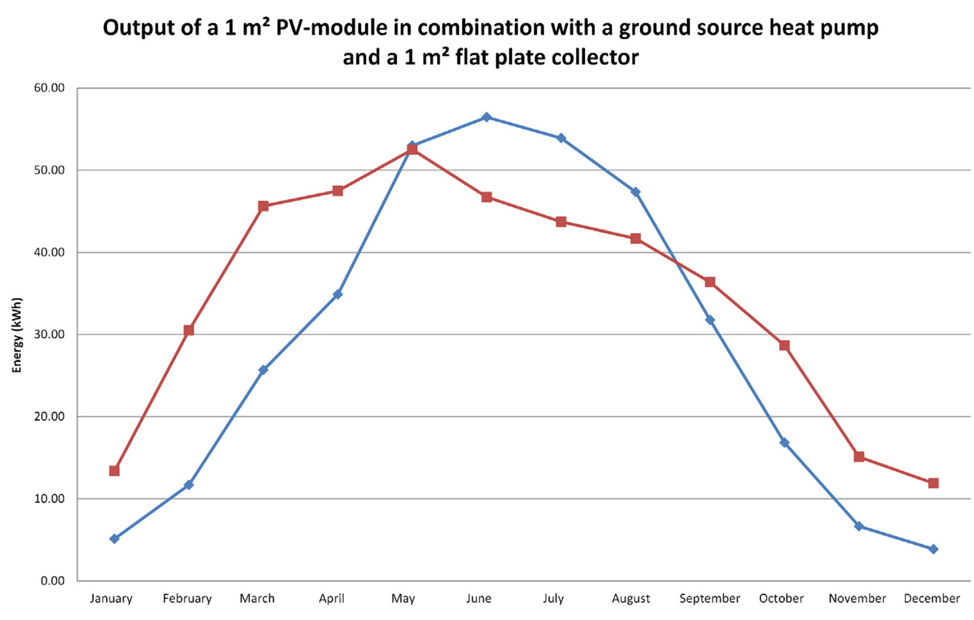

Fig. 6. Monthly output of a 1 m^2 PV-module in combination with a heat pump and a 1 m^2 flat plate solar collector.

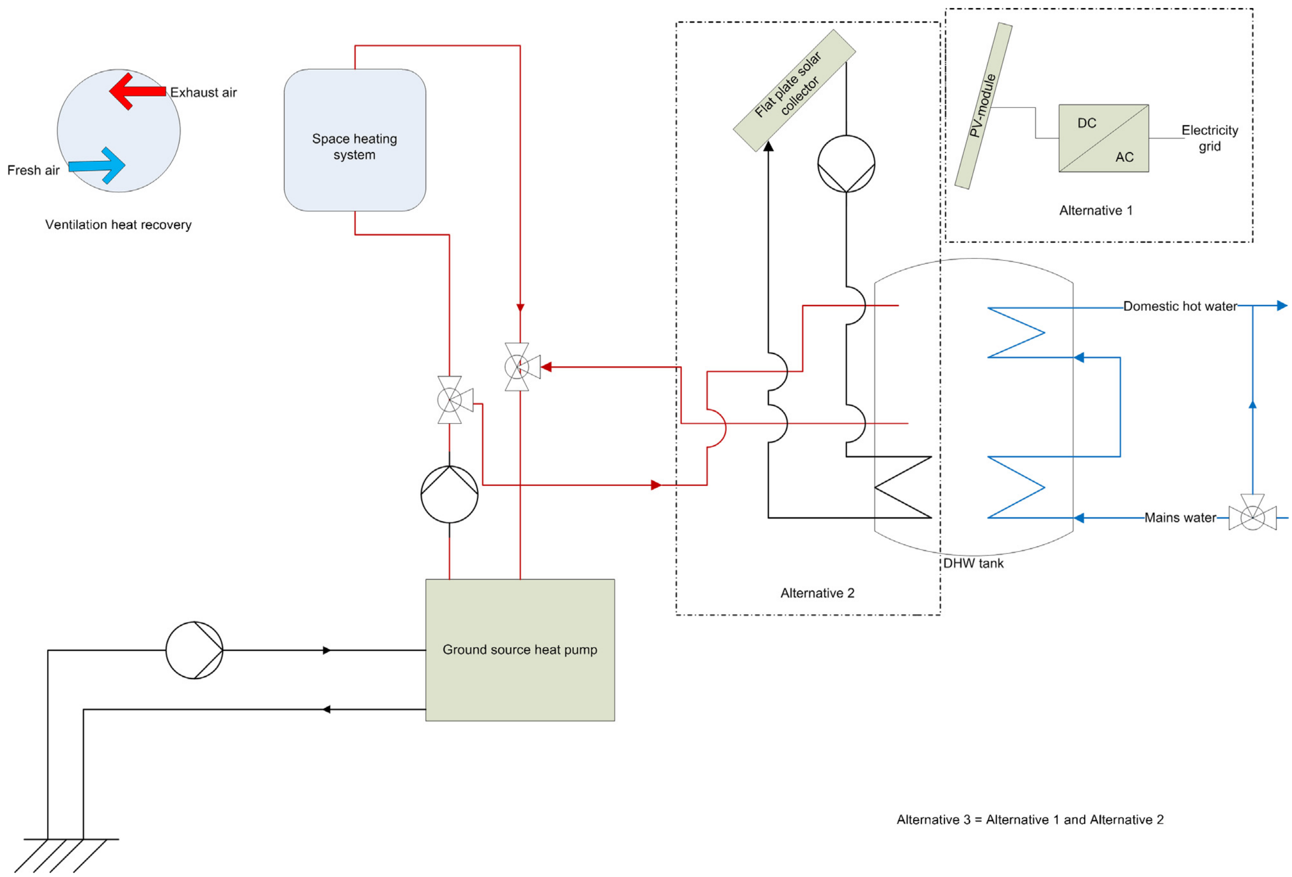

Fig. 7. Main components in alternative 1 with ground source heat pump and PV-system, alternative 2 with ground source heat pump and solar thermal system and alternative 3 which is a combination of alternatives 1 and 2.

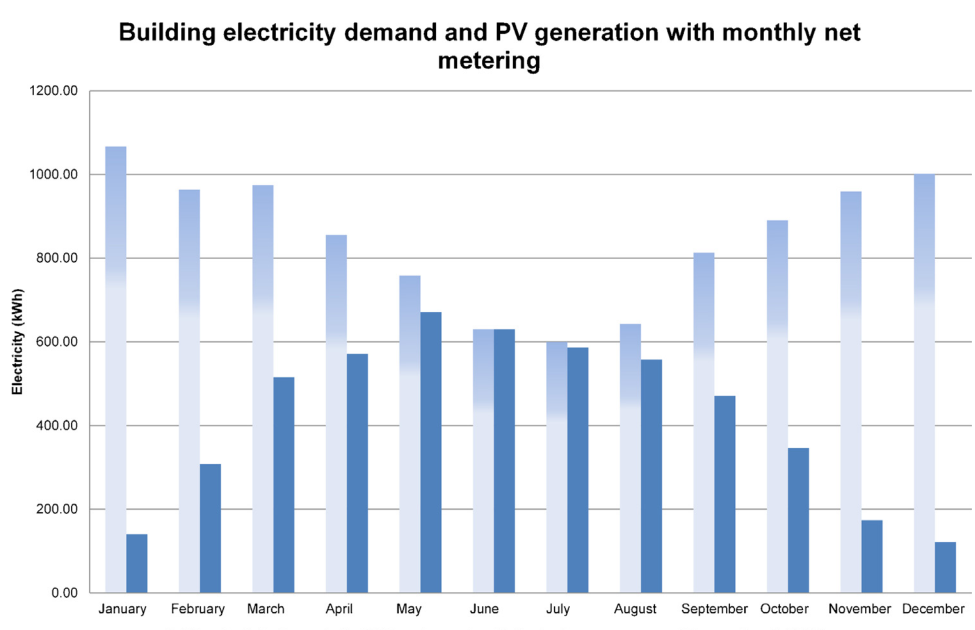

Fig. 8. The building energy demand and PV-generation with monthly net metering and 5.19 kWp PV-system and the PV-modules in 70° tilt.

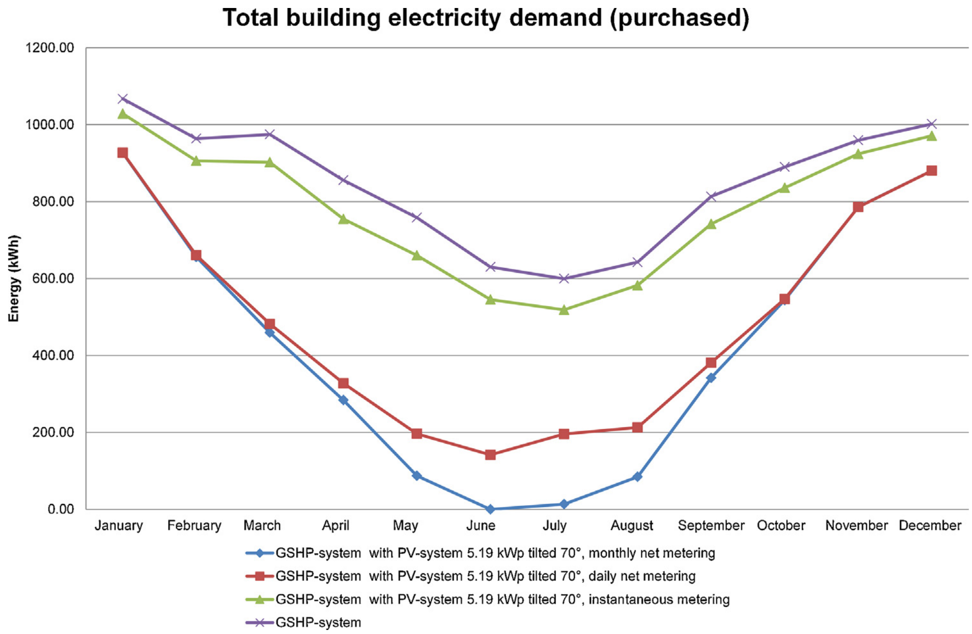

Fig. 9. Total building electricity demand with and without PV-system with instantaneous metering, daily net metering and monthly net metering.

The fraction of solar electricity in the building energy system is 43.5%.

6.1.3. *Alternative 1: GSHP in combination with 5.19 kWp PV-system with monthly net metering*

In this alternative all of the 5093 kWh PV generated electricity is used to limit the building electricity demand. When the PV generated electricity is deducted the building electricity demand is reduced to 5064 or 36.7 kWh/year and m^2 living area. Fig. 9 shows the monthly building electricity with and without the PV generation deducted.

The fraction of solar electricity in the building energy system is 50%.

6.2. *Alternative 2: ground source heat pump system in combination with flat plate solar collector system*

Previous studies have found that turning the heat pump off and using the solar collectors during the summer period for domestic hot water production is the best way of combining solar collectors and commercial available ground source heat pumps as can be seen in [7].

In [7], Kjellsson concluded that using the solar heat for charging a single borehole is very ineffective. If the borehole is deep enough the natural recharge is enough to cover the energy outtake during the heating season.

The solar thermal system generates 1428 kWh/year for the production of domestic hot water. If the ground source heat pump would have to produce the same amount of domestic hot water with the same prerequisites the electricity needed would be the energy generated by the solar thermal system divided with the heat pump coefficient of performance.

The generation of 1428 kWh of heat from the solar thermal system resulted in saving of 537 kWh due to the decreased operation of the heat pump.

The annual COP of the heat pump increased with 0.11 units to 3.09 and the annual operating time is decreased by 405–1452 h.

As can be seen in Fig. 10 the saved electricity due to the flat plate collectors is small. This is because it is difficult to combine heat pumps with systems that compete with the heat pumps operation, i.e. domestic hot water production or space heating.

The annual building electricity demand including household electricity is decreased from 10,157 or 73.6 kWh/m^2 living area to 9410 or 68 kWh/m^2 living area which is a decrease of 748 kWh or 5.4 kWh/m^2 living area.

The decrease in the annual building electricity demand is higher than the contribution from the flat plate solar collector system because of the higher heat pump coefficient of performance.

The fraction of solar energy in the building energy system is 5.7%.

6.3. *Alternative 3, ground source heat pump system in combination with flat plate solar collector system and PV-system with monthly net metering*

The third system is a combination of the first two with one important difference. The PV-system will be smaller because the flat plate solar collector system decreases the building total electricity demand during summer months and it is this demand the PV-system is dimensioned against. Therefore the system needs to be smaller to avoid overproduction.

The size of the PV-system in this alternative is 4.60 kWp which is a reduction of 11.3% in comparison with alternative 1.

The PV-system will generate 4058 kWh electricity per year and the flat plate solar collector system will generate 1428 kWh of heat which will save 537 kWh of electricity.

The building electricity demand including household electricity for this alternative will decrease from 10,157 to 5351 kWh/year or 38.8 kWh/m^2, living area.

Fig. 11 shows the building electricity demand in comparison to a system with only ground source heat pump and a system as in alternative 1.

The solar electricity fraction of the building energy system is 49% which is slightly lower than the alternative with only a PV-system.

7. Economic analysis of solar assisted heat pump systems

The discount rate in the calculations is 6% and the electricity price is assumed to increase by 4.7% each year with a starting price

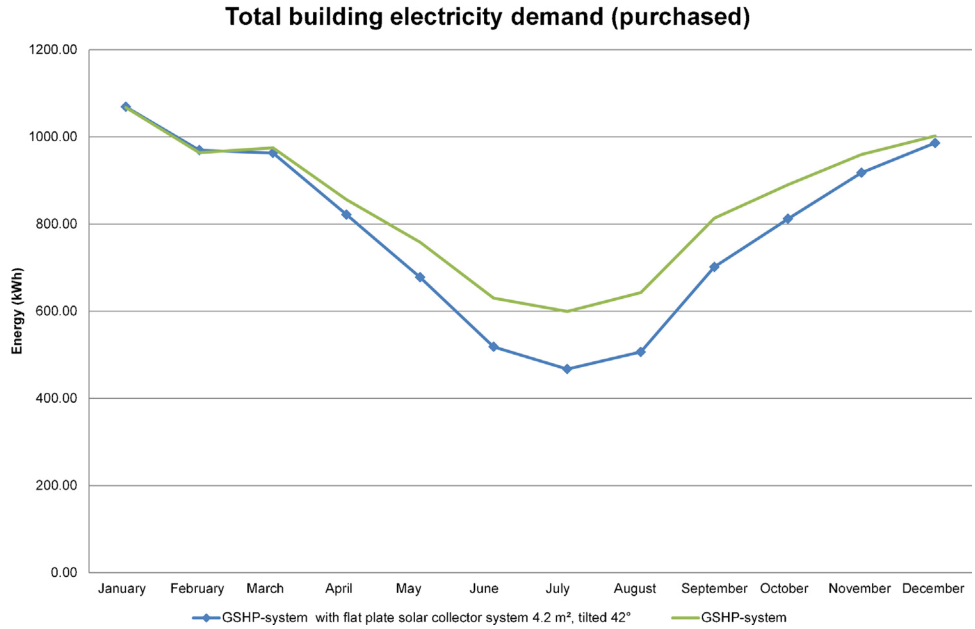

Fig. 10. Total building electricity demand with and without flat plate collector system.

of 0.18 €/kWh. This assumption is based on historical changes of the electricity price in Sweden during the past 10 years [14].

PV-module and solar collector degradation has not been taken into account in the calculations.

7.1. Alternative 1: ground source heat pump system in combination with PV-system

The investment cost for the PV-system is 14,443 or 2783 €/kWp.

The economic lifespan of the PV-system is assumed to be 20 years with regards to inverter lifespan.

The annuity of this alternative with continuous metering is −427 €/year and the system is unprofitable.

The annuity with daily net metering is 22 €/year and the system is profitable.

The annuity with monthly net metering is 106 €/year and the system is profitable.

7.2. Alternative 2: ground source heat pump system in combination with solar thermal system

The flat plate solar collector investment cost is 4121 or 981 €/m^2 collector aperture area.

The economic lifespan of the flat plate collector system is assumed to be 25 years.

The annuity of this alternative is −166 €/year which means that the system is unprofitable.

Solar collector systems used for producing domestic hot water in combination with heat pumps for space heating and domestic

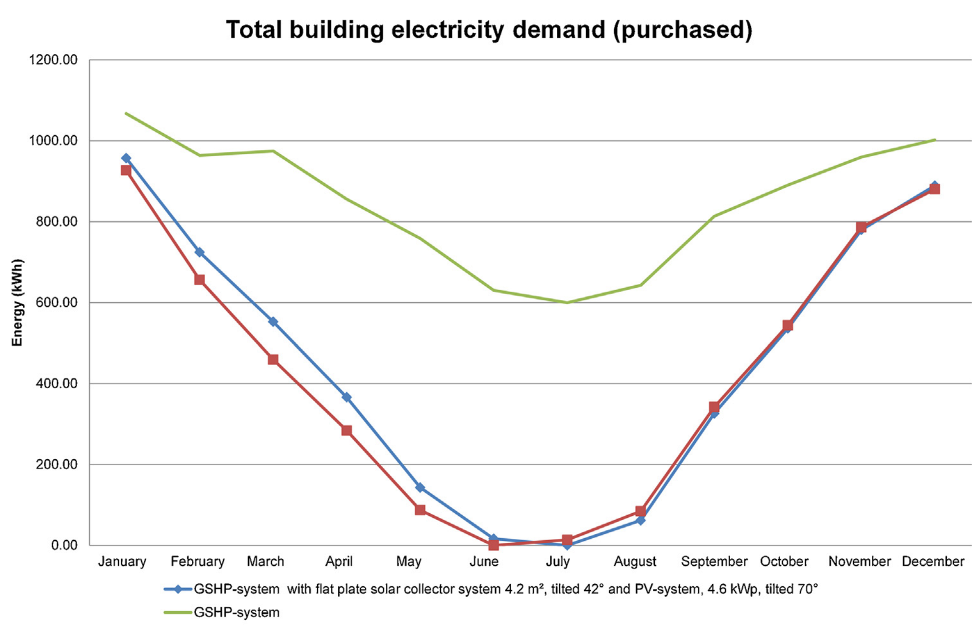

Fig. 11. Total building electricity demand with and without flat plate collector system in combination with PV-system.

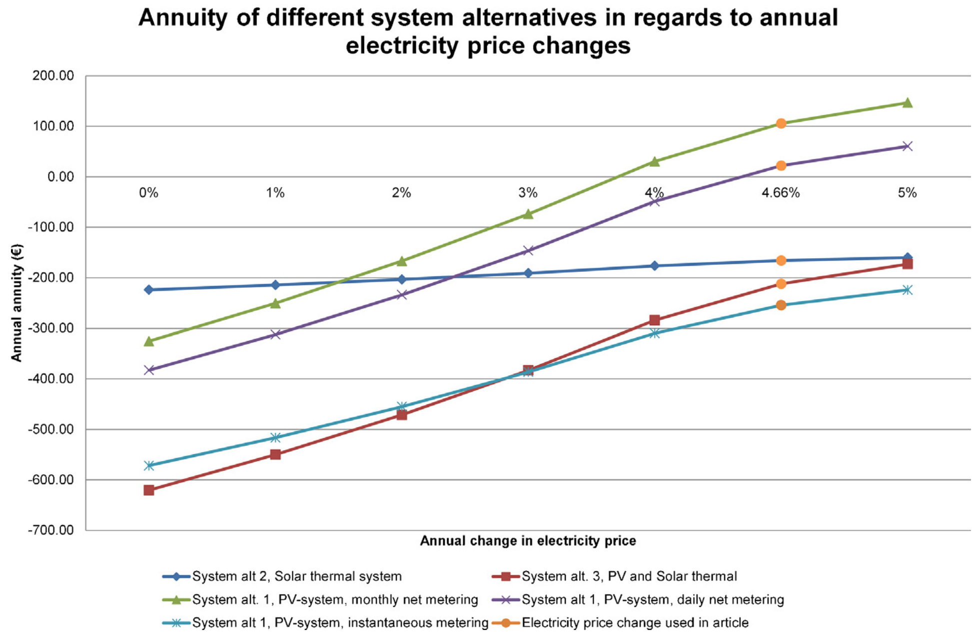

Fig. 12. Sensitivity analysis of annual electricity price change.

hot water production will be profitable in Sweden if the system price is reduced by approximately 50%.

7.3. *Alternative 3: ground source heat pump system in combination with flat plate solar collector system and PV-system with monthly net metering*

The economic lifespan of the system as a whole is assumed to be 20 years.

The investment cost for the flat plate solar collector system and the PV-system is 16,908 €.

The annuity of this alternative is −212 €/year which means that the system is unprofitable with monthly net metering.

7.4. *Sensitivity analysis of electricity price change*

One of the largest uncertainties in this paper is the assumption of the price for electricity. As stated earlier the assumption is based on historical changes of the electricity price in Sweden. The analysis shows that the increase in price must be almost 4% each year for system alternatives 1 with monthly net metering and 4.5% for system alternative 1 with daily net metering if the systems are to be profitable. All other alternatives need a price change much larger than 5%, see Fig. 12.

8. Results

The total building electricity demand with the different solar energy systems can be seen in Table 6.

System alternative 1 with instantaneous metering is unprofitable. The solar electricity fraction of this system is 21.5%.

System alternative 1 with daily net metering is profitable and yields a solar electricity fraction of 43.5%.

System alternative 1 with monthly net metering is an economic feasible way of reaching high solar electricity fractions in a building energy system. The solar electricity fraction is 50%.

System alternative 2, with ground source heat pump and solar collectors, is unprofitable and will reach a solar electricity fraction of 5.7%.

Table 6
Building electricity demand with different combinations of solar energy systems.

System alternative	Building electricity demand (kWh)	Building electricity demand per square meter living area (kWh/m^2)
1. GSHP with PV-system (instantaneous metering)	7975	58
1. GSHP with PV-system (daily net metering)	5739	41.6
1. GSHP with PV-system (monthly net metering)	5064	36.7
2. GSHP with flat plate solar collector system	9410	68
3. Alternative 1 + 2 (monthly net metering)	5351	38.8

Table 7
Annuity of the different system alternatives.

System alternative	Annuity (€/year)
1. GSHP with PV-system (instantaneous metering)	−427
1. GSHP with PV-system (daily net metering)	22
1. GSHP with PV-system (monthly net metering)	105
2. GSHP with flat plate solar collector system	−166
3. Alternative 1 + 2 (monthly net metering)	−212

System alternative 3 is unprofitable and will have a slightly lower solar electricity fraction, 49%, than alternative 1.

9. Discussion and conclusions

As can be seen in Table 7 only alternative 1 with daily and monthly net metering is profitable. Alternative 1 with instantaneous metering give a smaller decrease in the building electricity demands and export and sell larger amounts of the PV generated electricity than the profitable systems. This is the reason why alternative 1 with daily net metering is less profitable than the same alternative with monthly net metering and that the same alternative with instantaneous metering is unprofitable. This is explained in detail in Section 3.4.

All systems are sensitive to changes in the assumed electricity price but systems alternative 2 with a solar thermal system is the least sensitive. That is because the amount of saved electricity is low in that alternative and the reason for this is explained later in this section.

The conclusion is that the most effective way of using PV generated electricity is by reducing the amount of electricity needed to be purchased.

The reduction of purchased electricity by a PV-system and a heat pump system is a viable way of making the building more energy efficient. As can be seen in Sections 5 and 6 the reduction of purchased electricity can be large with relatively small investments. If monthly net metering is introduced in Sweden it is likely that the installation of a PV-system will be a popular way of making buildings more energy efficient.

The combination of heat pumps and solar thermal in a system, as in system alternative 2 and 3, where the heat pump produce domestic hot water is ineffective. The heat pump needs for example approximately 1 kWh of purchased electricity to produce 3 kWh of domestic hot water. When the solar collector system produces 3 kWh in a system like this the saving is the electricity the heat pump would have used to produce the same amount of domestic hot water, i.e. 1 kWh.

Because of this the savings from a solar collector system is 1/3 in a system with a heat pump in comparison to other heating and domestic hot water systems. This is not a problem only for solar collector systems but for almost all complementary systems.

On the other hand the combination of a PV-system with a heat pump that produces domestic hot water is a perfect match where the two systems do not compete for the same domestic hot water load. In fact the heat pump electricity need during the summer months in combination with the household electricity load make it possible to install larger PV-systems.

The conclusion is that a system with a ground source heat pump in conjunction with a PV-system is the most effective system with regards to energy and economics.

10. Further work

System alternative 1 with a PV- and a ground source heat pump will be studied further and the simulation model will be enhanced.

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