Energy Performance of Ground-source Heat Pump and Photovoltaic/thermal (PV/T) in Retrofitted and New Buildings: Two Case Studies Using Simulation and On-site Measurements

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Abstract

This paper aims to contribute by presenting calculated and measured electricity usage in two single-family case studies during the heating season of 2019-2020 located in Stockholm, Sweden. The electricity usage included consumption by heat pumps' compressor to cover space heating and domestic hot water, auxiliary energy for fans and pumps, and ventilation system. The first case study was built in 1936 with an oil burner, which was renovated to a ground-source heat pump (GSHP) in 2015, and the second case study was a new building built in 2013 with a GSHP. The application of photovoltaic/thermal (PVT) systems in combination with GSHP was theoretically investigated for both case studies. Buildings were modelled using the energy simulation tool IDA Indoor Climate and Energy (ICE), and the model was validated against the measured electrical energy usage. PVT was designed to balance the maximum heat production with domestic hot water consumption during the summer months. Simulation results revealed that combining GSHP with 5 m^2 grid-connected PVT gave 21% and 22% energy savings in case study 1 and case study 2, respectively. Employing a battery storage to store extra electricity production by PVT increased the energy savings to 24 % and 32 % for case study 1 and case study 2, respectively. Moreover, in both cases approximately half of the total annual domestic hot water need was prepared by 5 m^2 PVT.

Introduction

Background

An International Climate Panel forecasted an increase in the Earth's temperature by 6 °C on average by 2050 (National Research Council, 2011). To keep the climate change below 2 °C and to avoid the consequences of global warming, the European Union (EU) has ambition to become climate-neutral by 2050 (European Commission, 2018). In short term, EU has also set several key targets as to decrease the greenhouse gas emissions by 40%, to increase the energy efficiency by 32.5%, and to use at least 32% share of renewable energy by 2030 compared to 1990 levels (European Commission, 2014). In addition, Sweden has its own ambitions to have 50% more efficient energy use by 2030 compared with 2005, to have 100% renewable electricity production by 2040 and to achieve zero net greenhouse gas emissions by 2045 (Baylan I., 2018). In Sweden, the building sector is responsible for almost 40% of the total energy consumption and represents about a third of CO_2 emissions. To achieve the national and international energy policies, it is therefore vital to introduce sustainable and efficient renewable-based energy systems into near-zero energy buildings.

Heat pump has been known as one of the most efficient systems that extracts low-temperature heat from renewable and low-quality energy sources stored in the ambient air, in the ground or in groundwater, and converts it to useful heat of higher temperature to meet the energy demand in buildings. By using a heat pump with coefficient of performance (COP) of 4, at least 75% of total energy requirement in building is covered by renewable sources.

With double-digit growth for the fourth year in a row, the number of installed heat pumps in Europe was increased by 60% between 2014 and 2018 (EHPA, 2019). Raising with the same rate, European Heat Pump Association (EHPA) expects a doubling in the heat pump market by 2024. According to EHPA statistical data, Sweden was the fourth leading country in heat pump market by 2018 among 21 European countries. All these facts show that heat pump is a growing technology, and a further improvement in heat pump's configurations or in the control strategies would result in great energy savings potential and large reduction in greenhouse gas emission.

One enhancement in heat pump's configuration is to combine its compressor with photovoltaic (PV) to supply the required electricity from solar energy. Integrating grid-connected PV, which has been increased by more than 67% in Sweden between 2017 and 2018 (Ebenå G., Berard J., 2019), with heat pump would increase the self-consumption of installed PV and lead to less primary energy usage in building. Another improvement in heat pumps' configuration is to integrate it with a solar collector in series or in parallel (Vega J., Cuevas C., 2020). On parallel configuration, heat pump and solar system work independently to meet the energy demand in building. However, in series connection, heat pump's evaporator is fed by solar renewable energy, exclusively or in addition to other renewable sources, such as ground or air (Lazzarin R. M., 2012). In addition to individual PV and solar collector, a hybrid system, namely photovoltaic/thermal (PVT) can be combined with heat pump. PVT delivers both electricity and heat simultaneously in one and the same system, which results in higher efficiency compared to the individual system of PV. Previous study by Besgani et al. showed that combining an air-source heat pump with PVT would significantly increase the efficiency of the system by avoiding the defrost cycles (Besagni G., Croci L., Nesa R., Molinaroli L., 2019). Moreover, combining a ground-source heat pump with PVT can be cost effective as it reduces the borehole length and the required field compared to a conventional ground-source heat pump (Sommerfeldt N., Madani H., 2019). In addition, including more renewable sources in heat pump's evaporator through a seasonal thermal energy storage, which stores heat from summer to winter, would increase the efficiency and COP of heat pump (Hesaraki et al. 2015 a, 2015 b)

With respect to thermal efficiency and COP of heat pump, two sides of energy supplier in thermal side and the energy distribution in demand side are highly coupled. It means that less work is required by the compressor of the heat pump as the temperature difference between the renewable source side and the sink side decreases. As a rule of thumb, COP of heat pump improves by 1-2 % for every degree reduction in supply water temperature. Therefore, combining heat pump with low-temperature heat emitter, which works with supply temperature levels of lower than 45 ºC, could be efficient (Boerstra A., Veld P.O., Eijdems H., 2000). During recent years, more buildings have become more energy-efficient by having better thermal insulation, less infiltration and more efficient heating and ventilation systems. Therefore, the low space heating demand in buildings can be met by using a lower supply water. Hesaraki et al. have experimentally investigated the energy performance of low-temperature heat emitter with heat pump in five new buildings (Hesaraki A., Holmberg S., 2013) and in a climate chamber box (Hesaraki A., Bourdakis E., Ploskic A., Holmberg S., 2015)

We have observed that a number of researches have been carried out to investigate the performance of heat pump with solar system in forms of PV, collector, or PVT. However, to our knowledge there is a lack of studies clearly investigate the performance of a ground-source heat pump with PVT connected to low-temperature heating system in single-family houses located in cold climates. This research gap claims the need for more comprehensive study on the development and evaluation of this system in different buildings and to compare its distinctiveness from conventional ground-source heat pump. This paper tends therefore to focus on investigating the energy performance of a PVT-assisted ground-source heat pump in two case studies, including a renovated building with medium-temperature heating system, and a newly built single-family house with low-temperature heating system located in Stockholm, Sweden.

Description of the case study buildings

The first case study was a naturally ventilated two-story single-family house with 140 m^2 floor area, which was built in 1936 with an oil burner. In 2015, the house was renovated by installing a ground-source heat pump with a single 150 m borehole, and the roof was isolated with an additional 400 mm insulation layer. Moreover, all windows with poor U-value of 2.8 W/(m^2·K) were substituted by energy efficient three-pane windows. Two people were living in this house, whom kept the indoor temperature between 19-20 °C. Before renovation, the building used approximately 4 m^3 oil per year, corresponding to 285 kWh/m^2. This high energy usage, however, was decreased to 59 kWh/m^2 after installing a ground-source heat pump and improving the building's envelope.

For the second case study, we chose a one-story 130 m^2 single-family house built in 2013 with a ground-source heat pump connected to a single borehole with 190 m depth. The house was implemented by a mechanical balanced (supply/return) ventilation with a heat recovery system with efficiency of 80%, which supplied ventilation flow rate of 0.4 L/(s·m^2). Moreover, the heat was distributed in the house through low-temperature under-floor heat emitter. In this house with the indoor temperature of 21 °C, two adults and two children were living. The annual measured electrical energy consumption for space heating, domestic hot water, ventilation system, and auxiliary energy was 48 kWh/m^2.

Method

In this study, we used IDA Indoor Climate and Energy (ICE) 4.8 simulation tool to investigate the energy performance of case study buildings. IDA ICE is a dynamic simulation tool initially developed at KTH Royal Institute of Technology, Sweden to investigate energy usage, thermal comfort and indoor climate in buildings. IDA ICE has been validated in several studies with respect to CEN standards (Equa Simulation, 2010 a) (Kropf S., Zweifel G.) and ASHRAE standard (Equa Simulation, 2010 b).

Firstly, we used IDA ICE to model our case study buildings with a ground-source heat pump, and after that we improved our models by integrating PVT in the energy system. To validate our models, we conducted field measurements of electrical energy usage during heating season from 1st October 2019 to 29th February 2020. Measurements included electricity usage for space heating, domestic hot water (DHW), ventilation system, and pumps.

Model description

Two case-study buildings were modelled in ICA ICE according to their geometry, construction materials, heat pump specification, and their heating and ventilation system. To calculate energy usage for case-study buildings, ASHRAE's typical weather data of

International Weather for Energy Calculations (IWEC2) for Stockholm was used. The weather data derived from up to 25 years of avarage weather observations for at least every three hours of wind speed and direction, dry-bulb temperature, dew-point temperature, and global horizontal solar radiation from cloud cover.

In all models, we used a southward-oriented PVT with a slope of 45 degree and efficiency of 24,18% for PV. The efficiency of modelled PVT was taken from product specification of a commercial PVT produced by Samster AB (Samster). To avoid over production of heat, PVT's area was calculated to balance the maximum thermal production and the DHW consumption in summer.

Electricity produced by PVT was used to primarily feed the compressor of the heat pump, and the overproduction of electricity was supposed to either charge the battery or to be sold to the grid. Solar collector of PVT system was supposed to work in parallel with the heat pump for producing domestic hot water, which was then stored in a water tank with a capacity of 500 L, see Fig. 1. Since our measurements were conducted during heating season, we could not separate the energy usage for space heating from the energy usage for domestic hot water. Therefore, we assumed that the DHW consumption was equal for all months, which seems reasonable as hot water usage may not be dependent of weather condition.

To define variables that were dependent to occupants behaviour; such as DHW usage, internal heat gains from occupants, light, and equipment, Sveby Standard (Lindvall S., 2012) was used, see Table 1. Sveby, which stands for Standardize and Verify Energy Performance in Buildings, is a tool to define unpredictable variables from user behaviour in energy performance evaluation. Sveby's materials are in line with Swedish National Board of Housing, Building and Planning (Boverket).

To calculate the efficiency of the energy system, two terms of Energy Savings (ES) and Solar Fraction (SF) were used, see Eqs. (1) & (2). In Eqs. (1) & (2), $E_{PVT,self-consumed}$ refers to the electricity produced by PVT which was used inside the building, either directly by the heat pump or indirectly by charging the battery storage. Moreover, the total annual electricity demand for space heating, DHW preparation and ventilation system by building with GSHP and GSHP+PVT is indicated by $E_{total,GSHP}$ and $E_{total,GSHP+PVT}$, respectively.

$$SF = \frac{E_{PVT,self-consumed}}{E_{total,GSHP+PVT}} * 100 \qquad (1)$$

$$ES = \left(1 - \frac{E_{total,GSHP+PVT} - E_{PVT,self-consumed}}{E_{total,GSHP}}\right) * 100 \qquad (2)$$

Results

Simulation results

- Case study 1

After running a number of simulations, it was revealed that installing a 5 m2 PVT would match the maximum heat production in May with monthly DHW consumption. The results of energy flows including thermal and electrical production by PVT, DHW usage, and total required electricity in case of GSHP, and GSHP+PVT are given in Fig. 2. As can be seen in Fig. 2, the bars showing excess/required electricity in PVT+GSHP system have both negative and positive values. Positive figures demonstrate required (bought) electricity, and negative values indicate extra produced electricity by solar cells in PVT system, which occurred in summer as DHW need was covered mainly by solar thermal collector of PVT.

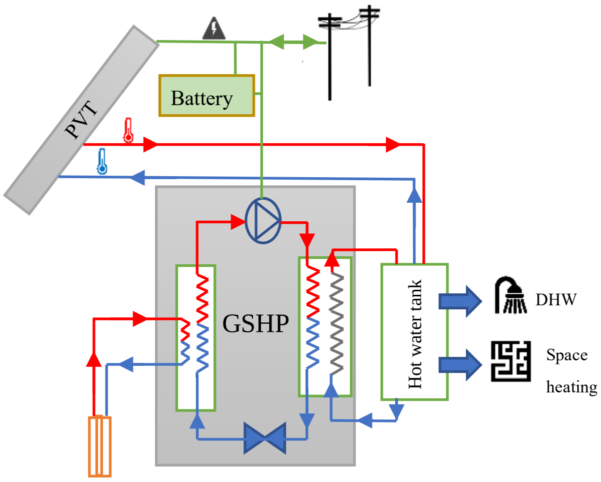

Figure 1 Configuration of the energy system studied

Table 1: Defined variables in IDA ICE based on Sveby Standard, the number of occupants is based on real data **(Lindvall S., 2012)**

Parameter	**Amount**	**Schedule in IDA ICE**	**Internal heat gain**
Occupants	Case 1: 2 people, Case 2: 4 people	Absent from 8:00 to 18:00, and present otherwise	Activity level of 0.8 MET, corresponding to 80 W
Household electricity	$\frac{30}{8.76} * \frac{A_{temp}}{A_{floor}}$ W/m2	Always on	70 % converts to heat
Domestic hot water	20 kWh/m2 with a repeated daily profile	Annual usage	20 % converts to heat

As stated earlier, extra generated electricity by PVT can be either stored in a battery or sold to the grid. In case of grid-connected PVT coupled with ground-source heat pump, the electricity usage for case study 1 was 46 kWh/m2, causing 21% energy savings compared to individual ground-source heat pump with 58 kWh/m2 electrical energy usage, see Fig. 3. Moreover, using Eq.

(1), the solar fraction was calculated as 18% if excess electricity was sold to the grid. On the other hand, storing extra electricity to a battery storage for later usage would increase the self-consumption, which resulted in decreasing the annual electricity demand from 58 kWh/m$_2$ to 44 kWh/m$_2$. Employing a battery storage in case study 1 caused 24% energy savings and a solar fraction of 22%. Additionally, annual simulation revealed that 49% of total domestic hot water need could be covered by 5 m$_2$ PVT.

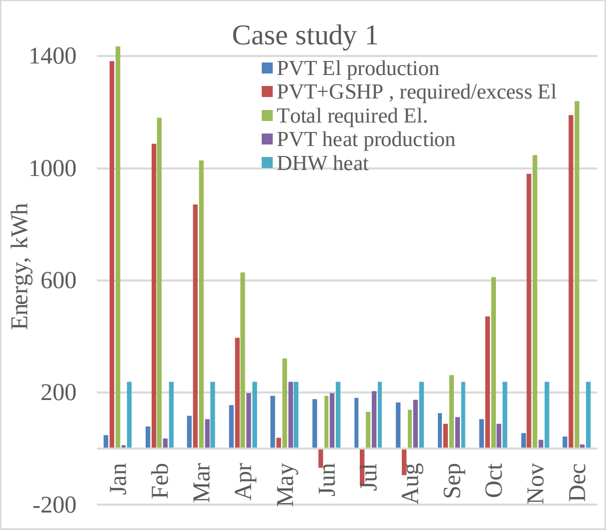

Fig.2: Energy flows in case study 1

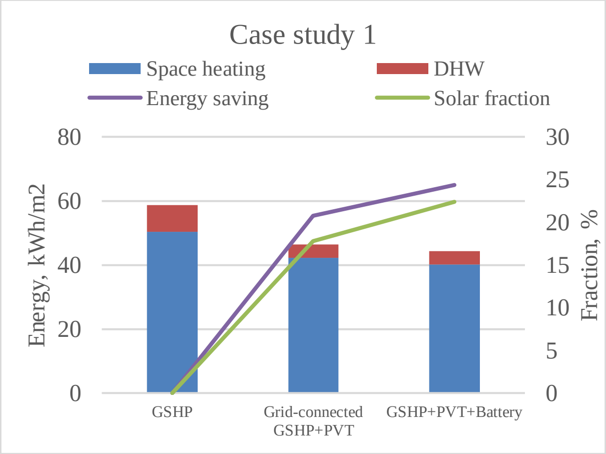

Fig.3: Electricity usage, energy savings, and solar fraction in case study 1

- Case study 2

Similar to the first case study, simulations showed that a 5 m$_2$ PVT was needed in case study 2 to create an acceptable balance between the monthly domestic hot water need and the maximum heat production in July, see simulation results in Fig. 4. Our results indicated that combining a ground-source heat pump with the grid-connected PVT would reduce the total electrical energy usage from 48 kWh/m$_2$ to 37 kWh/m$_2$. Moreover, selling extra electricity to the grid in PVT+GSHP system caused 22% energy savings and a solar fraction of 20%, see Fig. 5. As indicated in Fig. 5, storing excess generated electricity to a battery storage decreased the yearly electricity usage from 48 kWh/m$_2$ to 33 kWh/m$_2$. It means that energy savings and solar fraction were 32% and 34%, respectively. Furthermore, our results indicated that installing 5 m$_2$ PVT covered 54% of total DHW requirement in case study 2.

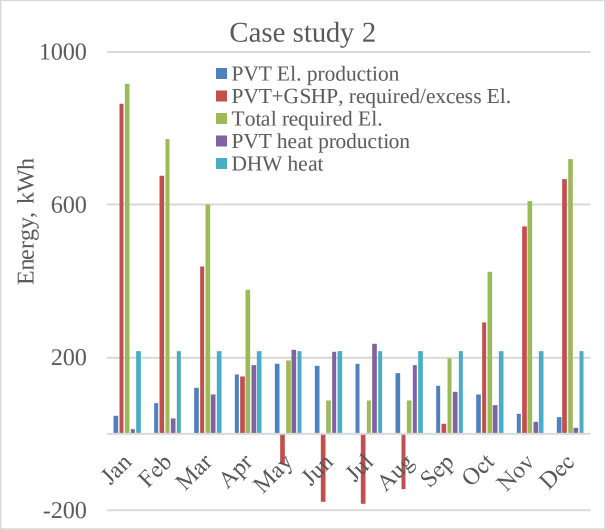

Fig.4: Energy flows in case study 2

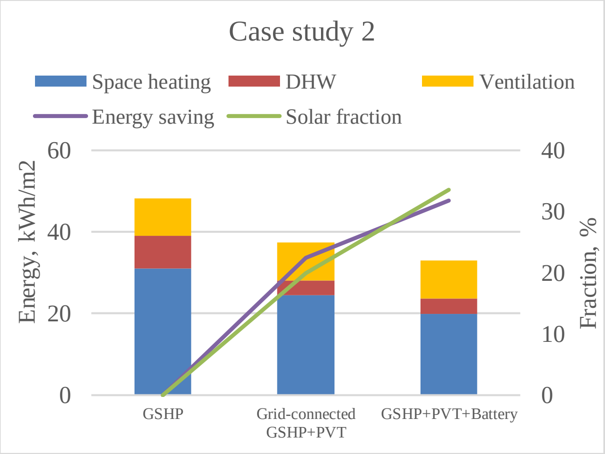

Fig.5: Electricity usage, solar fraction and energy savings in case study 2

Measurement results and model validation

IDA ICE model was experimentally validated against measurements of electricity usage for space heating, domestic hot water, ventilation and auxiliary energy used for fans and pumps during heating season of 2019-2020. Results of validation for case study 1 and case study 2 are presented in Fig. 6 and Fig. 7, respectively. As can be seen in Figs. 6 & 7, the measured electrical energy usage in October for both cases were approximately 30% higher than the simulated values. This large deviation can be attributed to the difference between standard weather data of IWEC2 used in simulation and actual weather condition in measurements. According to the Swedish Meteorological and Hydrological Institute, October 2019 had the coldest start days during the past 20 years compared to the October's normal temperature, and the winter of 2019 had arrived 1-2 weeks earlier than the normal year during the past 40 years (SMHI, 2019). This unpredictable actual weather conditions in October 2019 caused the underestimation of energy usage in our simulation compared to the reality.

On the other hand, the electricity demand in January was overestimated by simulation compared to the measurement. This deviation could be explained due to unpredictable occupants' behaivior during New year's holiday by for example taking a trip. Despite the fact that occupants' behaviour and actual weather conditions caused underestimation or overestimation of the actual energy usage, in other months of November, December, and February there appeared to be a good agreement between measurements and simulation.

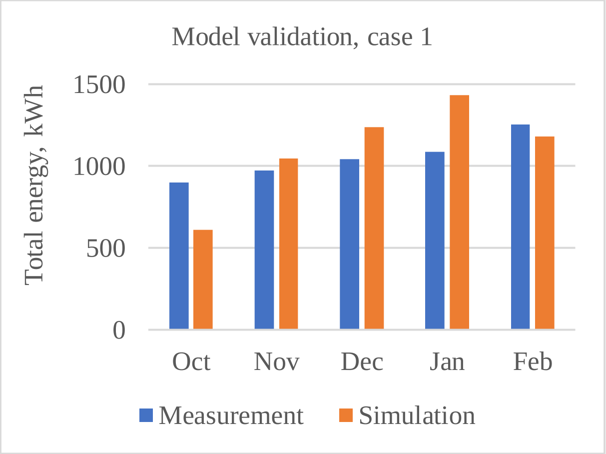

Fig 6. Comparison of measured and calculated electrical energy demand in case study 1

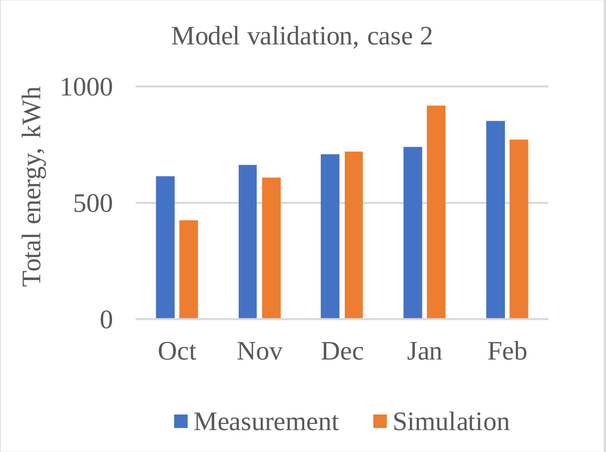

Fig. 7. Comparison of measured and calculated electrical energy demand in case study 2

Discussion

As shown by results, the ratio of self-consumed electricity to the total PVT generation plays a key role in determining two factors of solar fraction and energy savings. Results showed that the self-consumption ratio for case study 1 was considerably larger than that in case study 2; which was 81% for case 1, and 59% in case 2. The greater self-consumption in case 1 can be explained by the fact that some parts of the electricity generation by PVT were used to cover space heating need during summer nights in this old building, which was not required in case 2 as a new building.

To increase the self-consumption ratio, one possibility is to utilize a battery storage, which leads to higher solar fraction and greater energy savings. As shown by results, storing excess electricity to a battery storage in case 2 could significantly improve the solar fraction and energy savings, which were increased by 10-14 % compared to the grid-connected case with no battery storage. On the contrary, in case 1, employing a battery storage had minor impacts on energy savings and solar fraction, as those performance indicators were only increased by 3-4% compared to the grid-connected PVT cases. Therefore, it can be concluded that it would be more beneficial to have a battery storage in new buildings to achieve higher efficiency in energy system.

Moreover, in IDA ICE simulation the typical weather file of ASHRAE's IWEC2 was used, which was different from actual weather condition and resulted in deviation between measurement and simulation. Next step of our project is, however, to use the actual weather file in simulation for validating our model.

Conclusion

The objective of the study was to investigate the application of photovoltaic-thermal (PVT) system combined with ground-source heat pump (GSHP) in new and retrofitted construction. IDA ICE simulation tool was used to calculate total electricity usage of case-study buildings, which was validated against measurements conducted during heating season of 2019-2020. In our model, PVT worked in parallel with ground-source heat pump for covering domestic hot water usage, and the electricity produced by PVT was primarily used to feed the compressor of the heat pump. To evaluate the performance of the energy system two indicators of solar fraction and energy savings were used, which depended on self-consumption electricity and the total electrical energy demand.

Simulation showed that using 5 m_2 PVT for both cases could create a good balance between generating thermal energy by PVT and domestic hot water usage during the summer season, and it covered around half of the annual domestic hot water demand. Moreover, depending on the building type and the existence of a battery storage, solar fraction and energy savings varied between 18-34 % and

21-32%, respectively. The lowest values for both solar fraction and energy savings were achieved for the old building in case study 1 without a battery storage, and the highest values attributed to the new building in case study 2 with a battery storage. As employing a battery storage in energy system is very costly, its benefits should be justified considering building type and self-consumption ratio.

It should be noted, however, that this study was of two dwellings only; future study of other types and greater number of dwellings are needed before it is possible to generalize regarding all houses using PVT-assisted ground-source heat pump.

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