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An investigation of energy efficient and sustainable heating systems for buildings:

Combining photovoltaic with heat pump

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Abstract Renewable energy sources contribute considerable amounts of energy when natural phenomena are converted into useful forms of energy. Solar energy, i.e. renewable energy, is converted to electricity by photovoltaic systems (PV). This study was aimed at investigating the possibility of combining PV with heat pump (HP) (PV-HP system). HP uses direct electricity to produce heat. In order to increase the sustainability and efficiency of the system, the required electricity for the HP was supposed to be produced by solar energy via PV. For this purpose a newly-built semi-detached building equipped with exhaust air heat pump and low temperature-heating system was chosen in Stockholm, Sweden. The heat pump provides heat for domestic hot water (DHW) consumption and heating demand. Since selling the overproduction of PV to the grid is not yet an option in Sweden, the PV should be designed to avoid overproduction. During the summer, the HP uses electricity only to supply DHW. Hence, the PV should be designed to balance the production and consumption during the summer months. In this study two simulation programs were used: IDA Indoor Climate and Energy (ICE) as a building energy simulation tool to calculate the energy consumption of the building, and the simulation program WINSUN to estimate the output of the PV. Simulation showed that a 5.5 m^2 PV area with 15 % efficiency produces nearly the whole electricity demand of the HP for DHW during summer time. As a result, the contribution of free solar energy in producing heat through 5.5 m^2 fixed PV with 23^o tilt is 15 % of the annual heat pump consumption. This energy supports 58 % of the total DHW demand.

1 Introduction

Due to the scarcity of fossil fuel sources and their environmental impact, renewable energy has become an increasingly important topic over the past decades. On a global scale renewable energy sources only contribute less than 15 % (Lund 2007) to the primary energy supply; however, during the last few decades this percentage has increased considerably in some countries.

Energy from solar radiation can be obtained in two ways, passively and actively. Passive solar design is based on the optimal design of a building's shape leading to the capture of as much solar radiation as possible for space heating. Active solar design is based on converting solar radiation into energy by using solar thermal collectors or photovoltaics. Photovoltaics (PV) convert sunlight into electric power by a solid-state device called solar cells. The common PV module converts 15 - 20 % (Tyagia et al. 2012) of the incoming solar radiation into electric energy, depending on the type of solar cells. Our total present energy demand can be supplied if 0.1 % of the earth's surface were covered with solar cells with 10 % efficiency (Tyagia et al. 2012). Solar thermal collectors convert solar radiation into thermal energy through a transport medium, liquid or gaseous. Solar cells are more efficient than solar thermal collectors, since they are performing during the winter months at low irradiation with constant efficiency while the solar collector has very low efficiency during hours of low intensity due to a high heat loss (Gajbert 2008).

The electricity generated by PV could be utilised by a heat pump to produce heat. Depending on the Coefficient of Performance (COP) of the heat pump, the energy required for space heating and domestic hot water (DHW) may be decreased by a factor of the COP. The outputs of 1 m^2 of plane solar collector delivering hot water at 50 °C and 1 m^2 of PV modules of 15 % efficiency in combination with a heat pump (PV-HP system) with COP=3 in Stockholm were compared using the WINSUN program, see Figure 1. These two systems, solar collector and HP-PV are comparable since both produce hot water. It can be seen that the combination of the PV module and the heat pump has a higher annual output than the solar thermal collector. During winter time, i.e. low temperature and low irradiance, the solar collector has zero efficiency due to high heat loss. The heat loss of the solar collector is dependent on the collector efficiency factor (F´), heat loss coefficient from absorber to ambient (U_L ,W/m^2K) and temperature difference between ambient temperature (T_a) and collector temperature (T_c), Equation 1 (Duffie and Beckman 1991). PV is usable year round performing even at low intensity since it works on light not heat. In the summer time both the solar collector and PV have good characteristics. As a result, a PV-HP system is more efficient since it provides a higher annual solar fraction in comparison with a solar thermal collector system. Solar fraction (SF) gives the fraction of energy provided by solar energy to an annual heating demand. SF varies between 0 when no energy is supplied by solar energy to 1 when all required energy is supplied by solar technology.

$$P_{loss\_collector} = F^{'} * U_l * (T_c - T_a) \qquad (1)$$

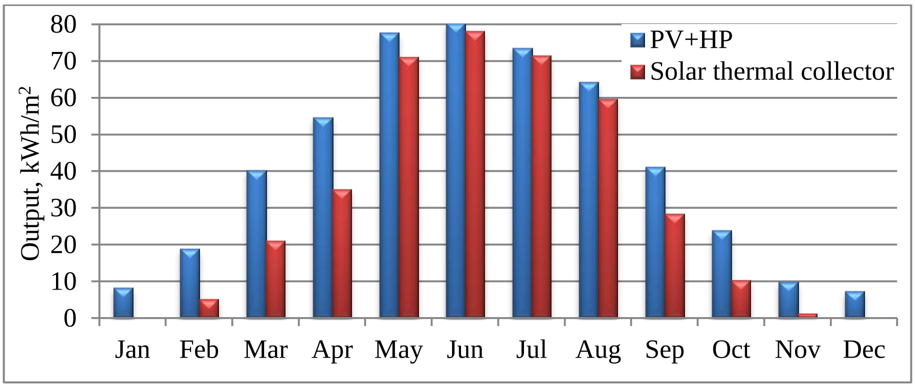

Fig. 1. Output comparison between photovoltaic + heat pump and solar thermal collector

The present paper points to the possibility of combining PV with heat pump in an actual building equipped with an exhaust air heat pump in Stockholm. For this purpose a Building Energy Simulation (BES) program, IDA Indoor Climate and Energy (ICE) was used to calculate the energy demand in the building. Then, using the System Simulation Program (SSP) WINSUN the output of PV with 15 % efficiency was calculated to produce the electricity for the HP. Since there is yet no regulation in Sweden concerning selling excess solar power to the grid, overproduction of electricity was avoided. Hence, the area of the PV modules required should be calculated to balance energy consumption and production when the production is at the highest point and the consumption is at the lowest value (during the summer season). However; in the future there might be a policy for selling extra electricity to the grid. It might then be profitable to produce more electricity than needed and export it to the grid.

2 Method

In this study two simulation programs were used, one for finding the energy requirements of the building and the other one for calculating the output of appropriate PV to partly meet this demand.

2.1 Building Energy Simulation (IDA ICE)

IDA Indoor Climate and Energy (ICE) is a Building Energy Simulation (BES) tool to calculate thermal comfort, indoor air quality and energy consumption in buildings. This program was partly developed at KTH (Jokisalo et al. 2008). An early validation of the IDA ICE program was conducted by comparing the results predicted by simulation with measurements; they showed good agreement (Travesi et al. 2001).

The purpose of using the IDA ICE program in this study was to calculate the monthly energy consumption for a whole year in order to find the electricity consumption of the heat pump. The electricity consumption for providing domestic hot water and space heating by the heat pump was calculated by dividing energy consumption by the Coefficient of Performance (COP) of the heat pump.

When performing IDA ICE analyses the input data include building location, geometry, construction type, HVAC system, internal heat gain (number of people, light and equipment) and DHW consumption. Referring to the Swedish building regulations (Boverkets byggregler, BBR), the average value for DHW usage is 30 kWh/m^2 of floor area. The area of the studied building is 160 m^2 leading to 4800 kWh/year of DHW. This theoretical value was used in this study since there is no available information regarding actual DHW consumption yet. Through creating a mathematical model and solving heat balance equations, the energy consumption in the building was estimated by IDA ICE. Details of the simulation and validation of results for the studied building may be found in a previous study (Hesaraki and Holmberg 2012).

2.2 System Simulation Program (WINSUN)

Simulation tools are preferred for analysing a system rather than implementing an actual device on site, since studying a model is essentially easy and inexpensive. WINSUN is a system simulation program developed at Lund University for designing solar collectors and PV (Hatwaambo et al. 2008). WINSUN is an abbreviation of Windows version of MINSUN usable in DOS (Boström et al. 2003). WINSUN is based and developed completely on PRESIM, TRNSYS and TRNSED version 14.2 (Boström et al. 2003). PRESIM is a graphical modeling program used for producing input data for TRNSYS, developed by the Solar Energy Research Center in Sweden (Beckman et al. 1994). In TRNSYS (TRaNsient Systems Simulation) thermal energy equations are solved based on a modular approach depending on the input data (Beckman et al. 1994). TRNSED is text editor program to create a user-friendly TRNSYS interface of a solar energy system, and convert the input file to a TRNSED-formatted document to be usable for other users, developed at the University of Wis-consin, Madison (Beckman et al. 1994, Hatwaambo et al. 2008). WINSUN aims to provide an output of a solar thermal collector and PV in kWh/m^2 depending on the location of system, azimuth, tilt, tracking mode and efficiency of PV. The program uses the weather data during 1983-1992 including diffuse and beam radiation collected by the Swedish Meteorological and Hydrological Institute (SMHI) (Boström et al. 2003). Comparing the solar radiation intensity during the long term at all weather stations, the divergence between measured solar radiations is less than 2 % (Hatwaambo et al. 2008). Hence, the results of the program though using old weather data appear reliable. The validation of the WINSUN program was conducted by comparing the simulation results with site measurements, which showed good agreement (Gajbert 2008). The results of WINSUN may be found in two ways: one as a table and plot file, and the other as an online plot where several variable changes may be watched and analysed at the same time as TRYNSY calculations are running to solve thermal energy equations. In this study, WINSUN simulation was conducted to evaluate the performance and output of fixed PV with 15 % efficiency at 23º tilt towards the south (according to the plan of the chosen building). Simulation was based on monthly net metering. Export of overproduction to the grid was avoided. Input data to the simulation include starting day of simulation, month and length of simulation, site of place, climate, tracking mode (1 for fixed, 2 for turning around vertical axes, 3 for turning around an axis in the plane of the glass, 4 for 2 axes tracking), ground reflectance (typical value 0.2-0.3), slope of surface from horizontal plane and azimuth of surface (azimuth angle from the south i.e. -90 for east, 0 for south and 90 for west).

3 Results and Discussion

3.1 IDA ICE Simulation Results

Using the IDA ICE program, the results for electricity usage in the heat pump to provide heat for space heating and DHW are shown in Figure 2. The DHW consumption was assumed to be equal for all months (Gajbert 2008) since it may not be dependent of weather condition. Considering the average COP of the exhaust-air heat pump producing hot water at 50 ºC, which is 2.7 according to investigation by (Nowacki 2007), heating demand was decreased by a factor of 2.7. The electricity consumption by the HP for space heating depends on the weather conditions, heat losses i.e. ventilation loss, transmission loss and leakage loss, and passive heating (contribution of free heating source such as people, equipment, solar energy and lights in heating the house).HP consumption for space heating varies for different months, it is at its highest level in winter and zero in summer; however, the electricity consumption by the HP for DHW was assumed to be constant over the year (1778 kWh/year or 148 kWh/month).

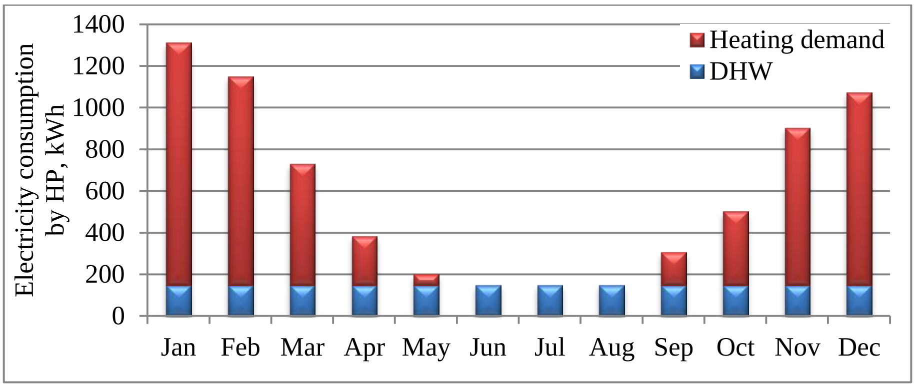

Fig. 2. Monthly electricity consumption of a heat pump with COP 2.7

3.2 WINSUN Results

Using the WINSUN program, the output for a fixed photovoltaic system is given in Figure 3. This is for one year with 15 % efficiency and southward orientation with a roof slope of 23º in Stockholm. As shown, the electricity produced by PV varies during the year depending on the solar irradiation. PV can work with acceptable output even during the cold and mostly dark winter time since they can work even on slight light. The output of the PV drops considerably during the winter months due to the low solar intensity in comparison with the summer months when the output has its maximum value. The annual output for the chosen PV is 228 kWh/m^2 year independently of the cell temperature.

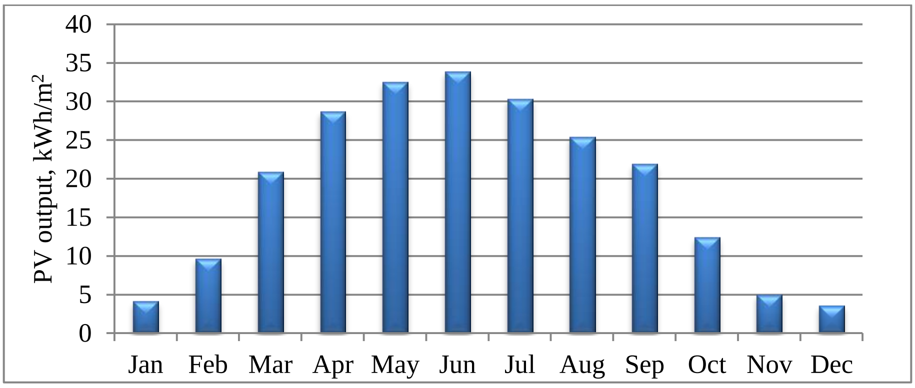

Fig. 3. Photovoltaic output at 15 % efficiency in Stockholm

The efficiency of the PV decreases by increasing the cell temperature, there are many factors that determine the operating temperature of PV such as ambient air temperature, type of module, intensity of sunlight and wind velocity.

The efficiency of a solar cell is usually determined under standard test conditions, i.e. cell temperature is 25 ºC and normal incidence is 1000 W/m^2. Solar cells are generally exposed to temperatures ranging from 15 ºC to 50 ºC (Singh and Ravindra 2012). Mainly, the operating temperature of the module is higher than 25 ºC and the angle of incidence is larger than 0° which is not considered in the WINSUN program. So, the output of PV should be multiplied by a correction factor φ. The correction factor varies for different months depending on the cell temperature, solar intensity and solar angle. Measurements conducted in Switzerland from 1992 to 1996 monitored the monthly correction factor for a PV, see Figure 4 (Häberlin 2012). In Sweden usually the value between 0.80 and 0.85 is used.

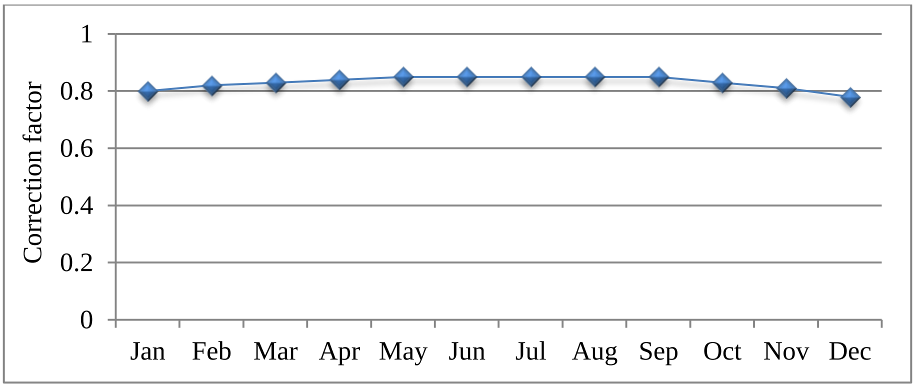

Fig. 4. Correction factor of PV output for different months (Häberlin 2012)

As mentioned before, to avoid overloading in the summer the PV should be designed to supply the electricity for DHW production. By monthly net metering of the simulation, to determine the module area (Equation 2), the month which gave the maximum output of PV was June. Thus, the production and load are in balance in June. Hence, to find the required area for the PV the energy demand (kWh) for this month was divided by the PV output (kWh/m^2) for the same month. So, by dividing 148 kWh by 27 kWh/m^2 the area demand of the PV was found to be 5.5 m^2.

$$\text{Area (m}^2\text{)} = \frac{energy\ demand\ in\ June\ \ (kWh)}{energy\ produced\ by\ PV\ in\ June\ (kWh/m2)} \quad (2)$$

To find the annual solar fraction (SF, Equation 3) the electricity generated by 5.5 m^2 PV was divided by the electricity consumption by the HP during the whole year. Figure 5 gives the comparison between production and consumption of electricity for each month. Simulation results showed that the solar fraction is 15 %. However, if export to the grid were allowed the solar fraction might be improved by increasing the area of the PV and then ignoring the overloading problem.

$$SF = \frac{\text{Electricity generated by PV}\left(\frac{\text{kWh}}{\text{year}}\right)}{Electricity\ consumed\ by\ HP\ \left(\frac{kWh}{year}\right)} * 100 \quad (3)$$

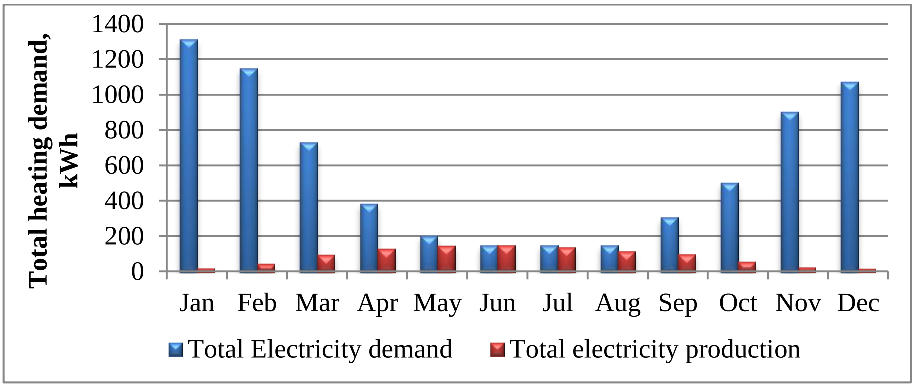

Fig. 5. Annual solar fraction calculation for total heating demand (space heating + domestic hot water)

4 Conclusion

The objective of this study was to investigate and evaluate the performance of the PV-HP system for the building in Stockholm. In addition, the solar fraction was calculated. The method included two simulation programs, one for calculating the energy demand of the building and the other for designing a PV system. Investigation of energy performance was conducted using the IDA ICE program. Simulation showed that the total energy consumption in the building is 13552 kWh/year including 8752 kWh for space heating and 4800 kWh for DHW. To avoid overproduction with monthly net metering, the PV-HP system should be designed to create a balance between production and demand during summer. WINSUN, a system simulation program, was used to design appropriate PV. Simulation showed that using 5.5 m^2 PV with 15 % efficiency would create a good balance during the summer season in generating and consuming electricity by PV and HP, respectively. In other words, the electricity consumed by HP is more or less totally supplied by PV during summer. The annual solar fraction (SF) in a designed HP-PV system was 15 %. If electricity generated by PV is used only for DHW the SF value is 58 % (Equation 4), i.e. more than half of the DHW need would be covered by implementing only 5.5 m^2 PV, Figure 6.

$$SF_{DHW} = \frac{\text{electricity generated by PV}\left(\frac{\text{kWh}}{\text{year}}\right)}{electricity\ consumed\ for\ DHW\ \left(\frac{\text{kWh}}{\text{year}}\right)} * 100 \quad (4)$$

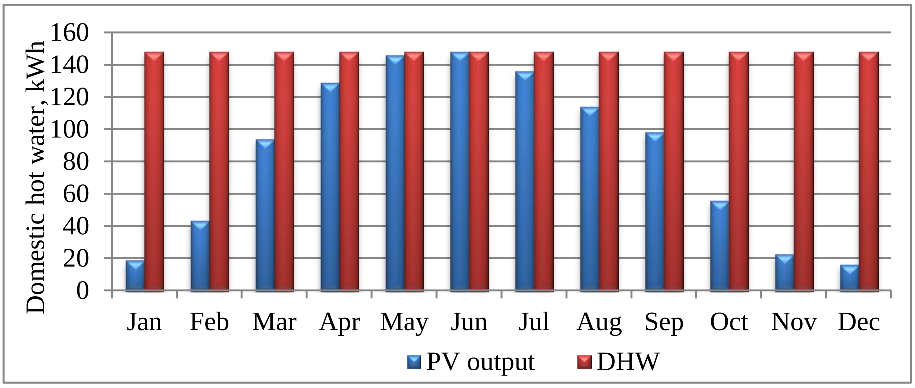

Fig. 6. Annual solar fraction calculation for domestic hot water consumption

It can be concluded that by implementing the HP-PV system with monthly net metering a relatively high solar fraction is achieved by the small PV area. The solar fraction may be increased when the heat loss is decreased which can be reached by minimising transmission, ventilation and leakage losses, i.e. using low U-value materials with high air tightness in the building envelope or using energy-saving equipment such as a heat pump or heat exchanger ventilation. Also, the solar fraction may be increased by increasing the PV area if the monthly net metering is disregarded. In this project, combining the heat pump with PV system (PV-HP) was introduced as an energy-efficient and sustainable solution. The need to supply 20 % of energy demand by renewable energy by 2020, as a European Union target (European Environment Agency Report 2006), will lead to the design of more sustainable and energy-efficient systems. Using renewable and sustainable systems particularly in the building sector will reduce environmental problems such as carbon dioxide concentration and the global warming effect.

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