Intelligent Control of Solar Power with Water Heating System

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KEY WORDS: solar power, control, heat storage, heat pump, water

ABSTRACT

Solar power capacity is globally increasing all the time. It has intermittent nature, and hence in order to avoid over production during day time, the electricity consumption should be moved to match with it. It has also the best profitability for the end-users, when the solar power generation is used by own without selling to the grid. The solar energy can be used in water heating or air cooling system. The best way to handle this, is to use automation. This paper presents an intelligent control method to use the surplus energy for some time independent practical target, such as for water heating or air cooling.

1 INTRODUCTION

The global capacity of installed solar power photovoltaics (PV) has increased exponentially during the last years. The worldwide solar PV capacity grew 38% during the year 2013 leading to the total capacity of 139 GW [1]. On the other hand, the growth of PV varies strongly in different countries. Currently, China has the pole position of the new solar PV installations with 12.9 GWp in 2013. The world leader in total PV capacity is Germany with 36 GWp in 2013. One reason for the growth is the desire to increase the renewable energy production. However, the main driver for the growth is the fact that since 70's the PV panel prices (eur/Wp) have dropped every time 20% when the installed solar PV capacity have doubled. Price is the main factor when the fossil and renewable energy sources are compared. It has been shown that the renewable energy, such as wind and solar, will become the cheapest electric energy generation form in 10 years in China [2] and also in other countries [3].

At this moment, the solar power is profitable only for electricity end-users in Finland, because the production price competes toward the total price of electricity that includes electricity market and transmission price, and taxes [4]. Most of the profit in solar power production in households comes from using the energy within the household, as the surplus energy sale price is considerable lower (one third) than the purchasing price. Sale prices are generally electricity market price. Because the production times of the solar power plant are intermittent, the maximum profit from the solar energy can be received by changing the consumption patterns. In the current state, most of this control is done manually with the actions of the house owner; by trying to do as much of energy intensive tasks during the production hours. On the other hand, the best production times are on day time when people are normally absent. However, hot water or/and air cooling are needed in households, and these can be automatized to work on day time. The surplus energy can be loaded to a heat storage, i.e. a boiler or to the cooled air. Other way is to reload batteries, but these are not yet profitable.

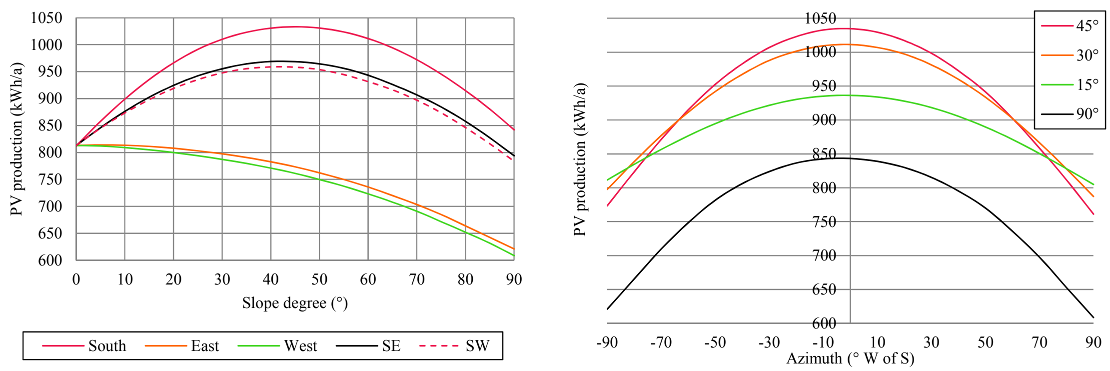
This paper studies a logic controlled automation of heating of domestic hot water or air cooling during the production hours of a solar power plant. Comparisons are done between thermostat control, logic control and heating moved to the hours around noon, when the maximum production can be expected. Logic is designed to minimise energy transfer between household and electrical grid by relying on hourly energy net metering. The method is verified by simulations that is applying measurement data.

This paper is organized as follows. Firstly, the solar power and the water boiling system are introduced. Next, general logic control that is suitable for different cases is presented. An example case is studied that verifies the suggested method. Finally, the paper is concluded.

2 ENERGY PRODUCTION AND STORAGE IN HOUSEHOLD

2.1 Solar power

Solar power production potential in Finland is studied in [4]. It can be said that the yearly production potential is almost at the same level in Lappeenranta and in Frankfurt. Only monthly distribution is different, because of seasonal changes that is coming from the location. The production of the solar power plant can be simulated to estimate the production potential in a certain place. For example, simulations can be carried out by Homer Energy® software [5]. Software enables simulations in local conditions. Local radiation, average temperature, azimuth angle, slope degree, and many other parameters can be set to the software. Simulated annual production of solar power as a function of slope degree and azimuth angle is presented in Figure 1.



(a) (b)

Figure 1. Simulated annual production of solar power in Lappeenranta without inverter losses. (a) As a function of slope degree. (b) As a function of azimuth angle.

2.2 Boiler

A boiler is required to storage heat energy for the load peaks of hot water consumption, because the instant power of hot water is huge. There is no sense to dimension the heating system according to this power requirement. A boiler can be dimensioned in different ways for the households. First way is to dimension it according to the assumed hot water peak consumption, second way according to the consumption of a single day, and third way according to the consumption of few days. The output water temperature from the boiler should be over 55 °C because of bacterial. Thumb rule is that people uses annually 1000 kWh energy for hot water per person. This means that the energy need for hot water is 11 kWh for four-person family per day, and 22 kWh for two days, etc. The day need of hot water for four-person family can be fulfilled by about 300 litre boiler at 87 °C assuming that the water is mixed inside the boiler. The bigger boiler the more losses, but these are not remarkable compared to the total energy need of hot water.

2.3 Combination

Simulations can be carried out in hourly based. This is important tool when sizing the solar power plant according to the consumption in a household. Nowadays, consumption data is also available as hourly based from the electric company. Both the consumption and production can be matched together and also estimating the possibility to use the surplus energy to reload the boiler or cooling the air or both of them. The energy need for water heating depends on the heating system. Electrical heating produces heat energy as much it consumes electric energy, but the heat pump produces more heat energy than it consumes electric energy. The amount of heat is depending on coefficient of performance (COP) of the heat pump. If the heat pump is inverter-based, it can be driven according to the produced surplus energy that can be measured. The dimensioning of the systems is depended on many things; which time range do we want to produce solar energy to fulfil the energy need and how long time storage do we need. This is a system optimisation task that is not studied in this paper. This paper discusses about three different methods to control the heating or cooling system; thermostat control, logic control and heating or cooling moved to the hours around noon, when the maximum production can be expected. These are illustrated in Figure 2.

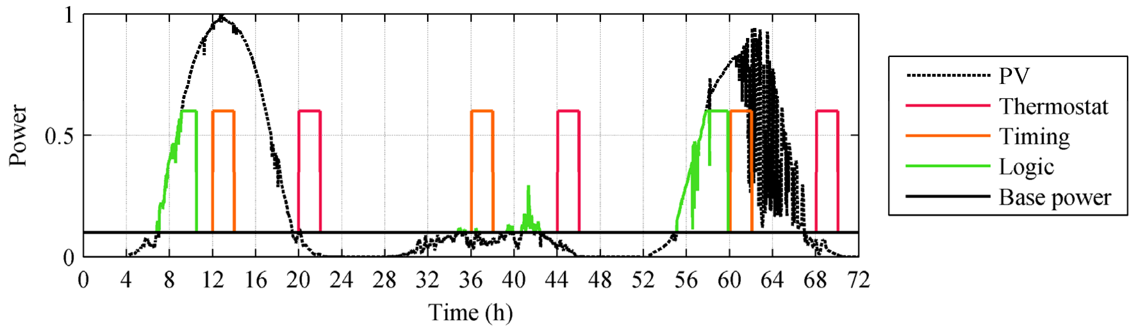


Figure 2. Different methods to control the heating or cooling system; thermostat control, logic control and heating or cooling moved to the hours around noon, when the maximum production can be expected. Solar PV and base power are also illustrated.

3 CONTROL

3.1 Daily

Logic control of controllable loads aims to keep energy transfer between the grid and household to a minimum during hourly net metering period. Controllable loads can vary anywhere from domestic hot water heating boiler to cooling with air-source heat pump. Simplified logic diagram is illustrated in Figure 3.

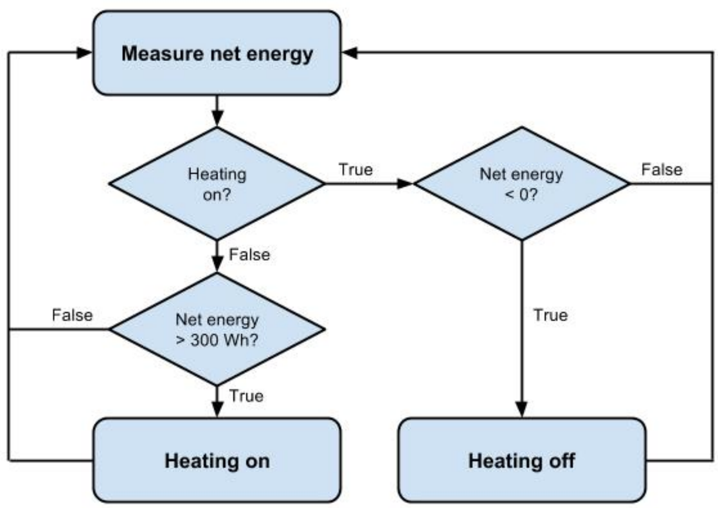


Figure 3. Simplified logic diagram.

Load is turned on once the hourly net energy reaches set threshold. The threshold acts as a buffer, trying to reduce the number of switching events, as control of electric power itself is most commonly done with electromechanical components. Load is kept on as long as the hourly net energy stays above 0 Wh or the set energy limit is reached. If the daily heat energy requirement is not reached by the evening, the load is turned on and kept on, as long as the required energy target is met. When the grid electricity is used, this can be timed according to the electricity market price.

If the measurement of energy is carried out from the electricity supply of the household, the logic takes all the consumption of the household automatically into account. This also allows multiple loads to be installed in parallel, using only a single energy meter. The logic could be expanded to include inputs from the device itself, such as temperature measurements from the boiler. With this improvement, as one load reaches full capacity and is turned off, other loads will effectively have more energy available for consumption.

3.2 Forecast

By scaling the energy storage large enough for multiple day usage, forecasting cloud coverage and using time of year as reference, the system can be expanded to make predictions of future energy production. The system could use this information to adjust energy target to produce as much energy as possible today, if the forecast for next day is unfavourable. On the other hand, if daily energy target is not met, forecasts could be used to determine if the missing energy can be produced the next day, trying to avoid the use of energy purchased from the grid. Another way to minimise energy costs for the household would be the use of spot prices to find cheapest hours for meeting the required daily energy quota. As electricity prices for next day are announced beforehand, instead of using simple time control to drive loads after 8 pm, the system could find the cheapest hours and control loads during these hours.

With implementing simple presence control, the system could be able to determine the need for driving different loads accordingly. For example, there is no need for domestic water heating when no-one is present. On the other hand, daily energy quota for device could be raised temporarily, for example if there are more people than normal in the household. As system evolves, these functions could, for example, be linked to presence of mobile phones in or near the household.

4 EXAMPLE CASE

4.1 Devices

Hardware for implementation of logic consists of two parts; a logic controller and a device for energy measurement. Both devices are attached to a local area network via Ethernet. Since the system does not require time-critical control, embedded Linux can be chosen as a software environment for the logic board. This choice also adds the possibility of easily extending the system to include home automation features as well as additional metering. There are multiple choices for the hardware that is cheap, off-the-shelf type, and includes embedded Linux. Boards also include all the necessary peripherals as standard; Ethernet-connectivity and general purpose I/O. Also there are peripherals for additional devices, such as a display for the system monitoring. Software itself can be designed to be portable to allow the use of multiple platforms for base of the system.

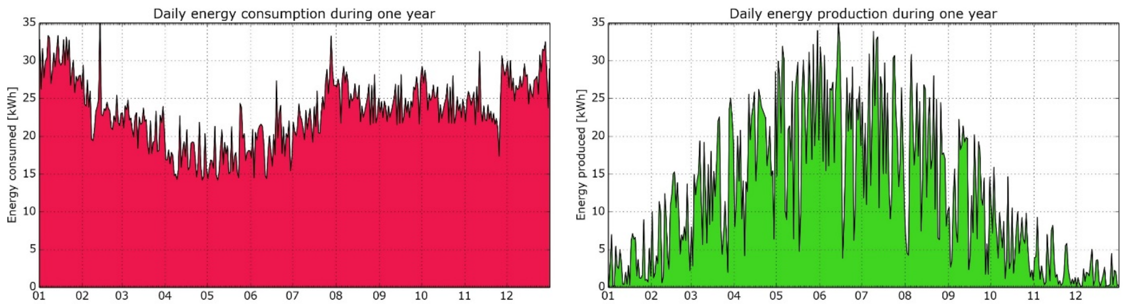
The choice between Linux-boards can be made between Raspberry Pi Model B+ [6] and BeagleBone Black [7] as they are currently the most popular boards with proper support through the community. Differences between these two are mainly the number of digital inputs and outputs as well as overall processing power. As the processing power requirements are fairly low, Raspberry Pi can be chosen because of wider user base; compatible products are more likely to be available in the future as well. In addition to the board, a custom add-on board is required for relay control. The add-on board makes the use of Raspberry GPIO pins to drive N-channel MOSFETs for control of external relays.

Energy measurement device has to be able to measure both the produced and consumed energy. Most households in Finland have already this type of energy meter, but the existing meters cannot be used because they provide no generic digital communication interface for consumer applications. Instead, an additional two-way energy measurement device with Ethernet-connectivity is required. Siemens PAC4200 can be chosen for an energy meter. It includes both two-way measurement and Ethernet-connectivity [8]. Data is transferred via Modbus TCP/IP, which allows simple communication with the rest of the system.

4.2 Example household

In the examined household electricity consumption is about 8500 kWh per year, with heating boiler responsible for 4000 kWh per year. Heating of domestic hot water is one of the most energy consuming tasks in a typical household, consuming in excess of 35% of total energy [9]. The house is equipped with a 5 kWp on-grid solar panel system that produces roughly 4500 kWh per year. Simulated energy consumption and production for one year is illustrated in Figure 4. It is clear from Figure 4 that the daily energy consumption stays roughly the same during the whole year, as domestic hot water consumption is quite stable throughout the year. As it is expected, energy production is at peak in midsummer, but varies significantly from the day by day.

Results were calculated using data measured from 5 kWp solar power plant at Lappeenranta University of Technology during time period from 1.6.2014 to 30.9.2014. The installation used is fixed to 15 degrees and is faced towards south. Total energy production during this period was 2 155 kWh [10]. Energy consumption was simulated for the same period, assuming a typical four-person household. Domestic hot water is heated with 3 kW boiler with 300 litre capacity that is sufficient for one day usage. Daily energy requirement for the boiler is assumed to be 11 kWh. Turn-on threshold for the load was set to 300 Wh. In the calculations, thermostat control is assumed to happen mainly when the hot water usage is at its peak; during morning and evening. Time relay is set to hours around noon, when the solar energy production is typically at its maximum.



(a) (b)

Figure 4. Example of daily energy during one year. (a) Measured energy consumption without heating plus simulated heating energy. (b) Simulated energy production.

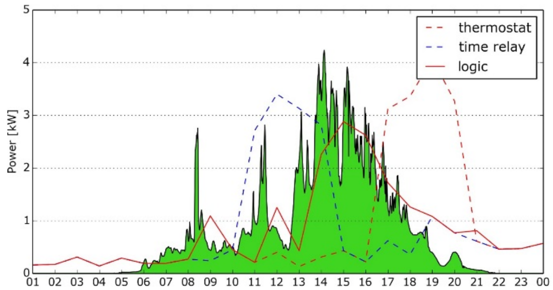
Table 1. Energy transfer between grid and household for different control methods.

Month	**Thermostat control**		**Time relay**		**Logic control**	
	Grid energy [kWh]	Sold energy [kWh]	Grid energy [kWh]	Sold energy [kWh]	Grid energy [kWh]	Sold energy [kWh]
June	375	382	247	255	186	193
July	445	446	272	272	214	216
August	261	520	150	407	84	342
September	199	598	79	477	43	442
Total	1 280	1 946	750	1 411	527	1 193
	100%	100%	59%	72%	41%	61%

Results clearly indicate that even time relay reduces significantly the energy transfer between the grid and the household. The best results are achieved by the logic control with the total energy transfer between the grid and the household reduced to almost half compared to the thermostat control. Example of one day in July is shown in Figure 5. In the example, the day production is mostly during afternoon, with production being 17.8 kWh in total [10]. The production during afternoon causes problems for time relay control. Logic control behaves as expected, minimizing the energy transfer to and from the grid. Compared the logic control with the thermostat control in Figure 5, the grid energy is reduced from 14.1 kWh to 4.3 kWh and the sold energy from 11.9 kWh to 2.1 kWh. In total, the energy transfer is reduced to one quarter compared to the thermostat control.

5 CONCLUSION

With the use of quite basic logic and cheap, off-the-shelf components it is possible to reduce energy transfer between the grid and the household that is equipped with solar panels by controlling the largest single electrical power consumer. The system could also be expanded to other energy storages and heating solutions, such as heat pumps. However, these devices normally require more advanced control than simple relays, as they include internal logic for different functionalities, such as keeping the system from gathering ice to heat exchangers. Many of these devices do not include external communication interfaces to allow adjustments and it is therefore quite hard to implement the control. To overcome these limitations, actions are required from device manufacturers.



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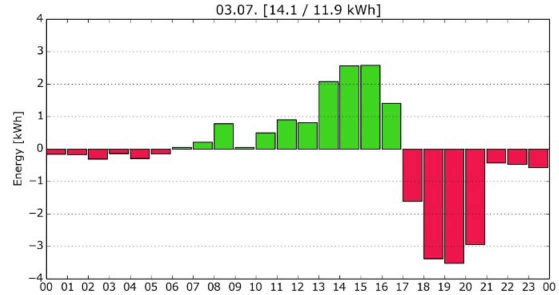

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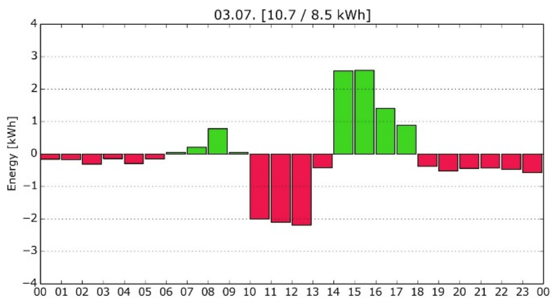
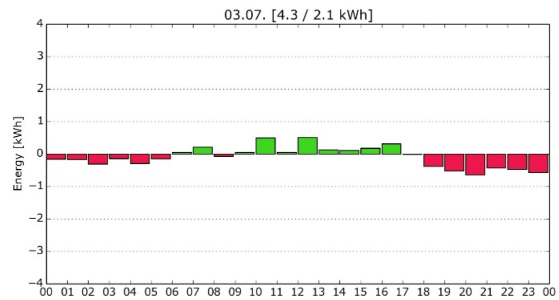


(c)



(d)

Figure 5. Comparison of different control methods on July 3, 2014. (a) Production and consumption. (b) Energy balance with thermostat control. (c) Energy balance with time relay. (d) Energy balance with logic control.

6 REFERENCES

[1] REN 21, "Renewables 2014 global status report," *Renewable Energy Policy Network for the 21st Century*, 2014, Available at http://www.ren21.net/Portals/0/documents/e-paper/GSR2014/index.html, Accessed on February 2015.

[2] C. Breyer, D. Bogdanov, K. Komoto, T. Ehara, J. Song, and N. Enebish, "North-East Asian super grid: Renewable energy mix and economics," in *Proc. 6th World Conf. on Photovoltaic Energy Conversion*, Kyoto, Japan, November 2014, pp. 1–40.

[3] Fraunhofer-Institute for Solar Energy Systems, "Current and future cost of photovoltaics – Long-term scenarios for market development, system prices and LCOE of utility-scale PV systems," *Agora Energiewende*, February 2015

[4] A. Kosonen, J. Ahola, C. Breyer, and A. Albó, "Large scale solar power plant in nordic conditions," in *Proc. 16th European Conf. on Power Electronics and Applications*, Lappeenranta, Finland, August 2014, pp. 1–10.

[5] *Homer Energy Software*, Available at http://homerenergy.com/software.html, Accessed on February 2015.

[6] RS Components, "Raspberry Pi Model B+ datasheet," August 2014, Available at http://docs-europe.electrocomponents.com/webdocs/1310/0900766b813109e6.pdf., Accessed on February 2015.

[7] G. Coley and D.R.P.J, "BeagleBone Black System Reference Manual," May 2014, Available at http://docs-europe.electrocomponents.com/webdocs/1310/0900766b813109e6.pdf, Accessed on February 2015.

[8] Siemens Industry Inc., "SENTRON PAC4200," 2010, Available at http://www.downloads.siemens.com/download-center/Download.aspx?pos=download&fct=getasset&id1=BTLV_35965, Accessed on February 2015.

[9] Adato Energia Oy, "Kotitalouksien sähkönkäyttö 2011," February 2013, Available at http://www.motiva.fi/files/8300/Kotitalouksien_sahkonkaytto_2011_Tutkimusraportti.pdf, Accessed on February 2015.

[10] Lappeenranta University of Technology, "Green Campus – Production Figures," February 2015, Available at http://www.lut.fi/solar, Accessed on February 2015.