ENERGETIC PERFORMANCE AND ECONOMIC FEASIBILITY OF ONSITE GENERATION TECHNOLOGIES IN A NEARLY ZERO ENERGY BUILDING

Benjamin Manrique Delgado[1], Sunliang Cao[1], Ala Hasan[2], Kai Sirén[1]
[1]Aalto University, Espoo, Finland
[2]VTT Technical Research Centre, Espoo, Finland

ABSTRACT

By the end of 2020, all new buildings must be nearly zero energy as instructed by the European Commission. In southern Finland, a demonstration project building tries to reach the zero energy level by minimizing energy demand and integrating photovoltaic panels, solar thermal collectors, and a ground source heat pump. An analysis of measured data has been conducted. The net energy consumption per unit area was 15 and 21 kWh/m^2 in 2014 and 2015, respectively. With said measured data and a simulation model of the building, several installed capacities of photovoltaic panels and an alternative wind generation system are simulated. An economic analysis is conducted for the proposed systems, based on simple payback period, internal rate of return, and levelized cost of electricity. The results provide three lessons: i)energy self-consumption makes the investments more attractive, ii)the notion of economies of scale (cost benefits through larger output) should be taken with caution in residential generation systems, and iii)neither the commercially available photovoltaics nor the wind turbine residential systems are attractive investments under the current conditions in Finland.

INTRODUCTION

Through the Energy Performance of Buildings Directive, the European Commission has established that all new buildings must be nearly zero energy from the beginning of 2021. In Finland, a country characterized by low temperatures and long winters, reaching such goal requires minimizing the energy demand through strict technical regulations and instructions, as well as maximizing the generation from renewable energy systems. This approach has been followed with Villa ISOVER, a demonstration project to study the energy performance of a single-family zero energy building in Hyvinkää, in southern Finland. The building can be seen in Figure 1. It is equipped with photovoltaic panels, solar thermal collectors, and a ground source heat pump. As well, the electricity and heat generation and demand are monitored and recorded along with other conditions, such as the interactions with the electric grid and domestic hot water (DHW) consumption. The building had a net energy consumption, i.e. imported

Figure 1 – Villa ISOVER [Energiatehokas Koti,2015]

minus exported electricity, of 15 and 21 kWh/m^2 in 2014 and 2015, respectively, thus not reaching a net zero energy balance. This raises a first question: what installed capacity of photovoltaic panels would allow to reach the net zero energy balance?

Moreover, the generation profile from the photovoltaic system is notably seasonally unbalanced. Figure 1 shows the electrical generation, import, and demand in the building in 2015. It is seen that from May to September, the majority of the generation represented an energy surplus, and had to be exported to the grid. This has significant disadvantages, such as low self-consumption, poor matching between generation and demand, and potentially overcharging the grid. An alternative system has been proposed for electricity generation, namely a residential-scale wind turbine. Therefore, besides PV, this paper also investigates how a residential-scale wind turbine would perform in southern Finland.

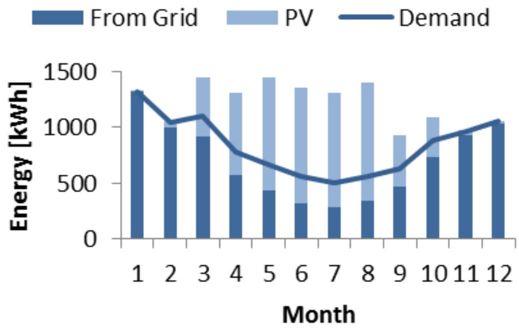

Figure 2 – Monthly electricity generation, import, and demand in 2015

Finally, but of the utmost importance, is to reach cost-optimal energy performance requirements (European Commission, 2012). That is, the measures taken to improve the energy balance of the building should also be beneficial from an economical point of view. Thus the discounted payback period, the internal rate of return of the investment, and the levelized cost of electricity are calculated as indicators of the economic feasibility of the systems. The simple payback period (SPP), while having limitations (Tuominen et al. 2015, Perez et al. 2004), offers a quick and straightforward suggestion of the viability of the investment (Short et al. 1995), as it shows the amount of time it would take for the net cash flow to cover the investment costs. The internal rate of return (IRR) is the discount rate at which the net present value of the investment is equal to zero; a high IRR is an incentive to invest (OECD, 2007). The levelized cost of electricity (LCOE) gives the cost at NPV of the energy generated throughout the lifetime of the system (Short et al. 1995). Moreover, the improved LCOE methodology developed by Hirvonen et al. can be used for showing the effective cost at NPV of the utilized PV generation throughout the lifetime of the system by taking the matching and the dynamic electricity market price into account.

METHODOLOGY

To address the aforementioned research topics, a simulation model has been created based on the existing building, its geometrical and non-geometrical characteristics, and its recorded energy demand. Next, a second model simulates the energy generation and exchange with the grid. Finally, the economic indicators are calculated in Excel®.

Four installed capacities for the PV system and one for the WT system are investigated. For PV, the STC (standard test condition) system capacities are as follows:

- 1.6 kW: the smallest system capacity in the PV product catalogue of the supplier of the existing system.
- 4.5 kW: system capacity closest to the capacity of the investigated WT, offered in the PV product catalogue of the supplier.
- 9.4 kW: system capacity installed in the existing building.
- the PV system capacity that leads to a net zero-energy balance.

For WT, a capacity of 4 kW is investigated, which corresponds to one residential-scale turbine. Please note that the systems are mutually exclusive: only one is considered to be present in each simulation.

Villa ISOVER features and energy demand

The building fulfils and exceeds the D3 Standard in the National Building Code of Finland (Finnish Ministry of the Environment, 2013). Furthermore, it includes 80 m^2 of photovoltaic panels, 6 m^2 of flat-plate solar collectors, and a ground-source heat pump with a nominal rated output of 6.3 kW and COP of 4.61 (NIBE, 2016). The building exchanges energy with the electrical grid, but it is not connected to a district heating grid. The net heated area comprises 175 m^2, and it is inhabited by a typical Finnish family with two adults and two children.

Two years of energy demand, exchange and generation measured data at a 1-hour time resolution are available. Table 1 shows some key annual sums for electricity demand and generation. It also includes the net electricity consumption, which is the difference between imported and exported electricity. The increase in net energy consumption between 2014 and 2015 is mainly due to an increase in the demand from heating systems, and by a decrease in generation from the photovoltaic system. The percentage of energy self-consumption from the PV system in 2014 and 2015 are 22% and 27%, respectively.

Table 1 – Annual sums for measured electricity demand and generation, in kWh

Concept	**2014**	**2015**
Demand from Appliances & Lighting	5118	5421
Demand from Heating System (incl. GSHP)	4129	4630
Generation from PV system	6611	6342
Exported Electrical Energy	5148	4625
Net Electricity Consumption	2636	3710

Generation systems

The photovoltaic panels in the simulation model are based on the ones installed in the real building. They are CIS thin-film modules PowerMax® STRONG, with a nominal power of 130 W under standard test conditions (AVANCIS, 2013).The wind generator is based on the model Tuule E200 grid-connected electricity generator, with a nominal power of 4 kW at 10 m/s (Finnwind Oy, 2015). This product is commercially available in Finland.

Simulation

A building model has been created in TRNSYS 17. A tri-dimensional representation in TRNSYS3d was used to input the geometry of the multi-zone building, and the properties of materials and windows required for the energy demand calculation were input via TRNBuild, as well as other non-geometrical information. A simulation for 25 years was conducted in order to obtain an hourly profile for the total electricity demand in the building, which includes the demands for appliances, lighting and ventilation, and the demand from the ground source heat pump.

For electricity demand of appliances and lighting, the measured consumption profile for the years 2014 and 2015 is used repeatedly. The internal heat gains from the inhabitants are based on the D3 Standard (Finnish Ministry of the Environment, 2013). For DHW, a demand profile has been created based on measured data in 2015 from the existing building.

The years 2015 and 2014 were the warmest and third warmest years on record in Finland (Finnish Meteorological Institute, 2015 and 2016), respectively, and thus using the measured data from these two years may misrepresent the weather conditions in the country. Therefore, the energy reference year TRY12 weather data for the Helsinki region has been used as input for the 25-year simulation. It is designed to be a representation of the typical weather in the region, and thus it is appropriate for use in mid- to long-term simulations (Kalamees et al., 2012). Figure 3 shows monthly averages for wind speed and global radiation on the horizontal in TRY12. A clear seasonal behaviour can be seen in the solar radiation, with higher values during the warmer months. In the other hand, the wind speed has slightly higher values during the colder months.

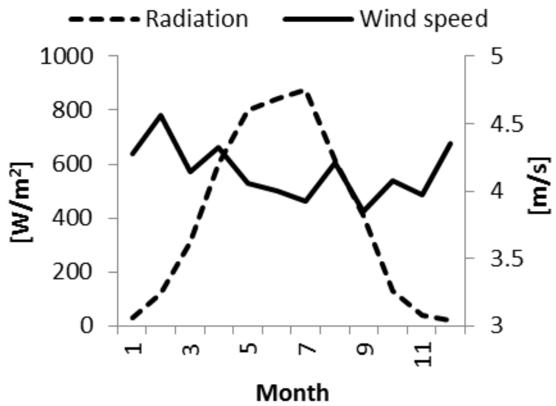

Figure 3 – The monthly averages for global radiation on the horizontal and wind speed in TRY12 (based on Kalamees et al., 2012)

A second model has been created for the simulation of the electrical output from the generation systems, and the resulting energy exchange with the electricity distribution grid. The thin-film modules have been modelled by means of Type94b, whereas the wind turbine has been modelled with Type90.

Economic indicators

To calculate the SPP, it is necessary to divide the investment with the annual net income. Thus, it requires calculating the benefits and expenses for each time period of the system lifetime. In this case, the benefits include the savings derived from electricity self-consumptions, and the monetary income from exporting electricity to the grid. The expenses include operation and maintenance costs, as well as a replacement of the inverter on the 12th year. Since no interest rate is defined for the calculation of SPP, the cost of replacing the inverter is assumed to be half of its current price. This way the cost is not omitted while no interest rate is set. The SPP is calculated as

$$SPP = \frac{I_{gensys} + I_{inverter}/2}{E_{exp}p_{exp} + E_{self}p_{self} - I_{O\&M}} \quad (1)$$

where E represents energy, p represents prices and I represents costs. Please, refer to the nomenclature for a detailed description of the terms used in these equations. The IRR is calculated in an iterative process using the equation

$$\sum_{n=0}^{25} \left(\frac{A_n - I_{gensys,n}}{(1 + IRR)^n} \right) = 0 \quad (2)$$

where A_n is the difference between benefits and expenses in the nth year calculated as

$$A_n = E_{exp,n}p_{exp,n} + E_{self,n}p_{self,n} - I_{O\&M,n} - I_{inverter,n} \quad (3)$$

The LCOE is calculated with Equation 4, based on the equation defined by Hirvonen et al. where e is the price escalation rate of electricity and i is the interest rate. The equation has been modified to include the cost at NPV of the operation and maintenance costs, and inverter replacement in the 12th year of service. The equations for SPP and IRR are based on (Beggs, 2002) and (Short, 1995).

Costs, prices and rates

Generation system

The prices for the generation systems consist of two parts: the system components, and the installation costs. Table 2 shows the prices for the systems under investigation in this research. A tax credit of up to 45% of labour costs for jobs in private homes is available in Finland (Finnish Tax Administration, 2015); it is assumed that this credit is utilized for the installation costs.

$$LCOE = \frac{I_{gensys} + \frac{I_{inverter}}{(1+i)^{12}} + \sum_{n=0}^{25} \frac{I_{O\&M,n} - E_{exp,n}p_{exp,n}(1+e)^n}{(1+i)^n}}{\sum_{n=0}^{25} \frac{E_{self,n}(1+e)^n}{(1+i)^n}} \quad (4)$$

Table 2 – Investment costs of the generation systems

Type	Capacity [kW]	System price [€]	Installation cost[a] [€]	Inverter price [€]
PV	1.6 kW	2870[b]	1550[b]	569[d]
	4.7 kW	7825[b]	2875[b]	1814[e]
	9.4 kW	14910[b]	4700[b]	2464[e]
WT	4.0 kW	15900[c]	1800[c]	1814[e]

a: Installation costs shown here do not include the tax credit.

b: Fortum, 2016. c: Finnwind, 2016. d: Nettiosa, 2013.

e: Aurinkoinsinöörit, 2016.

Operation, maintenance and replacement costs

For the PV system, the operation and maintenance (O&M) costs per year are estimated as 1% of the initial investment cost, as suggested in (Short et al. 1995); for the wind turbine, O&M costs correspond to 1.5% of the initial investment (Wind Measurement International, 2016). For the inverters, a lifespan of 12 years is assumed. The cost of replacing said component is included in the economic indicators as required. The inverter prices are shown in Table 2. The lifespans of the PV and WT are assumed to be 25 years (AVANCIS, 2016; Myers, 2014).

Electricity prices

A profile for hourly electricity prices has been created based on the prices from 2012 to 2015 in Nord Pool, the Nordic electricity market (Nord Pool, 2016). This four years profile is used in a cyclic manner to obtain a profile for 25 years, as proposed by Hirvonen et al. To represent electricity market development an annual price escalation rate of 4% has been set based on the evolution of energy prices in Finland (Statistics Finland, 2016). This price profile is used as follows:

- For exported electricity, the grid operator will pay the market price (Helen, 2016).
- For saved electricity, an electricity tax and a transmission fee are added to the market price. In the first year, they amount to 2.79 and 3.14 c/kWh, respectively (Caruna Espoo Oy, 2016).

A feed-in tariff is available for wind generation systems in Finland but it cannot be applied in this investigation, as a minimum installed capacity of 0.5 MVA is required to obtain this subsidy.

Interest rates

Four real interest rates (combining nominal interest rate and inflation rate) are investigated: 1, 3, 6 and 10 percent, based on (European Commission, 2012). 3% and 6% represent typical macroeconomic and commercial interest rates, respectively, while 1% and 10% help to characterize the sensitivity of the results. For ease of reading, the "real interest rate" is referred to simply as "interest rate" in this document.

RESULTS & DISCUSSION

Net zero energy balance

It can be seen in Table 1 that the installed capacity of 9.4 kW is not sufficient to reach the net zero energy balance in the building. Thus, the size of the PV system must be increased in order to reach that threshold. After an iterative process, the necessary installed capacity has been found to be 12.0 kW.

Under the tested weather conditions, this system provides 10,451 kWh per annum, which is sufficient to cover the electricity demand of the building, including the energy required to operate the ground-source heat pump. Nevertheless, the reader should keep it in mind that only a fraction of this energy is consumed onsite: there is still import and export of energy from/to the grid. The calculated self-consumption for this system size is 13%.

Wind Turbine

The alternative generation system based on wind power generates 6677 kWh per annum, which is approximately the same as the measured generation from the existing PV system in 2014. The calculated self-consumption with this system is 60%, a significantly higher percentage than the self-consumption in the measured data or with the system size required to reach the net zero energy balance.

Economic indicators

To calculate the economic indicators for the PV system with an installed capacity of 12.0 kW, the following assumptions were followed:

- The system price per installed capacity is the same as for the 9.4 kW system. This gives a price of 19115 €.
- The installation cost per installed generation capacity decreases as the system size increases. Based on the installation costs for the other systems, a linear expression for the installation cost per unit of installed energy in €/kW was defined. It yields a total installation cost of 5206 €.
- The inverter price is 3119 € (Aurinkoinsinöörit, 2016).

Simple Payback Period

The SPP obtained for the proposed systems can be seen in Table 3. Under the conditions stated in subsection *Costs, prices and rates*, none of the generation systems under investigation has a simple payback period shorter than the expected lifespan. This means that the NPV of the cash inflows over 25 years derived from self-consumption and export of onsite generation are not enough to cover the investment costs.

Internal Rate of Return

The IRR obtained for the proposed systems can be seen in Table 3. The negative values indicate that these investments would be attractive if the value of the currency would increase over the lifespan of the system. While this is not impossible, as deflation and currency appreciation may happen, a negative IRR is an indication that the investment should not be pursued, as its NPV is negative (OECD, 2007).

Levelized cost of electricity

The calculated LCOE as a function of interest rate for the studied systems can be seen in Figure 4. The lowest value corresponds to the WT system, at 12.88 €cent/kWh with an interest rate of 1%. All values are higher than the average retail price of electricity in 2015.

Table 3 – Simple payback period and internal rate of return for the proposed generation systems

Type	Capacity	SPP [years]	IRR
PV	1.6 kW	69	-2.5%
	4.7 kW	80	-3.5%
	9.4 kW	85	-3.5%
	12.0 kW	88	-3.7%
WT	4.0 kW	58	-0.6%

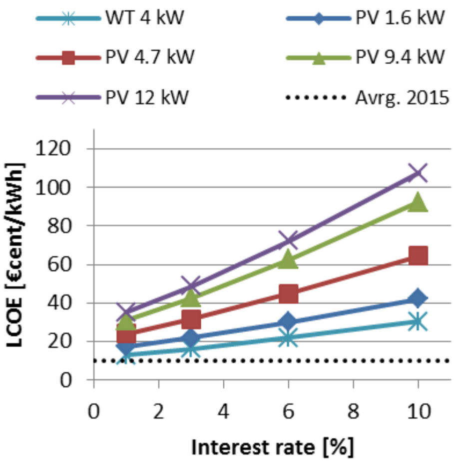

Figure 4 – LCOE as a function of the interest rate. The dotted line shows the average retail price of electricity in 2015

Figure 5 shows the annual energy generation of each system, indicating the proportion of self-consumed and exported energy. It also shows the LCOE calculated for each system with an interest rate of 6%. Some key pieces of information are extracted from this figure. It can be seen that the amount of self-consumed energy only increases marginally as the system size and total generation increase for PV. Also, it is shown that the proportion of self-consumed energy in the total generation decreases as the PV system size increases. For example, the self-consumption for the PV system with 1.5 kW installed capacity is roughly 50% of the total generation, whereas the self-consumption for the PV system with 12.0 kW installed capacity is roughly 15% of the total generation.

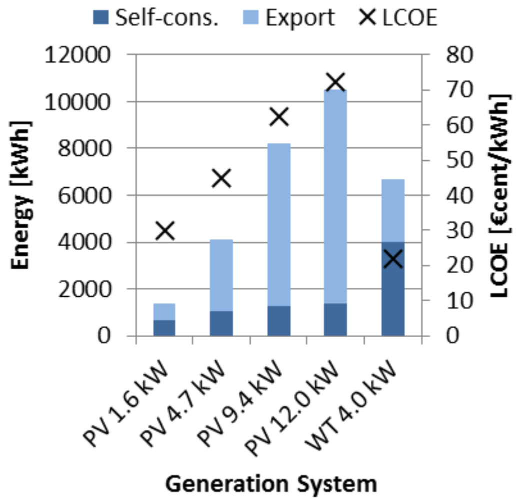

Figure 5 – Annual energy generation and LCOE for the proposed generation systems with an interest rate of 6%. The proportions of self-consumption and export are shown for each system

This has a notable effect in the savings from reducing electricity import from the grid. Figure 6 shows the monetary savings from reduced import from the electrical grid in the first year of operation. The savings per kW of installed capacity from the WT is approximately three times that from the closest competitor. Moreover, for the PV systems the savings seem to increase with exponential decay as the installed capacity increases.

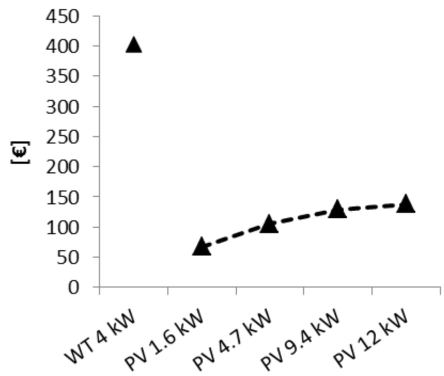

Figure 6 – The savings from reduced electricity import in the first year of operation, in Euro

If we now focus our attention on the LCOE, we can see two important findings. First, that the LCOE is not dependent on the total generation. This is shown by the LCOE of the WT system: if total generation were the defining factor, its LCOE would be somewhere between those of the 4.7 and 9.4 kW PV systems. Second, that the LCOE is correlated to the proportion of self-consumed energy. The reader can see this in the figure by noting that the higher the proportion of self-consumption, the lower the LCOE, regardless of the type of generation system.

The low self-consumption for PV systems is a consequence of two aspects that are intrinsic to the seasonal and daily behaviour of the generation by the PV panels. From the seasonal approach, generation takes place mostly during the summer season, as can be seen in Figure 7, when the heating demand is low. As can be seen in Table 1, the consumption from the heating system accounts for approximately 45% of the total electricity demand, but the heat pump is mostly operated during winter. Moreover, when the solar resource is high, the solar thermal collectors can provide heat to the tank, further reducing the need to operate the heat pump. This mismatch between PV generation and heating demand is detrimental for self-consumption.

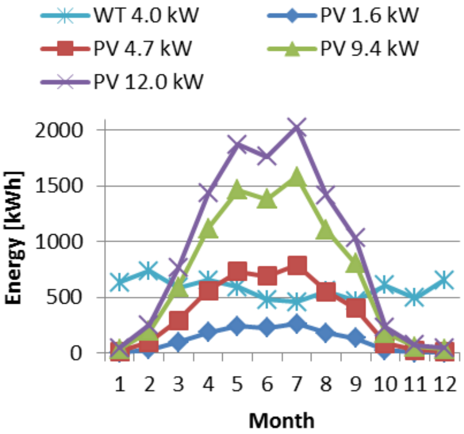

Figure 7 – Monthly energy generation

From the daily approach, one must consider the occupation of a typical residential building: during weekdays, one or both of the parents go to work, while the children attend school. Thus, around noon and early afternoon, when power generation is high, the building occupation and its energy demand for appliances and lighting are low. To exemplify this, the energy generation and demand for a day in winter (top) and a day in summer (bottom) can be seen in Figure 8. During winter, the PV systems barely generate any electricity (thus their curves in Figure 4 are barely visible), whereas the WT can cover a significant part of the demand. Furthermore, most of its generation is consumed onsite, and only a small fraction is exported. In contrast, in the summer day the energy generation by all the proposed systems is significant, but the energy demand is low, particularly during daytime.

The difference between market price and retail price of electricity explains why self-consumption increases the economic attractiveness. By self-consuming the onsite generation, the investor pays less energy at retail price, whereas by exporting it, the investor sells energy at market price. As mentioned in Subsection *Electricity prices*, the retail price of electricity in Finland is composed of the market price, an energy tax, and a transmission cost, so the retail price is always higher than the market price. This means that for the investor, the more the onsite-generated energy is consumed onsite, the larger the cash flow will be.

An option to increase onsite consumption consists on the use of electricity storage systems, such as batteries. By storing energy for later use, batteries could significantly increase self-consumption of the onsite-generated energy. Nevertheless, batteries would represent an increase in initial investment cost, and might need to be replaced before the end of the service life of the generation system. Furthermore, round-trip efficiencies would maim the benefits. Thus, purposeful conclusions could only be reached after a detailed investigation, which lies beyond the framework of this document.

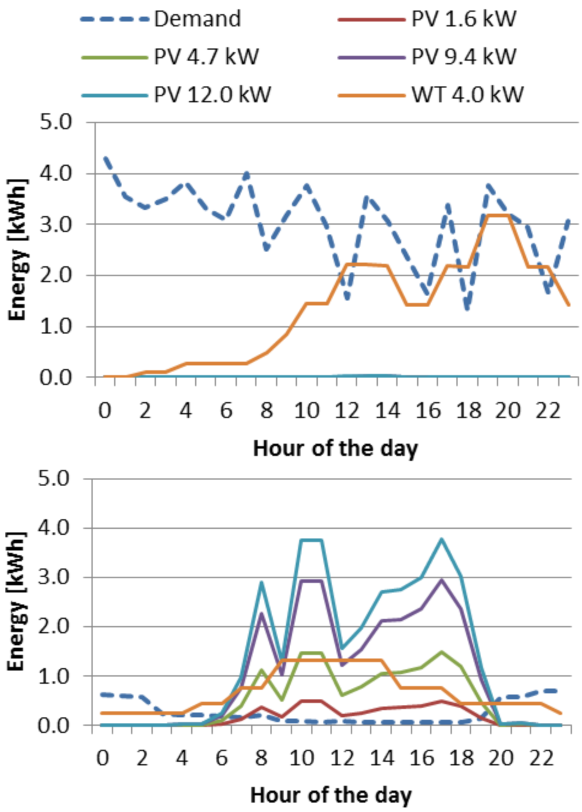

Figure 8 – Energy generation and demand during a winter day (top) and a summer day (bottom)

Another aspect to highlight from the results is that the concept of economies of scale applies to the investment costs of the photovoltaic generation systems, but it does not lead to more attractive investments within the given context. That is, while the cost per unit of installed PV capacity decreases as the system size increases, the economic indicators give better results as the system size decreases.

CONCLUSIONS

The results provide three lessons regarding economic feasibility of residential energy generation systems: i)energy self-consumption makes the investments more attractive, ii)the notion of economies of scale should be taken with caution in residential generation systems, and iii)the commercially available PV and WT residential systems are not attractive investments under the current conditions in Finland. Particularly, the third point could be explained by the low electricity prices in Finland. At least since 2008 Finland has had electricity prices well below the EU average; in 2015, the prices were 25% lower than the average (Eurostat, 2015). Furthermore, a high price escalation rate was used: more conservative (lower) rates would lead to even less financially attractive results. While the authors do not suggest a raise in electricity prices, monetary incentives such as feed-in tariffs could be put in place to make investments in PV or WT systems attractive to single-family houses.

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NOMENCLATURE

CIS	Copper Indium Selenide
COP	Coefficient of performance
DHW	Domestic hot water
E	Energy, in kWh
e	escalation rate
exp	export
GSHP	Ground source heat pump
gensys	Generation system
I	Cost, in €cents
IRR	Internal rate of return
LCOE	Levelised cost of energy, in €cents
MVA	Mega volt-ampere
n	Year n
NCF	Net cash flow, in €cents
NPV	Net present value, in €cents
O&M	Operation and maintenance
p	price, in €cents
PV	Photovoltaic
SPP	Discounted payback period
self	self-consumption
TRY	Test reference year
WT	Wind turbine

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