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Application of low-carbon technologies for cutting household GHG emissions

Aiga Barisa*, Marika Rosa, Ilze Laicane, Reinis Sarmins

Riga Technical University, Institute of Energy Systems and Environment, Azenes iela 12/1, Riga, LV 1048, Latvia

Abstract

This article attempts to evaluate the potential of greenhouse gas emission reduction from power and transportation needs in a household by introducing a solar photovoltaic array and an electric vehicle. The study is based on analysis of data collected from a case study household and a photovoltaic unit located in Latvia. Results show that a small-sized photovoltaic system can ensure around 40 % of daily electricity demand of a four-person household on an average summer day. In addition, introducing additional electric vehicle load is helpful for cutting greenhouse gas emissions related to household mobility. In the best case scenario, CO_2 balance can be improved by 60−90 %.

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Keywords: Electric vehicle; household; photovoltaic; solar

1. Introduction

1.1. Research background

The European Union (EU) has set itself ambitious targets for reducing greenhouse gas (GHG) emissions. In its Roadmap for moving to a competitive low-carbon economy in 2050 (adopted in 2011), the European Commission has suggested that the EU should cut its emissions to 40 % by 2030, 60 % by 2040 and 80 % by 2050 below 1990 levels. The first mid-term target has just been approved by EU leaders [1]. Besides GHG emission reduction, the

* Corresponding author. Tel.: +37167089908; fax: +37167089908
E-mail address: aiga.barisa@rtu.lv

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commitment involves a binding target of increasing energy efficiency and renewables by at least 27 % by 2030. There is no doubt that meeting the goals involves significant transformation of all major sectors responsible for Europe's emissions.

Electricity and transport are among the dominant GHG emitters in the European Union. GHG emissions from transport and energy use made 47.9 % in 2010 [2]. Overall trends show improving energy efficiency in the EU (a 1.2 % annual progress was observed between 2000 and 2010 [3]). However, it is projected [4] that despite the increased energy efficiency, the total demand for electricity will continue to grow in Europe, mainly due to new applications powered by electricity.

Growing electricity consumption can be attributed to a great extent to the changing role of electricity in transport. Electricity as an energy vector for vehicle propulsion is a promising technology pathway for cutting oil use and carbon dioxide (CO_2) emissions. The European Union has acknowledged this potential by placing electric mobility among leading technologies for decarbonizing the European transport sector [5]. The International Energy Agency has estimated [6] that electric vehicle (EV) sales in Europe could reach 2 million and 6.4 million by 2030 and 2050, respectively. Many European countries have already set indicative targets for EVs and plug-in hybrid EVs (PHEVs), e.g., the Netherlands (200,000 EVs by 2020 and 1 million EVs by 2025), Spain (250,000 EVs/PHEVs by 2014), Germany (1 million EVs/PHEVs by 2020), and Norway (50,000 EVs by 2018). Such increase in the numbers of electric vehicles will undoubtedly have an effect on future power demand [7]. At the same time, EVs can provide certain services for the power grid, including load shifting and congestion management [8] and thus allow wider penetration of renewable-based power generation [7].

1.2. Study focus

Sectoral breakdown of energy consumption and GHG emissions in Europe features households a crucial player. The residential sector is responsible for around one third of the total electricity consumption in EU [9]. Further, around 10 % of total GHG emissions and 25 % of emissions from energy use in the EU are relevant to households [10]. Although considerable improvements in energy efficiency have been achieved in home appliances and lightning, electricity consumption in the EU household sector has increased at an average annual rate of 2 % between 1990 and 2009 [9].

Within this context, the concept of a smart household (smart home) has been introduced in literature in the recent decade. The focus of these research studies is to develop strategies for home management systems that help to reduce the energy consumption of a household. Various authors have analysed elements of such systems, e.g. introduction of intelligent control of home appliances (see e.g. [11−12]) and renewable energy sources [13], as well as energy storage systems and power recovery [14]. More recently several smart household studies have paid attention to the complex analysis of system elements based on mathematical models [15−16].

Considering the expected rise in the number of households in Europe [4] and the crucial role of introducing low-carbon technologies both in power and transport sectors, this study combines all three vital elements in one system to address the effort of cutting GHG emissions and meeting EU climate goals. We propose a hypothetic household with a roof-top solar photovoltaic (PV) array and a battery electric vehicle. The proposed system is applied to Latvian conditions with a purpose of estimating the potential of reducing GHG emissions from power and transportation needs of a household. This study can thus be considered one of the first steps in trying to introduce the principles of a smart home under Latvian conditions.

1.3. Regional characteristics

Power consumption in households in Latvia accounts for a significant share of the final electricity demand. In 2012, residential buildings consumed 1.783 GWh, i.e., 27.1 % of the final electricity demand [17] being the second largest consumer after the tertiary sector. Moreover, electricity consumption in households has increased over the past decade. The increase is mainly explained by economic growth. The growing number of appliances utilized in households (e.g. freezers, washing machines, dishwashers, PCs and other small appliances) is mentioned as the major reason for increased electricity consumption [18].

The key legal act creating framework for promoting end-user energy efficiency in Latvia is the 'Energy End-use Efficiency Law' (adopted in 2010). According to the second national energy efficiency action plan (issued on the basis of the law) Latvia has set a target to achieve 2.701 GWh energy savings in the household sector in 2016 compared to 2008. This accounts for 77.5 % of the total final energy savings in Latvia in the corresponding period [19]. However, these savings are mainly attributed to reduced heat consumption due to improved building energy efficiency.

The first attempt to monitor household electricity consumption in Latvia took place in 2013. Within a national level pilot project 500 households were equipped with smart meters providing information on the actual power demand of the household at a five minute interval. The preliminary results show that, on average, electricity consumption has reduced by around 20 % in the pilot project households [18]. These results indicate that smart metering is a promising pathway in contributing to power savings.

Meanwhile the popularity of decentralized electricity generation in Latvian households is small. To date, the Climate Change Financial Instrument in Latvia has been a major national-level measure to increase renewable electricity generation in households. With financial support from the government, projects with total installed electric capacity around 0.6 MW have been developed in Latvia. A step towards wider renewable electricity generation in households was taken by introducing a legal framework for net metering in Latvia on 1 January, 2014. The system allows residential customers who generate their own electricity to feed the excess electricity back into the grid to offset their consumption over a billing period.

2. Methodology

The major goal of the study is to assess the potential of reducing GHG emissions from power and transportation needs of a household. As shown in Figure 1, such reduction is theoretically possible due to changes introduced in the current system:

- Replacement of a conventional fossil-fuelled car with an electric vehicle;
- Installation of a solar PV array with the smart metering option, and;
- Application of smart charging and the vehicle-to-grid (V2G) concept.

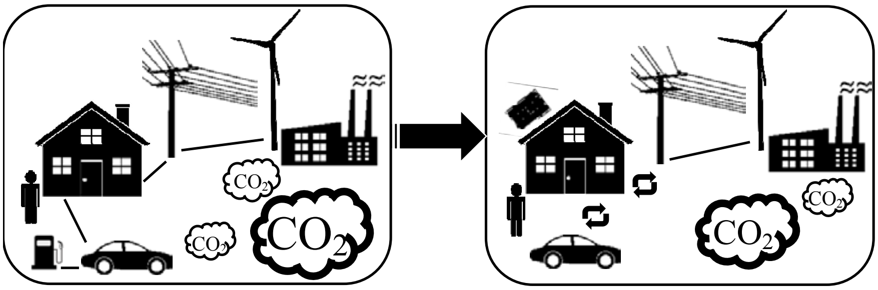

Fig. 1. Conceptual framework of system operation addressed in this study.

In order to address the research question, authors introduce a hypothetic system consisting of three major elements: (i) a household of four residents, (ii) a solar PV system, and (iii) an electric vehicle. The study is based on analysis of data collected from the case study household and a PV unit located in Latvia. Thus, Latvian specific conditions are taken into account as much as possible. The study was limited to power and transport fuel analysis excluding energy demand for heat, since in most private households in Latvia, biomass is already used [17].

2.1. Electricity consumption and generation

A household with an installed smart meter that provides information on the actual electricity consumption was chosen as a representative case study. According to the data collected over a period of one year, the household consumes around 400 kWh of electricity per month. Figure 2 shows hour-by-hour year-average daily power use of the household, as well as the expected solar radiation in Latvia. As can be seen in Fig. 2a, the residential load demand depends on the work time pattern. Overall electricity demand is very high in the evening, low during the night time and average during the daytime. The first increase of the consumption takes place in the morning, around 7.00 a.m. reflecting the time when residents wake up and prepare for their daily activities. Evening peak takes place around 19.00–21.00 when the majority of load comes from lighting, television, preparation of meals, etc.

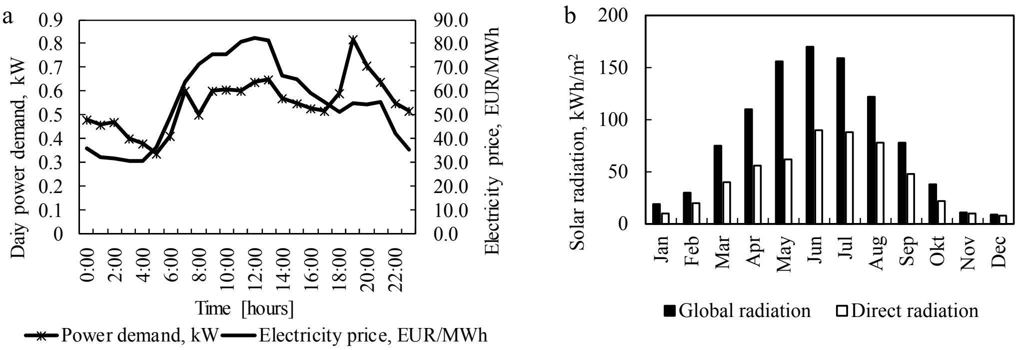

Fig. 2. (a) Year-average daily household electricity consumption; (b) Expected solar radiation in Latvia [20].

Since the particular household is not equipped with a solar PV array, measurement data of a PV system located in Latvia were collected and applied to the case study. A 1.26 kWp PV unit installed parallel to the roof-top was chosen for further study. The particular capacity choice is attributed for two reasons. Firstly, it was an optional limitation related to data availability. And secondly, this capacity was assumed to reflect an appropriate solution for a private household which is usually limited by space requirements. It is assumed that electricity generated by the PV system is firstly used for self-consumption. In the situation whereby excess energy may be created, it is fed into the power grid. Storing excess renewable electricity in the EV, thus providing balancing capacity as suggested in e.g. [21], is not an option in the proposed system since major solar output is during the daytime when the EV is not parked at home.

2.2. Travel behaviour and EV charging patterns

In the third step, an EV is introduced into the system for two purposes. First, it is used to ensure the mobility needs of the household residents. And second, the battery of EV can be used to store and later supply electricity. This is known as the vehicle-to-grid (V2G) principle [22]. To estimate the charging profile of the EV, several assumptions regarding the daily car travel behaviour in the household were done. Since no national level surveys have been performed, authors have referred to European level survey results [23] which suggest that the majority of individuals have two car trips per day. A usual morning peak of car travel is between 07.00 and 08.00 and afternoon peak between 17.00 and 18.00. Following these findings, authors assume similar driving pattern during working days. In comparison, on the weekend fewer working trips occur and people tend to start activities later [23]. The distance of each journey was selected based on the road transport statistics for Latvia. According to the census [17] the average household in Latvia travelled 35 km per day by car in 2010. In order to reflect increasing demand of mobility we assume a 30 % increase in average daily distance travelled up to date. The duration of a trip was calculated on the basis of a range of average speeds where longer distances are completed at a higher average speed as in [24].

It is noted that in this paper, the term EV refers to battery electric vehicles only. Performance characteristics of a typical EV (Nissan Leaf) were used with a range of 160 km, a battery capacity of 24 kWh and energy consumption of 0.16–0.21 kWh/km. A model with on-board 3.3 kW charger is assumed which can be fully recharged from empty in 8 hours. Charging efficiency of 90 % is assumed.

Table 1. List of assumptions

	Value	Dimension
EV's battery capacity	24	kWh
Charge time from empty	8	hours
Daily urban distance	15	km
Daily highway distance	30	km
Energy consumption in city driving	16.2	kWh/100 km
Energy consumption in highway driving	20.5	kWh/100 km

We assume two scenarios of EV charging: uncontrolled scenario and controlled home charging scenario. In both cases EV charging takes place during the parking period at home. There is no workplace or public charging done by the EV owner. In the first case it is assumed that the driver starts home charging immediately upon arrival at home, i.e. from 18.00 p.m. to the next day 02.00 a.m. Meanwhile the second charging alternative assumes that the charging is conducted by selecting the cheapest possible charging period in the available timeframe. In such scenario charging time is delayed to the off-peak night time period from 22.00 p.m. to 06.00 a.m. the next morning. Assuming the daily car usage, charging is performed every second day. In addition, a scenario was introduced by using the existing energy in EV battery after returning home for the clipping of peak hour power demand via V2G mode. Finally, GHG emission savings from solar PV and introduction of EV were calculated based on Latvian specific emission factors.

3. Results and discussion

In Figure 3 household hour-by-hour electricity consumption is presented in relation to solar PV generation and the chosen EV charging strategy. Household electricity consumption with an additional EV load is presented under three scenarios: (i) household consumption with EV and business as usual or uncontrolled charging strategy, (ii) household consumption with EV and controlled charging strategy and (iii) household consumption with EV, controlled charging strategy and V2G. According to the uncontrolled charging strategy, the EV is connected to the power right after return to home, i.e. at 18.00 p.m. Features of the lithium ion battery provide that the major battery capacity is charged during the first four hours thus adding extra demand on the evening peak. Alternatively, the controlled charging strategy postpones the beginning of charging after the evening demand peak and starts at 22.00 p.m. Under this strategy, the EV charging takes place during the night time, when the household electricity demand is the lowest and the price of electricity is the lowest. The third charging strategy follows the time schedule of the controlled charging strategy. The only exception is that the excess energy stored in the battery of EV after two days of driving is used to supply electric power to the household. This happens during the peak hours from 19.00 to 21.00.

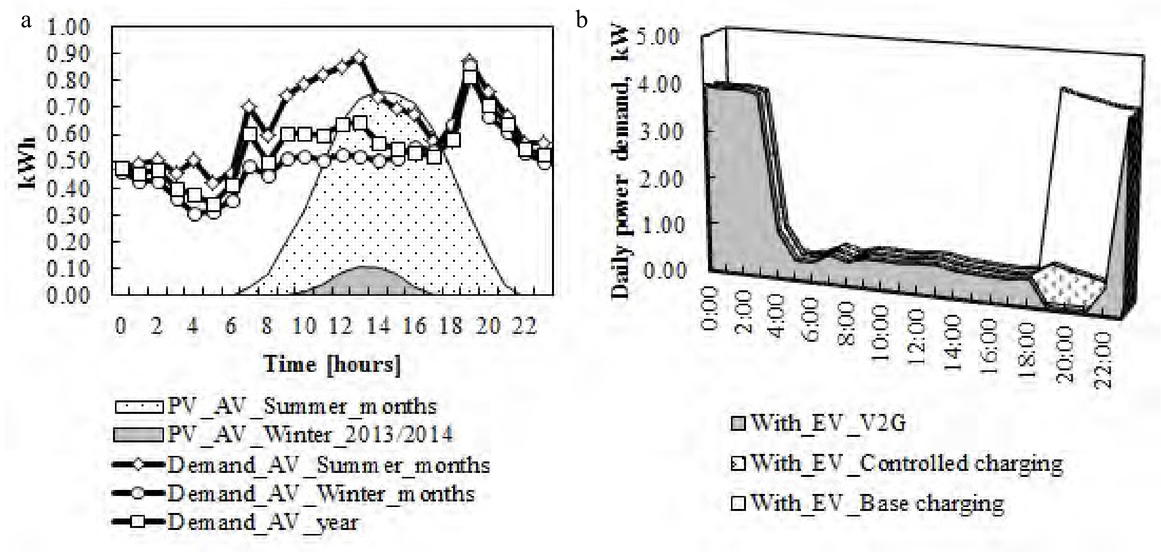

Fig. 3. (a) Household power consumption and PV generation on average summer and winter days; (b) Daily household electricity demand under various EV charging strategies.

Results show that during the summer months, a 1.26 kW PV array can ensure around 40 % of electric energy demand in a household of four persons. During the winter period electric output of the PV array is much lower resulting in 4 % of power demand. Some excess energy exceeding the self-consumption is generated during sunny summer days. Further, the performance of the household under this study is presented in Table 2. Four scenarios are compared with the reference case in terms of household electricity demand and CO_2 emissions. These are: (i) household with installed PV array (HH+PV); (ii) household with electric vehicle (HH+EV); (iii) household with installed PV array and electric vehicle (HH+EV+PV), and (iv) household with installed PV array, electric vehicle and application of V2G. Summer and winter periods are distinguished to represent seasonal extremes specific to Latvia.

Table 2. Household electricity demand and CO_2 emissions under various scenarios (EV – electric vehicle, PV – photovoltaic, V2G – vehicle-to-grid, E – electricity supply, T – transport)

Electricity demand					
	Reference, kWh/day	HH+PV	HH+EV	HH+PV+EV	HH+PV+EV+V2G
Summer day	15.4	−41%	+117%	+76%	+62%
Winter day	12.1	−4%	+109%	+105%	+107%
CO_2 emissions					
	Reference, kg_{CO2}/day	HH+PV	HH+EV	HH+PV+EV	HH+PV+EV+V2G
Summer day	6.1 (E) + 9.7 (T) = 15.8	−41%	−56%	−79%	+87%
Winter day	4.8 (E) + 9.7 (T) = 14.5	−4%	+3%	+1%	−2%

Introduction of an electric vehicle in a household doubles household electricity consumption on the day of charging. Such an increase results in additional 7.2 kg_{CO2} emissions per charging time (assuming Latvian specific electricity emission factor – 0.397 t_{CO2}/MWh). However, the replacement of fossil fuel used for a conventional diesel engine gives a 19.4 kg_{CO2} reduction. Overall environmental pressure is reduced by almost 60 %, if the electric vehicle is used to replace an existing conventional car. A combination of electric vehicle and a solar PV allows reducing overall electricity demand and results in almost 80 % emission savings compared to the reference scenario. Implementation of smart charging by V2G gives additional energy savings of 14 % and emission savings of 8% compared with the scenario with EV and PV but without V2G. These results present the best case scenario which can be achieved on a summer day. On a winter day, in turn, reference electricity consumption in the household is smaller than on a summer day because hot water preparation is transferred from the electric boiler to a pellet boiler. An increase in electricity consumption for EV on winter days compared to summer days is explained by the fact that the mileage of the EV reduces in cold climate, thus there is a necessity to charge it more often. Increased electricity consumption is also the reason why overall CO_2 emissions under various scenarios on winter days does not show a considerable improvement compared to the reference scenario.

4. Conclusions

Reducing GHG emissions is a top priority of European policy. Electricity and transport sectors are among dominant GHG emitters in the European Union. In the meantime, households are responsible for around one third of the total electricity consumption in the EU. To address this problem, authors propose a system consisting of three major elements, including a household of four residents, a solar PV system, and an electric vehicle. The overall target of the study is to estimate the potential of reducing GHG emissions from power and transportation needs of a household.

Results show that a 1.26 kWp PV array installed in Latvia can ensure around 40 % of electric energy demand on a summer day and 4 % of electric energy demand on a winter day of a household with average electricity consumption of 400 kWh per month. Under set conditions, the introduction of an electric vehicle in the system doubles household electricity consumption on the day of charging, thus increasing emissions from power generation. However, the replacement of fossil fuel for mobility needs of a household, gives a positive CO_2 balance allowing to reduce overall household power and transport emissions by 60 %. Additional GHG emission savings can be achieved by introducing a solar PV and by applying the vehicle-to-grid concept.

This study provided first steps in trying to introduce the principles of a smart household under Latvian conditions. The results confirm previous findings that a switch to less-carbon intensive technologies has the potential to lower household climate impact in Latvia [25]. Although Latvia was considered a specific case study, it is suggested that these results can be applied to countries with similar solar radiation as in Latvia. The particular case study is limited to a group of households with an average monthly electricity consumption of 400 kWh. Further studies thus might be dedicated to research of other household groups. Some of the other aspects for further studies include the feasibility analysis of households to introduce low-carbon technologies, and evaluation of the effects of wide penetration of PVs and EVs on the power grid. The potential of smart metering in Latvian conditions should also be further analysed from the perspective of a smart home.

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