Effects of electric vehicles and heat pumps on long-term electricity consumption scenarios for rural areas in the nordic environment

Effects of Electric Vehicles and Heat Pumps on Long-term Electricity Consumption Scenarios for Rural Areas in the Nordic Environment

Juha Haakana, Jouni Haapaniemi, Jukka Lassila, Jarmo Partanen
LUT School of Energy Systems, Lappeenranta University of Technology, P.O. Box 20, FI-53851 Lappeenranta, Finland
Email: juha.haakana@lut.fi

Harri Niska
Research Group of Environmental Informatics
University of Eastern Finland
Kuopio, Finland

Antti Rautiainen
Laboratory of Electrical Energy Engineering
Tampere University of Technology, Finland

***Abstract*—Electrical energy consumption is undergoing major changes driven by several factors. Trends in electric vehicle (EV) purchases and heating system conversion indicate that changes in electricity demand can be significant between today and year 2030. For instance in Finland, the target for EVs is 250 000 passenger cars by 2030. At the same time, a significant number of heat pumps (HPs) will be installed in detached houses replacing old heating systems such as oil-fired boilers. In this paper, the effects of EVs and HPs on electricity consumption in Finnish rural areas are modeled and analyzed.**

***Index Terms*— Electric vehicles, energy consumption, heat pumps, load modelling**

I. Introduction

Electrical energy consumption patterns are changing as electric vehicles (EVs), battery energy storage systems (BESS), heat pump (HP) systems, distributed generation such as photovoltaic (PV) systems, and demand response (DR) facilities are becoming increasingly popular. In addition to changes in consumption patterns, migration from rural to urban areas has an effect on electricity consumption. These changes in customer-side loads may significantly affect the planning and development of electricity distribution networks [1]–[4].

In the electricity distribution business, component lifetimes are typically long, even 50 years, which means that network investments have to be planned well, and long-term planning plays a key role in asset management. However, customer-side loads may change significantly in the next ten years, which creates a risk in asset management.

In Finland, legislation poses an additional challenge for asset management. The Electricity Market Act provides that by 2028 interruptions in electricity distribution may not last for longer than six hours in urban areas and for 36 hours in rural areas. In practice, often this means that the electricity distribution networks have to be weatherproof, which would often require replacement of present overhead lines with underground cables [5]. At present, the networks do not typically meet the requirements, which often calls for investments in weatherproof network technologies. This is a challenge for the network planning and asset management, because long-term network plans for the coming years will be made soon, and the predicted load changes should be analyzed before new network investment plans so that they can be taken into account. Otherwise, if future changes in loads are not taken into account, there is a risk for premature reinforcement investments or excessive investments.

The research is carried out by analyzing customers' hourly load data and databases such as the property data of the Finnish Population Register Centre. The customer data are gathered from the operating areas of four Finnish distribution system operators (DSOs). The case areas are mainly located in rural areas, but they also include small population centers.

The paper focuses on studying the impact of an increasing number of EVs and HPs on electricity consumption in the near future and until the year 2030, with a special emphasis on rural areas. The paper presents some long-term EV and HP scenarios for Nordic rural area distribution networks where the research data is gathered from Finnish networks. Other trends (such as PV and migration of population) affecting the future electricity demand are outside the scope of this paper.

II. Modeling Principles

Modeling of customers' electricity consumption behavior is essential to be able to analyze how changes in the consumption patterns impact the electricity networks. The present consumption of the customers is modeled using customer-group-specific electrical load curves, which are based on a clustering method that uses automatic meter reading (AMR) data collected from the case area from 10 000 customers over a period of several years. The clustering method is described in [6].

In the modeling, outside temperature correction is made for the electricity consumption, in other words, the consumption is normalized to the long-term average temperature so that the effect of changing weather is removed from the data. The correction function for the fixed hourly power P_{fix} is given by

$$P_{fix}(t) = \frac{P(t)}{1+\alpha(T_{avg,day}-T_{avg,month})}, \tag{1}$$

where t is the hour of the year, α is the temperature dependence of the customer, P is the measured hourly electricity consumption within time t, $T_{avg,day}$ is the average temperature of the considered day of the time t, and $T_{avg,month}$ is the long-term average temperature of the month.

In this paper, the electricity consumption scenarios are constructed based on consumption curves that reflect each customer group. The estimated consumption changes are modeled using the present customer group load curves, which are modified by applying the EV and HP models. To be able to model the effects of EVs and HPs, information is required about the households and the patterns in electricity use, such as the temperature dependence of the households' electricity consumption. This enables verification of the heating systems, and thereby, correct modeling of the HPs. For instance, when heat pumps become more common in households, they can either increase or decrease the supplied energy as well as increase or decrease the supplied power depending on the type of the initial heating system.

A. Electrical vehicles

Electric vehicles such as battery electric vehicles or plug-in hybrid electric vehicles can be a significant additional load on an electricity distribution system. Furthermore, the charging method affects the supplied power, not energy, because the supplied energy is almost equal regardless of the charging power. The effects of electric vehicles on the future electricity demand are modeled using the methodology reported in [7] for modeling EV charging loads. The paper presents charging models for 3 kW and 10 kW chargers. In this study, we have applied a 10 kW charger assuming that customers would like to charge their EVs as fast as possible, even at home. An example of EV charging is presented in Fig. 1, which shows a summertime charging curve for a working day. The selected charging scenario weights daytime charging so that nighttime charging is minor.

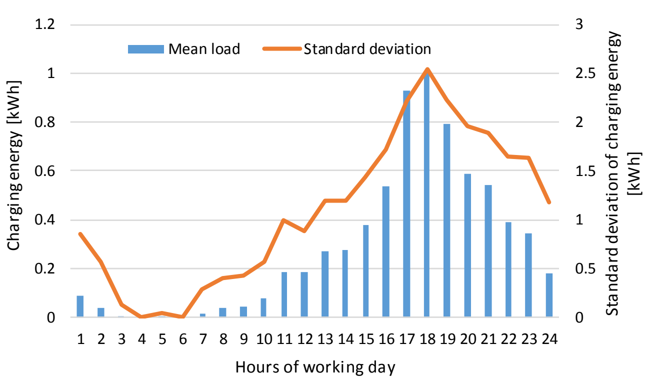

Fig. 1. Electric vehicle charging curve (summertime). The energy capacity of the EV battery is 30 kWh and the charging power is 10 kW [7].

B. Heating systems

Heating system is often the main energy user in a household especially in countries where the heating season in long and cold as in Finland. Another application consuming a considerable amount of energy is the water heating system. These applications can be observed, for instance, in the annual electricity consumption curve of the customers. Fig. 2 presents an electricity consumption example of a household with a direct electric heating system. By comparing the electricity consumption and the outdoor temperature we can see that electricity consumption is higher in the heating season.

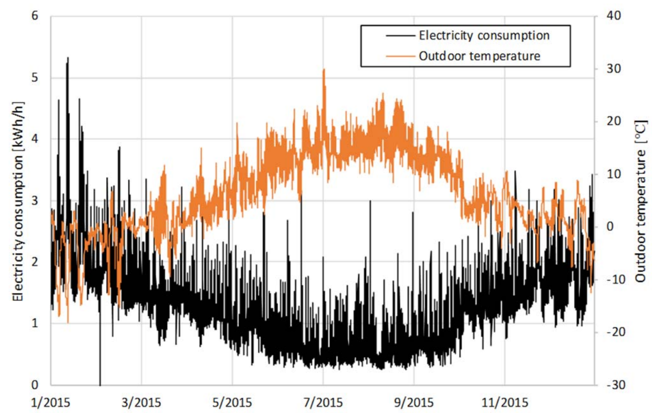

Fig. 2. Example of temperature-dependent electricity consumption in a household.

Fig. 3 presents average annual electricity consumption curves for a few different main heating systems of the detached houses generated from the data of 10 000 customers of the year 2016. Here, the electricity consumption includes only space heating, meaning that other daily household electricity consumption (such as water heating, electric refrigerator, lighting, and TV) is excluded. The presented main heating systems are direct electric heating, a ground source heat pump (GSHP) with full load capacity, and a GSHP with partial load capacity. Full load capacity means that all the heat demand can be supplied using the compressor of the heat pump, and additional heating resistors are not needed. Partial load capacity means that additional heating resistors are used to cover the peak heating demand when the compressor cannot supply the whole demand.

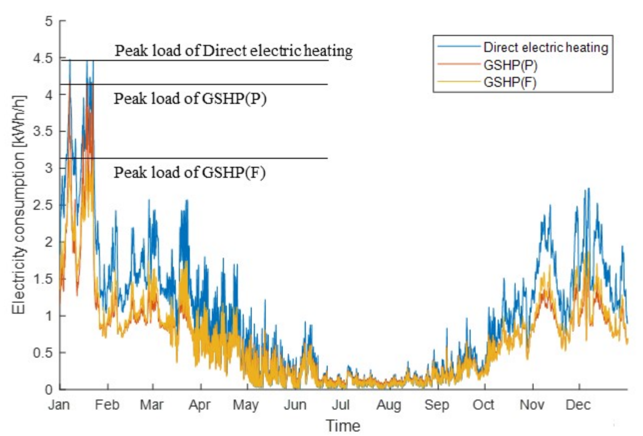

Fig. 3. Annual electricity-based heating loads for households with different main heating systems (direct electric heating, oil heating, full load capacity GSHP, partial load capacity GSHP). The curves are generated from the data of the year 2016 from 10 000 electricity consumption places.

The electricity consumption curves in Fig. 3 are generated based on an analysis of large hourly metered electricity consumption data, which are combined with information of the households' heating system. In Finland, the Population Register Centre is the national agency that maintains a property register, which contains a lot of information of households, including the heating types of the buildings [8]. Fig. 3 shows that direct electric heating has the highest consumption of electrical energy and heating with ground source heat pump (GSHP) with full load capacity the lowest. Comparison of the consumption of partial and full load GSHPs show that the consumption is almost equal throughout the year but the peak loads differ. This occurs because the partial load capacity GSHP cannot supply the whole heat demand meaning that the heating resistors have to be used to cover part of the demand.

Consumption of air source heat pumps (ASHPs) have been modeled using the estimated coefficient of performance (COP) curve [9]. Fig. 4 presents the COP values applied in the modeling.

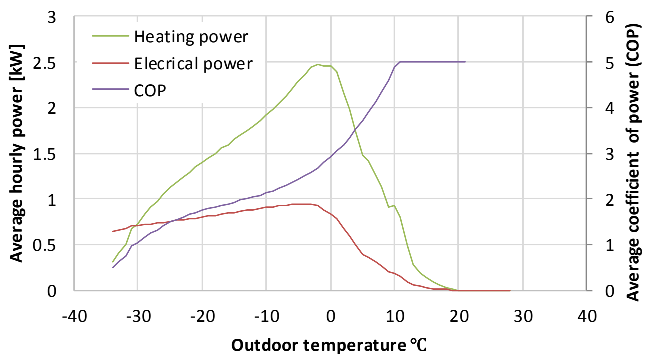

Fig. 4. Estimated heating power, electric power, and COP of ASHP [9].

III. Consumption Scenarios

Electricity consumption scenarios are modeled based on a number of studies concerning for instance the usage of heat pumps in households [10] and the role of electric vehicles in the Finnish transportation. Table 1 and Table 2 present the forecasted changes in the heating systems of Finnish households between 2016 and 2030.

Table 1.
Forecasted changes in the main heating systems of households between 2016 and 2030 in Finland [10].

Heating system	Year 2016 [pcs]	Year 2030 [pcs]	Change 2016-2030 [pcs]	Change 2016-2030 [%]
District heating	62 983	62983	0	0 %
Natural gas heating	22 638	13638	-9 000	-40 %
Direct electric heating	387 255	378255	-9 000	-2 %
Electric storage heating	90 048	45048	-45 000	-50 %
Oil heating	184 985	76985	-108 000	-58 %
Wood heating	235 079	226079	-9 000	-4 %
Ground source heating	120 000	300000	180 000	150 %

It can be seen that heat pumps such as ground source heat pumps and air source heat pumps will become more common in the near future. For instance, the number GSHPs will increase by 180 000, which means an increase from 11% to 27% of the total number of households by the end of 2030. A closer view shows that GSHPs will replace a significant number of oil-fired heating systems and electric storage heating systems. This means that electrical loads will increase in areas where oil heating systems are common, whereas electrical loads will probably decrease in areas with electric storage heating.

Table 2.
Increase in the number of air source heat pumps in households in Finland between 2016 and 2030 [10].

Number of ASHPs in heating systems	Year 2016 [pcs]	Year 2030 [pcs]	Change 2016-2030 [pcs]	Change 2016-2030 [%]
District heating	0	0	0	0 %
Oil heating	35000	40000	5000	14 %
Natural gas heating	5000	10000	5000	100 %
Wood heating	160000	175000	15000	9 %
Direct electric heating	270000	340000	70000	26 %
Electric storage heating	30000	35000	5000	17 %
Sum of air source heat pumps	500000	600000	100000	20 %

The effects of ASHPs on the electricity consumption resemble those of GSHPs. Most of new ASHP installations are found in houses with direct electric heating, where the consumption of electrical energy will probably decrease, but because the COP is relatively low in cold temperatures, the peak load will not change. In houses with oil and wood heating systems, the electrical energy consumption will increase, which will probably be the case also with the corresponding peak load.

The number of electric vehicles will probably increase significantly by 2030. One of the main drivers for this is the political support for alternative power sources in transportation. For instance, the European Union has set ambitious goals to reduce greenhouse gas emissions. The first target [12] was to reduce CO_2 emissions by 20% before 2020, and the current goal [13] is to reduce CO_2 emissions by 40% from the 1990 emission level by 2030. The transportation sector plays a key role in the emissions reductions, and electrification is one of the most efficient technologies to further reduce greenhouse gas emissions [14]–[16]. For instance in Finland, the Ministry of Transport and Communications has set a target to raise the number of EVs including plug-in hybrid electric vehicles (PHEV) to 250 000 passenger cars by 2030 [11]. The goal is ambitious when compared against today's numbers, 1400 battery EVs and 5700 PHEVs [17]. Thus, electrical loads are anticipated to increase considerably within the next 15 years.

IV. Case Areas

Changes in electricity demand are modeled in four case areas, which have been selected to represent different customer types. The case areas are described as follows:

- Case A; most (85%) of the electricity consumer places are leisure homes.

- Case B; the area contains a considerable number of farms (30%) in addition to scattered settlements covering 60% of the households.
- Case C; the distances between electricity consumer places are long, and the population density is relatively low. The proportions of households, leisure homes, and farms are 50%, 30%, and 10%, respectively.
- Case D; the area contains some village centers in addition to scattered settlements. The proportions of households, leisure homes, and farms are 60%, 30%, and 10%, respectively.

Table 3 presents key information of the four case areas based on the statistics of year 2016.

TABLE 3.
KEY INFORMATION OF ELECTRICITY CONSUMPTION IN THE CASE AREAS

	Number of customers	Number of secondary substations	Peak power [MW]	Delivered annual energy [GWh]	Average peak power per customer [kW/cust.]	Average annual energy per customer [MWh/cust.]
Case A	1995	258	4.1	11.2	5.8	5.6
Case B	4026	386	14.6	49.5	8.3	12.3
Case C	1988	391	5.1	16.3	6.7	8.2
Case D	2799	276	11.6	31.6	8.6	11.3

The presented information supports the knowledge of the customer types in the case areas. For instance, the low average electricity consumption in Case A indicates that the area contains customers whose electricity consumption is not steady throughout the year; the phenomenon is typical of an area with a large number of leisure homes. Further, the consumption in Case D is higher on average than in the other case areas, because there are newer buildings in the area (especially in village centers), which implies more electrical devices and more electric heating systems compared with older buildings. The modeled electricity consumption scenarios are based on the %-unit values given in Table 4 for the increase in the application of certain technologies. GSHPs and ASHPs are modeled using information of the existing heating system and the floor area of the customers' buildings. This means, for instance, that GSHPs have been applied to 58% of the buildings with oil heating. Thus, the increase in the number of GSHPs varies between 2–9 %-units in the case areas. The increase (%-unit) in the number of EVs means that 7% of the customers in each case have purchased an EV.

TABLE 4.
INCREASE IN THE APPLICATION OF DIFFERENT TECHNOLOGIES IN THE CASE AREAS.

	Increase in GSHPs [%-unit]	Increase in ASHPs [%-unit]	Increase in EVs [%-unit]
Case A	2	5	7
Case B	9	4	7
Case C	3	6	7
Case D	5	5	7

V. RESULTS

Electricity consumption scenarios for the year 2030 have been generated based on historical consumption data and estimated changes in the load demand. The modeled load changes are EV and heat pump scenarios, which include both ASHPs and GSHPs. The GSHPs have been modeled with two distinct methods. In the first method we have used full load capacity GSHPs and in the second method partial load capacity GSHPs. The present electricity consumption in all case areas is modeled using customer type load curves. The consumption changes are modeled applying the present-state models, which are modified with the load change models for EVs and HPs. Table 5 presents modeled load changes in the case areas in percentages of supplied annual energy and peak power.

TABLE 5.
AVERAGE LOAD CHANGE SCENARIOS IN THE CASE AREAS. APPLIED LOAD CHANGES ARE EVS AND HPS INCLUDING FULL/PARTIAL LOAD CAPACITY GSHPS AND ASHPS.

SCENARIO	**Change in supplied annual energy in case areas [%]**				**Change in peak power in case areas [%]**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
HPs (GSHPs are operating at full load capacity)	-3.1	-2.3	-4.0	-3.3	0.3	-0.6	-1.6	-1.3
HPs (GSHPs are operating at partial load capacity)	-2.9	-2.1	-3.9	-3.1	0.7	0.6	-1.3	-0.3
EVs	3.3	1.6	2.4	1.7	4.4	2.7	3.3	0.6
EVs + HPs (GSHPs are operating at full load capacity)	**0.2**	**-0.7**	**-1.6**	**-1.6**	**5.0**	**2.3**	**1.7**	**-0.7**
EVs + HPs (GSHPs are operating at partial load capacity)	**0.3**	**-0.5**	**-1.5**	**-1.4**	**5.4**	**3.6**	**2.2**	**0.3**

The results show that EVs significantly increase both the delivered electrical energy and power in the case area as a whole. The load change caused by EVs is greater in areas where the initial loads are smaller. The effects of EVs are nearly equal in all the case areas excluding Case D, where the change in peak power remains relatively low. This is a consequence of the electricity consumption pattern, which causes the initial peak load in case D to be on the evening hours between 9–11 p.m., which is not the time of the peak load in the EV charging modeled in this paper. In the other case areas, the initial peak loads occur more or less at the same time with EV charging, meaning higher peak loads.

The effects of HPs on changes in electrical energy and power seem to be more variable. A common trend seems to be that energy decreases in all the cases. On the other hand, the effects of HPs on power can be the opposite; depending on the building stock, there can be a slight increase but also a decrease in power. The peak power can decrease in areas where the present houses are heated with electric storage heating systems, and they are replaced with GSHPs. The results of the two different GSHP scenarios (full/partial load capacity) do not seem to differ considerably from each other, even though the difference in loads (especially peak loads) at the single customer level were significant. This is a consequence of the relatively low proportion (2–9%) of GSHPs in the building stock in the case areas. Thus, the difference in peak loads between the full and partial load capacity GSHP scenarios is between 0.3%-unit and 1.2%-unit.

The sum of the EV and HP scenarios indicates a slight decrease or no change (from -1.6 to +0.3%) in the electrical energy. The change in peak power is more considerable, between -0.7 and +5.4%. In Case D, the total change differs from the other case areas because of the timing of the initial peak load and EV charging.

VI. CONCLUSIONS

In this paper, electricity consumption scenarios have been modeled for case areas located in rural areas in Finland. The scenarios contain a significant number of electric vehicles (EVs) and conversion of heating systems in detached houses, including installation of ground source heat pumps (GSHPs) and air source heat pumps (ASHPs).

The scenarios show that energy consumption is decreasing on average in the case areas, whereas the peak loads are increasing. The total change in energy consumption is between -1.6% and +0.3% in each case, and in peak loads between -0.7% and +5.4%. The results indicate that the difference between partial and full load capacity GSHPs is small when considering load changes in the case areas, because the heat pump installation rate remains relatively low in the cases.

The results of the paper reflect the average load changes at the level of medium-voltage line (10–30 kV) sections or primary substations (110/20 kV) in the case areas. However, when considering changes in the electricity network sections downstream the medium-voltage network, such as at the secondary transformer or low-voltage network level, the changes can be more significant. This means that EVs or HPs may cause significantly higher load changes, for instance, at the secondary transformer level, where the existing load capacity can be exceeded.

The various changes in energy consumption and peak loads pose challenges for the electricity distribution business, because the electricity network is typically dimensioned for a certain power, but the revenue in the business is collected as a function of delivered energy. This tendency intensifies the discussion related to power-based tariffs where the whole or part of the revenue would be collected using a power component.

The load change scenarios presented in this paper do not contain distributed generation, demand response, or migration of population, which all have effects of their own on the total consumption; thus, they should be incorporated into future studies on the topic.

ACKNOWLEDGMENT

The authors would like to thank Dr. Hanna Niemelä for editing the paper.

REFERENCES

[1] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, “Integration of Electric Vehicles in the Electric Power System,” in *Proc.2011 IEEE*, vol. 99, no. 1, pp. 168-183, Jan. 2011.

[2] A. Rautiainen, “Aspects of Electric Vehicles and Demand Response in Electricity Grids,” Doctoral dissertation, Tampere University of Technology, 2015.

[3] A. Mutanen, “Improving Electricity Distribution System State Estimation with AMR-Based Load Profiles,” Doctoral dissertation, Tampere University of Technology, 2018.

[4] M.S. El Nozahy, & M.M.A. Salama, “Technical Impacts of Grid-Connected Photovoltaic Systems on Electrical Networks—A Review,” *Journal of Renewable and Sustainable Energy*. vol. 5. 2013.

[5] J. Lassila, T. Kaipia, J. Haakana, and J. Partanen, “Major blackouts in the development of electricity distribution networks,” in *Proc. 2014 IEEE PES General Meeting Conf. & Exp.*, National Harbor, MD, 2014, pp. 1–5.

[6] S. Viljakainen, 2017, “Power customer classification and load forecasting with electricity consumption data,” *Sähkönkäyttäjien luokittelu ja sähkönkäytön ennustaminen sähkönkulutustietojen avulla*, (in Finnish), Master’s thesis, Lappeenranta University of Technology

[7] A. Rautiainen, S. Repo, P. Järventausta, A. Mutanen, K. Vuorilehto, and K. Jalkanen, “Statistical Charging Load Modeling of PHEVs in Electricity Distribution Networks Using National Travel Survey Data,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1650–1659, Dec. 2012.

[8] Population Register Centre of Finland, http://vrk.fi/en/frontpage

[9] A. Laitinen, M. Ruska, and G. Koreneff, “Impacts of large penetration of heat pumps on the electricity use,” SGEM project report VTT-R-03174-11.

[10] Gaia Consulting, “Effects of heat pumps on electrical loads,” *Lämpöpumppujen vaikutukset sähkötehon tarpeeseen* (in Finnish), Report, 2016.

[11] Ministry of Transport and Communication of Finland, “Plan for a distribution network for alternative transport fuels. Working group proposal,” *Työryhmän ehdotus liikenteen vaihtoehtoisten käyttövoimien jakeluverkon suunnitelmaksi* (in Finnish), 2016.

[12] Directive 2009/29/EC of the European Parliament and of the Council

[13] European Council 2014, European Council 23/24 October 2014 – Conclusions

[14] H. Ma, F. Balthasar, N. Tait, X. Riera-Palou, and A. Harrison, “A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles,” Energy Policy, vol. 44, 2012, Pages 160–173, ISSN 0301–4215

[15] V. Tikka, J. Lassila, J. Haakana, and J. Partanen, “Electric vehicle smart charging aims for CO2 emission reduction?,” in Proc. *2016 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Ljubljana, 2016, pp. 1–6.

[16] European Environment Agency 2016, Electric vehicles in Europe, EEA Report, No 20/2016, ISBN 978-92-9213-804-2

[17] Finnish Transport Safety Agency (Trafi) 2018, Number of cars in Finland 31.12.2017.