EFFECTS OF THE FUTURE TRENDS IN DISTRIBUTION NETWORKS

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ABSTRACT

The main target of this paper is to clarify which way different future trends effect on electricity network. The paper illustrates changes in load rates for instance on the distribution transformer level in different scenarios with electric vehicles and distributed generation. Results help DSOs to create a suitable network development strategy for the future. Results reflect the situation mainly in sparsely populated rural areas and they are based on actual network and hourly measured customer-specific load data of 10 000 customers from several years.

INTRODUCTION

Electricity distribution is facing significant changes in the near future. This is due to distributed generation (DG), electrification of transportation and energy efficiency renovations in households. At the same time, the tightening requirements against major storms increase the pressure to renovate the aging infrastructure in a fast and reliable way. From the supply reliability perspectives, operational conditions for electricity distribution are challenging in the Nordic countries (Figure 1).

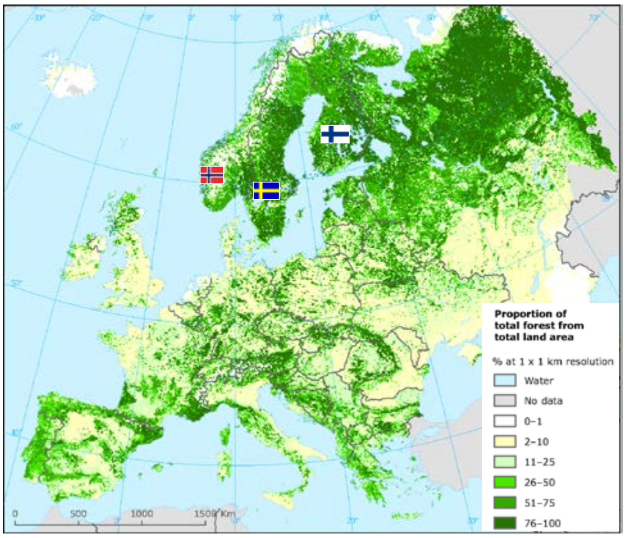

Figure 1. Forest map of Europe. [1]

The question of renovation strategy is even more relevant for distribution system operators (DSOs) operating in the rural areas where the distances are long and load levels relatively low. Customer density varies strongly in European countries as presented in Figure 2. Numbers are average values and in rural areas line lengths are significantly higher.

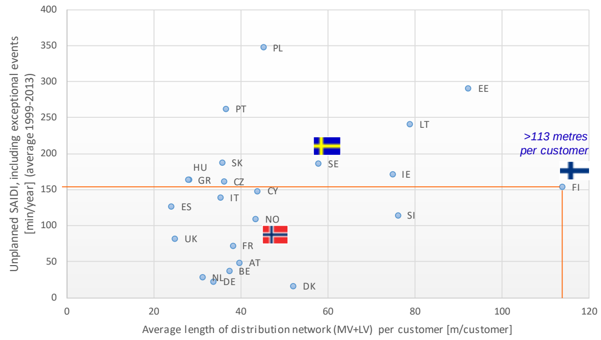

Figure 2. Average line lengths (m/customer) vs. interruption time in European countries. Adapted from [2],[3]

Reliability is not the only reason for network renovations. Globally, electricity distribution infrastructure is old and this is situation especially in rural areas. Typical age profile of distribution network may look like in Figure 3 where the structure (type and location) and installation year of medium voltage (MV) network in a case area is illustrated. Need for renovation strategy and implementation of network investments is tight especially for the companies where the age of infrastructure is high.

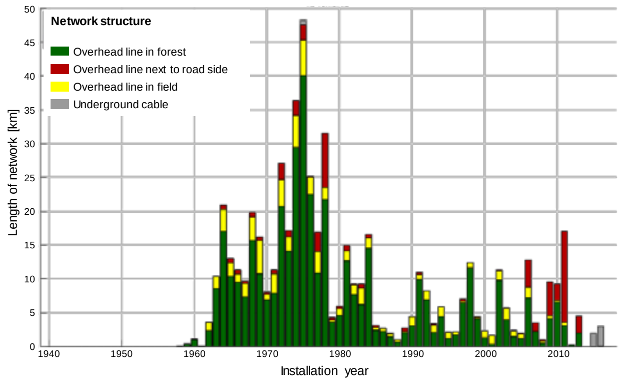

Figure 3. Age distribution of distribution network (MV lines) in a rural case area.

In above described conditions need for well-taught renovation strategy is crucial and urgent. In the network development strategy, DSO is obligated to define long-term targets for instance for the goals of supply reliability, development technologies, dimensioning principles and calculation parameters applied in technical and economic analyses. These guidelines are used in long-term development planning process [4]. To be able to define strategy principles, future trends related to the electricity demand have to be studied. Over or under estimation of load development leads unnecessary high investments and in opposite situation, lack of distribution capacity.

The challenge of uncertainty in dimensioning of networks is highly relevant in rural areas especially because of regressive development of population (Figure 3). In several municipalities migration from rural areas to the population centres has been strong in this century and forecasts for the near future stay similar. This kind of development increases risk of unnecessary renovations in the areas where electricity end-users move away [5]. Load forecasting in regressive population areas has been discussed in more detail in [6].

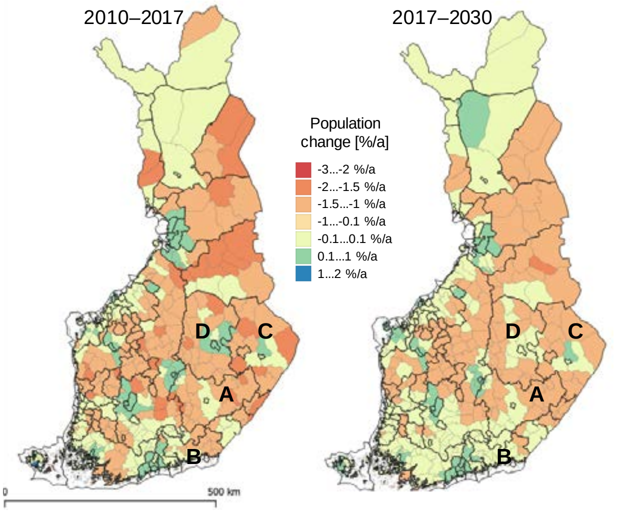

Figure 4. Statistics and forecast of population (%/a) in municipalities in Finland [7]. DSOs, from where the case areas have been chosen, are marked with letters.

In network dimensioning process, it is crucial to define effects of future trends to peak powers (kW). Future trends effect either as growing or decreasing of energy and power. For instance solar photovoltaic (PV) may decrease amount of delivered energy depending on self-consumption possibilities of customer where power plant is installed. Trend of photovoltaic is strongly growing in Finland (Figure 5).

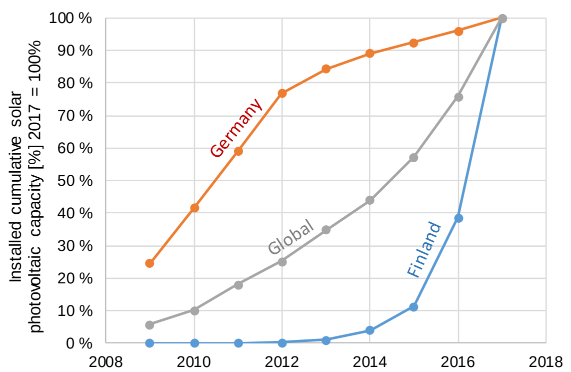

Figure 5. Relative development of PV installations globally, in Germany and in Finland [8],[9]

PV does not effect to peak powers widely in the Nordic environment because of electric heating -type use of electricity has forced to dimension existing networks with relatively high distribution capacity. Traditional dimensioning allows residential end-customers to use in connection point at maximum 17 kW (3x25 A with 400 V) peak power. However, with PV there are no deviations when the area is relatively small (such as district of secondary transformer supplied area).

Electrification of transportation targets reduction of emissions. For electricity distribution business growing trend of plugin hybrids and full electric vehicles (EVs) mean need for large scale analysis of network effects. In short term, EVs are more popular in the population centres where the daily driving distances are relatively short. In long-term, portion of EVs will grow also in rural areas. In Finland, the latest estimations indicate that about 30% of passenger cars would be EVs in 2030. Even the forecast is rather strong (penetration in 2018 only 0.3 %), when keeping in mind long life-times of electricity infrastructure, electrification of transportation has to be taken into account seriously in network planning. The growth of penetration of EVs may effect both an amount of delivered energy and peak powers. From network dimensioning perspective it is essential to be able to analyse charging solutions and possibility and willingness of customers to flexibility actions (demand response) to avoid unwanted peak powers in distribution network. In different scenarios, role of home charging with long-lasting (night time) with relatively low power (< 10 kW) is emphasized. In population centres there will be available fast charging stations for EVs but their location near the primary substations do not form challenge for the rural area electricity distribution.

In Finland, due to cold winter time, electric heating has been significant role as a building heating solution. Especially in the last decade electric and oil heated (with water storage) houses have been renovated with ground heating system. Depending on the original system and dimensioning principles of the heat pump, effect on electricity demand has grown or decreased.

In addition, above mentioned trends, also effects of climate change and global warming were estimated on energy consumption. In overall, it is estimated that climate change will effect on electricity business in the Nordic countries through the change in precipitation, ground freezing and temperatures (mean and peaks) [10]. Effects of these should be separately evaluated in network planning, operation and construction activities. In this study, effect of climate change in the electricity demand was estimated.

PROCESS FOR ESTIMATING FUTURE ELECTRICITY DEMAND

As discussed in previous chapter, there is need for network renovations and for estimation of future electricity demand. Several factors such as distributed generation, electric vehicles, heating system renovations and regressive population in rural areas effect on demand profile. These factors do not always effect on end-customers the same way. Depending for instance on existing building age and heating type (e.g. direct electric heating, electric heating with a storage, oil based heating, etc.) or compass orientation (roof directed to west or south), effect on profile may differ significantly. In Figure 6 main steps of the process for estimating customer-specific changes in electricity demand is illustrated.

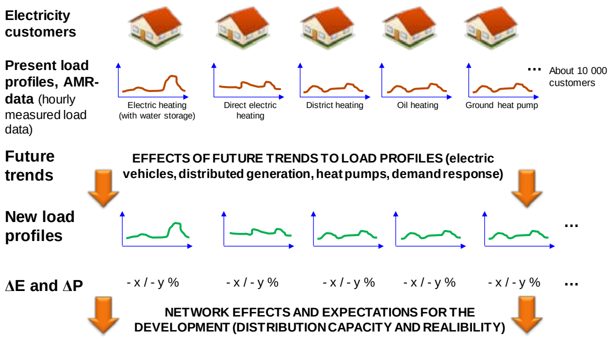

Figure 6. Main steps of the process for estimating customer-specific changes in electricity demand.

In the beginning of the analysis, large amount of load and building data were studied through the DSO measurement databases, public open databases and direct customer interviews. In this phase, target was to understand present electricity demand and load profile and reasons behind that. Study was done for four different case-areas (Table 1) having more than 10 000 electricity end-users with individual load measurements. Case-areas represent rural area with relatively low customer density (agriculture areas, leisure homes, residential houses).

Table 1. Case-area –specific values. LV = low voltage.

Case area	Custo-mers	**Transformers** (20/0.4 kV) [pcs]	[cust/tr]	**Network** [km] MV	LV	LV/MV	**LV** [km/cust]	**Peak load** [MW]	**Annual energy** [GWh]	**Avg. customer peak power** [kW]	**Avg. annual energy** [MWh/cust]
Case A	1 995	258	8	335	548	164%	275	4.1	11.2	5.8	5.6
Case B	4 026	386	10	431	606	141%	151	14.6	49.5	8.3	12.3
Case C	1 988	391	5	562	449	80%	226	5.1	16.3	6.7	8.2
Case D	2 799	276	10	333	470	141%	168	11.6	31.6	8.6	11.3

In the next phase future trends (DG, EV, heating renovations) were allocated to the existing customers with different penetration scenarios; *BAU* (business as usual), *fast* and *slow* scenarios. In two last scenarios forecasts were either quick-growing or slow-growing. Finally, estimations for area-specific changes in the use of electricity were done and new demand were implemented into network analysis. Network models used in analyses are based on actual distribution network information (primary substations, MV lines, secondary substations, LV lines and customer points) with coordinates and electro-technical data. More detailed description of the process in presented in [11] and [12].

RESULTS

Results of the analyses indicate that different future trends as a summary will decrease distribution of electricity in MV and LV networks in rural areas. However, peak powers may slightly increase. Decreasing delivered energy (kWh) is expected result when considering effect of growth of distributed generation (PV) and heat pump installations in customer-end. The main reason for growth of peak powers in the Nordic environment seems to be electrification of transportation (EVs). Eventually, effect on peak load depends on base load, charging type (power) and scheduling of charging (morning/day/evening-time vs. night-time).

Summary of changes in the demand of electricity

Summary of the case-area and trend –specific results for BAU -scenario for the distributed energy (kWh) and peak powers (kW) are presented in Table 2. Penetration rates are shown next to the each trend. Forecast is extended to year 2030. Results for fast -scenario are presented in Table 3.

Table 2. Summary of the results for BAU –scenario, year 2030.

	Case A	**Case B**	**Case C**	**Case D**	**Case A**	**Case B**	**Case C**	**Case D**
Present annual delivered energy and peak power in a case area	12.9 GWh	56.1 GWh	18.2 GWh	36.7 GWh	3.6 MW	14.3 MW	5.0 MW	10.4 MW
Factor (and penetration)	**Change in energy in 2030 [%]**				**Change in power in 2030 [%]**			
PV (8 %)	-4.9	-2.3	-3.5	-2.4	0	0	0	0
Heat pumps (2–9%)	-4.0	-1.8	-3.1	-2.7	-2.4	-0.6	-0.9	-0.8
Electric vehicles (7%)	+2.9	+1.4	+2.1	+1.5	+7.4	+3.4	+5.6	+1.0
Effect as a total	**-6.0**	**-2.7**	**-4.5**	**-3.6**	**+5.5**	**+2.7**	**+4.9**	**+0.2**

Table 3. Summary of the results for fast –scenario, year 2030.

	Case A	**Case B**	**Case C**	**Case D**	**Case A**	**Case B**	**Case C**	**Case D**
Present annual delivered energy and peak power in a case area	12.9 GWh	56.1 GWh	18.2 GWh	36.7 GWh	3.6 MW	14.3 MW	5.0 MW	10.4 MW
Factor (and penetration)	**Change in energy in 2030 [%]**				**Change in power in 2030 [%]**			
PV (35%)	-21.7	-10.0	-15.3	-10.7	0	0	0	0
Heat pumps	-4.7	-2.7	-3.8	-3.8	-2.0	-1.2	-1.3	-2.3
Electric vehicles (30%)	+12.5	+5.9	+8.9	+6.2	+21.6	+10.4	+14.7	+3.8
Effect as a total	**-13.8**	**-6.9**	**-10.2**	**-8.2**	**+21.4**	**+9.2**	**+14.1**	**+1.7**

In all scenarios, climate change (global warming) was included in analyses. For Finland, estimated average speed for warming is 0.4±0.1°C/10 a [9]. When taking into account case-area –specific dependencies between electrical load and outside temperature (heating degree-day), estimations to year 2030 can be done (Table 4).

Table 4. Effect on electricity demand due to global warming.

	Case A	**Case B**	**Case C**	**Case D**
A change in electricity consumption due to global warming (year 2030)	**-0.8 %**	**-0.4 %**	**-0.7 %**	**-0.5 %**

Grid capacity

Previous results reflect changes in overall use of electricity. From the network development perspective, it is important to analyse effects on different voltage levels for instance to be able to select economically feasible cross-sections for conductors. In Figure 7 changes in peak powers are presented in MV level in a case-area in different scenarios. Results indicate, that EVs may increase peak powers in MV network by 30–40% on the average in the quick-growing scenario. Trends of PVs and heat pumps do not effect on peak powers in the case area.

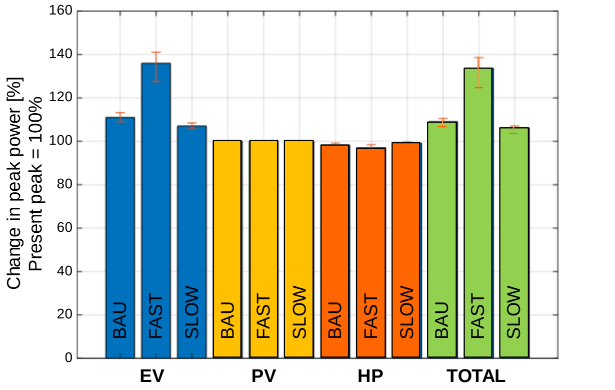

Figure 7. Changes (and variations) in peak powers in MV level in a case-area in different scenarios. Variations illustrate situation with different feeders. EV = electric vehicles, PV = photovoltaic, HP = heat pumps.

Even the forecasted changes in peak powers are rather significant especially due to EVs, in the dimensioning (MV conductors and cables) this does not have to be taken necessarily into account in rural area because existing lines have usually additional capacity for load growth. This is due to fact that long overhead feeders are dimensioned based on short-circuit currents and voltage drops, not based on distribution capacity. If the first two objectives are fulfilled, sufficient capacity has come automatically.

In the secondary substation level interesting questions are, how the future trends effect on transformer peak load and does they have to be taken into account in dimensioning? In addition to this, should there be capacity available for load growth or is it possible that peak load does not grow or may they even decrease for instance due to regressive population in the area. In sparsely populated rural areas, typical transformer (20/0.4 kV) sizes in overhead line networks have been 16, 30, 50 and 100 kVA and average number of customers in low voltage network 5–10 customers per transformer as presented in Table 1. Figure 8 illustrate percentage of secondary substation transformers, which would be overloaded due to EVs. Typically peak loads exist in the Nordic countries on cold seasons when the cooling possibilities for transformers are favorable. It can be seen, that about 25–30% of transformers would be overloaded (S_{max} >100% of S_n).

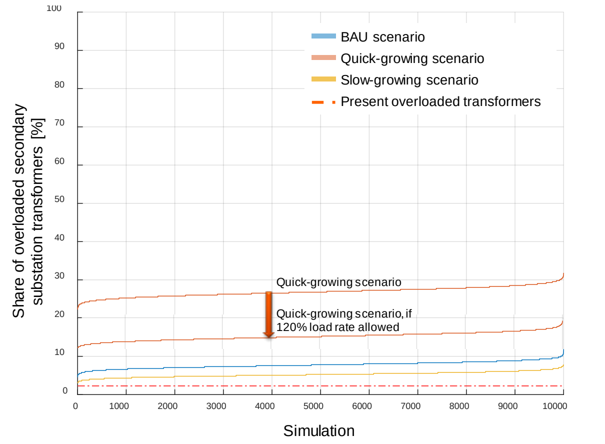

Figure 8. Overloading of transformers due to EVs in secondary substation level in a case-area in different scenarios. The second line in quick-growth scenario illustrates alternative, where 120% (over)loading of transformer is allowed.

In Table 5 summary of effects have been described. Numerical values illustrate situation in a case area.

Table 5. Summary of effects of future trends to different network level.

<table>
<tr><th>Trend
Network level</th><th>Electric vehicles</th><th>Distributed generation</th><th>Heat pumps</th><th>Population</th><th>Distribution tariffs</th></tr>
<tr><td rowspan="2">P (kW)
Customer point
U (V, %)</td><td>Sufficient capacity, if customer consider reasoable size of charger and scheduling of charging event</td><td>Sufficient capacity, if customer consider reasoable size of power plant</td><td>Sufficient capacity, if customer consider reasoable size and type of heat pump</td><td rowspan="4">Significant part of LV-lines (50–65%) supply only one customer. Has to be analysed, if network renovation should be delayed or avoided with these line sections in the situaton, where customer moves away (and distribution network is not needed anymore)</td><td rowspan="2">Power based tariffs create incentive for the customer to avoid of growing peak loads (e.g. optimized charging of EVs and reasonable sizing of PVs)</td></tr>
<tr><td>Voltage rigidity has to be evaluated (minimum short-circuit current)</td><td>Voltage rigidity has to be evaluated (minimum short-circuit current)</td><td rowspan="3">Voltage rigidity has to be evaluated (minimum short-circuit current)</td></tr>
<tr><td>LV-network</td><td>Overlapping of the base load and charging has to be evaluated</td><td>Area -specific penetration scenarios have to be evaluated and peak powers in network</td><td rowspan="2">Long-term effects of new tariff structures has to be evaluated. Possibility to take into account in network capacity dimensioning process.</td></tr>
<tr><td>Distribution transformer</td><td>Overlapping of the base load and charging has to be evaluated. In quick-growing scenario 20–30% of transformers may be overloaded.</td><td>Peak powers during low base load level have to be evaluated.</td></tr>
<tr><td>MV-network</td><td>Overlapping of the base load and charging has to be evaluated. In quick-growing scenario peak powers grow 35% from the present.</td><td>Peak powers during low base load level have to be evaluated.</td><td>No or only minor effects.</td><td>No or only minor effects.</td><td>No or only minor effects.</td></tr>
<tr><td>Primary substation</td><td>Overlapping of the base load and charging has to be evaluated. In quick-growing scenario peak powers grow 20–30% from the present.</td><td>Peak powers during low base load level have to be evaluated.</td><td>No or only minor effects.</td><td>No or only minor effects.</td><td>No or only minor effects.</td></tr>
</table>

In the study, trend and network level –specific analyses were done for all case areas. EVs as a trend seems to be the most essential trend leading to the growth of peak powers. Results indicate that there exist risk of overloading due to growing penetration of EVs.

CONCLUSION

Electricity demand in the future is shaped by the several trends and phenomena. Some of these trends may decrease delivered energy but instead, increase peak powers, or vice versa. This depends for instance on dimensioning of technology (size of PV plant or EV charger) and type of existing house heating system. Future electricity distribution networks are planned and dimensioned based on the best understanding of the future load profiles. This emphasizes importance of scenario working and load profile analyses. Both under and over dimensioning of the network components lead to the additional costs finally paid by the electricity end-users. The challenge of uncertainty exists especially in the areas where network renovations are needed urgently due to supply reliability requirements and/or aging infrastructure. In that case, network dimensioning for the future needs have to be done earlier than in the areas, where existing reliability level is higher and/or pressure of aging is lower. In the second case, there are possibility to delay renovation investments and gives thus time to follow future trends and their effects on load profiles before making investment decisions.

In overall, results indicate lowering demand for electric energy (kWh) without lowering peak powers (kW). This means that requirements for distribution capacity in rural area networks do not get easy. Effects are the strongest in LV networks and in secondary substations (transformers). In MV networks and primary substations (transformers) natural load levelling decrease risk of growth of peak loads (higher peak operating times). In the Nordic countries, existing distribution capacity is relatively high in LV networks due to cold winter times and electric heating systems. In LV networks and in customer-ends, the highest risk is related to the under voltages during overlapping and high-power charging of EVs and to the over voltages with high penetration of PVs during low-loaded seasons. Negative effects of trends do not necessarily oblige to over dimension cross-sections and transformer sizes. Several flexible resources will be available in future networks such as intelligent control of charging, battery energy storages, reactive power management with power electronics and other demand response applications. In addition to this, negative effects may be prevented by power based tariff structures where residential customers have higher incentives to manage his peak powers. However, in the dimensioning analyses, possibility to reform distribution pricing was not taken into account. This is discussed for instance in [13]. In theory, power based bad pricing could encourage customer to avoid growing peak loads from the present situation or even lower them by intelligent control of present electrical loads (load alternation for instance with electric heating and electric sauna or charging of electric vehicle).

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