Analysis of Future Loading Scenarios in a Norwegian LV Network

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Abstract— **This paper identifies the effect of Electric vehicles (EVs) and solar panels/ photovoltaic (PVs) on the distribution grid with and without the use of demand response. A method to generate realistic profiles of EVs and PVs based on statistical data is presented. The paper documents the impacts of EVs and PVs on a selected Norwegian LV distribution network by using up-to-date scenarios of the loads and actual network and household load data. The simulation study reveals that undervoltage problem caused by EV is considerably more likely than overvoltage problem caused by increased PV integration. In another dimension, flexibility resources such as shiftable loads from household appliances showed greater potential to solve overvoltage problems due to PV integration than undervoltage problems due to increased EV integration.**

Keywords—demand response, flexibility, EVs, PVs, power quality, loading

I. INTRODUCTION

We are witnessing multiple developments in the distribution network; the wide integration of distributed generation such as solar PVs (Photovoltaic) and small wind turbines, the ubiquity of smart appliances, the increased integration of Electric Vehicles (EVs) and the growing number of household and/or neighbourhood level battery storage systems. The Norwegian parliament has set a 2025 target where the new passenger and light commercial car market should consist of 100% zero emissions vehicles (ZEVs) [1]. Compared to the total number of vehicles sold, Norway is currently the largest market in the world for EVs. At the end of 2017, there were more than 142.000 EVs in Norway and EVs represent around 5,6% of the total fleet of 2.5 million private vehicles in Norway [2]. The ownership of both EV and Plug-in Hybrid EV (PHEV) is increasing steadily since 2011. On the other hand, in 2017 alone, 18MWp solar energy capacity has been installed in Norway. This one-year installation alone increased the total installed capacity in Norway by 59%. This impressive growth happened while there is still low power prices and weak support mechanism for solar power installations [3]. Other types of changes in the network can be associated with certain types of loads; compact Fluorescent lamps have worse harmonic performance than incandescent lamps and plasma TVs consume much higher active power than the old CRT TVs [4].

There is greater need by Distribution System Operators (DSOs) to understand the potential challenges such as overloading and power quality problems associated with these new generation units and peculiar loads. Conversely, there is also greater interest to use the same generation units, storage elements and smart appliances as flexibility resources to alleviate the foreseeable challenges in the network on different voltage levels. Hence, one must estimate the possible upcoming problems and opportunities with high degree of accuracy to put forward economical and reliable planning measures in place.

There are various studies in the literature dealing with impact analysis of EV and PV integration and their optimal planning and operation in the network [5] [6]. In [7], a multi-objective optimization problem is formulated to obtain objective variables in order to reduce power losses, voltage fluctuations, charging and demand supplying costs, and EV battery cost. A model is developed for optimal operation of flexible transmission technologies for coordinated integration of plug-in EVs and renewables in power transmission networks in [8]. Nevertheless, most of the reviewed literature has developed theoretical models lacking realistic load and network data. Besides, for flexibility resources to be considered as a reliable resource in the network planning activities there is a need for accurate profile generation methods, which is missing in most of the reviewed literature.

In this study, expected scenarios in Norwegian LV network associated with the emerging new types of loads, generation methods and the activation of flexibility resources are simulated and presented. The aim of this analysis is to support the realistic understanding of the potential network loading and power quality related problems and to what extent flexibility resources could reduce or eliminate those challenges. In addition, the study presents EV and PV profile generation method based on realistic statistical and survey data.

Section II explains the test network. The impact of EVs is analysed in Section III and that of PVs in Section IV. Section V demonstrates the benefits of flexibility resources in alleviating increased voltage level issues caused by PVs. The last section 6 concludes the main findings in the project.

II. THE LV TEST NETWORK

A LV test network supplying residential area from 22 kV/ 230V secondary substation in Steinkjer in central Norway is used for the analysis (see Fig. 1). In addition, high time resolution (1 minutes) timeseries measurements of appliances, household level consumption data (hourly) and publicly available statistical data is used for the load flow analysis, for creating uniformly distributed EV charging profiles and for the quantitative estimation of flexibility potentials.

The impacts of PV and EV on power quality in the selected test network has been investigated. More specifically, the voltage level problem is the focus in this study. According to EN50160, voltage magnitude variation in LV and MV system is defined ±10% variation for 95% of week for the mean 10 minutes rms values [9]. The Norwegian regulation is even tighter, where the ±10% limit is calculated based on one-

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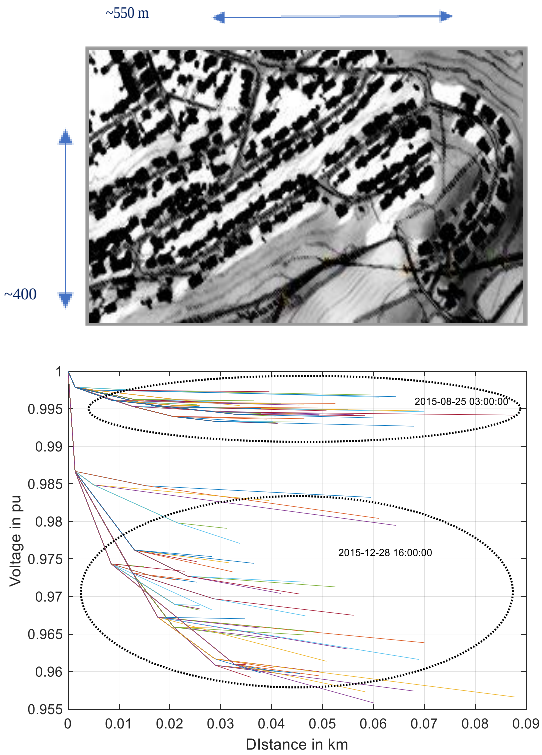

Fig. 1 Approximate map of the residential area (a) and the high and low voltage profiles associated with lowest and highest power consumption of the year for the households in the network (b)

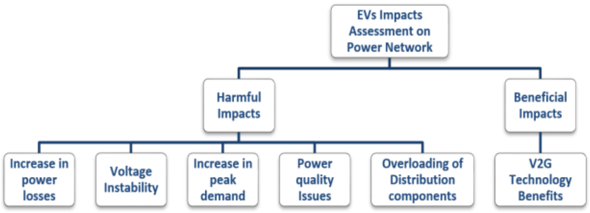

Fig. 2 Classification of EVs impacts on distribution grid *[7]*.

minute average rms values [10]. Hence, this standard is applied to investigate the impact of PV and EV in the selected LV network. Smart meter measurement hourly data pool of one year for about 100 households is used to populate the LV network supplying 53 households. For the base case scenario, one-year-round voltage profile is calculated. The highest and the lowest voltage level hour is selected and plotted in Fig. 1.

III. THE IMPACT OF EVS IN LV NETWORK

The increased integration of electric vehicles in a LV system brings in both opportunities and challenges. Understanding these would enable the economic optimal planning of the network and the increased integration of renewables. Some of the beneficial and harmful impacts of electric vehicles on power networks are summarized in Fig. 2 [11]. In [11], it is evaluated that random charging scenarios with level 2 charging stations and massive penetration can severely impact the distribution components, especially the power cables and power transformers. In the study presented in this paper, the impact of EVs on the Norwegian LV network is simulated using Monte Carlo Simulation (MCS) technique.

A stochastic simulation aims to provide the joint outcome of any set of random variables. Monte-Carlo simulation (MCS) is such stochastic numerical simulation method which can be applied to problems involving random variables. If one have distribution of random variable, Monte Carlo estimation procedure suggests that the average results of enough randomly sampled variables would resemble the true average of the random variables due to the law of large numbers [6] [12].

In this study, a script written in MATLAB is used to generate random events based on the probability of occurrence of the specific events. MATPOWER, power system simulation package, is used to run power flow analysis. Independent variables used for generating synthetic charging profiles of EV are provided in Tables I and II and in Fig. 3. The probabilities for charging durations, in Table I, are calculated based on km/day information attained from Norwegian EV ownership survey conducted in 2017 [13]. In Table II, the EV battery energy and charging power are provided with respect to ownership statistics in Norway. The Norwegian EV ownership survey [13] is used for EV ownership statistics and the EV database [14] is used to estimate the charging power and energy capacity of the EV batteries. The process for synthetic generation of EV charging profiles is illustrated in Fig. 4.

TABLE I PROBABILITIES FOR CHARGING DURATION NEEDS

km/day	Charging duration every day (min)	Percent of EVs in the survey
5	6	0.04
10	12	0.09
20	24	0.16
40	48	0.25
60	72	0.22
100	120	0.18
>100	570	0.07

TABLE II TOP 10 EVS IN NORWAY AS OF JUNE, 2018 AND THEIR APPROXIMATE BATTERY SPECIFICATION

	Ownership number as of June, 2018 [13]	Battery (kWh) [14]	Onboard charger (kW) [14]	Probabilities
Nissan Leaf	41580	40	6.6	0.279
Volkswagen e-Golf	27011	35.8	7.2	0.181
Tesla Model S	17309	75	17	0.116
BMW i3	16627	33.2	11	0.112
Kia Soul	13373	33	6.6	0.090
Volkswagen e-UP!	8071	20	3.7	0.054
Renault ZOE	7749	41	22	0.052
Tesla Model X	8326	100	17	0.056
MercedesBenz (PHEV)	5083	6.2	3.7	0.034
Hyundi IONIQ	3906	30.5	6.6	0.026

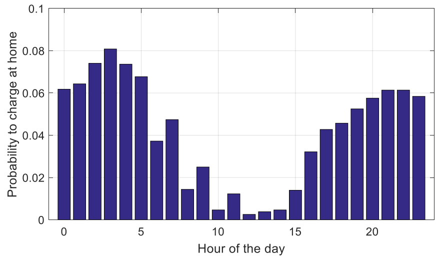

Fig. 3 Probability of time of charging at home

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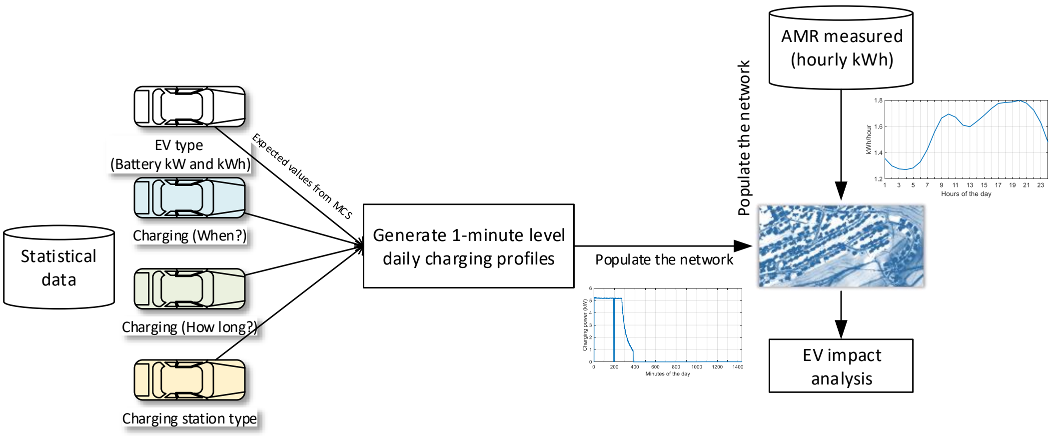

Fig. 4 Analysis method for EV

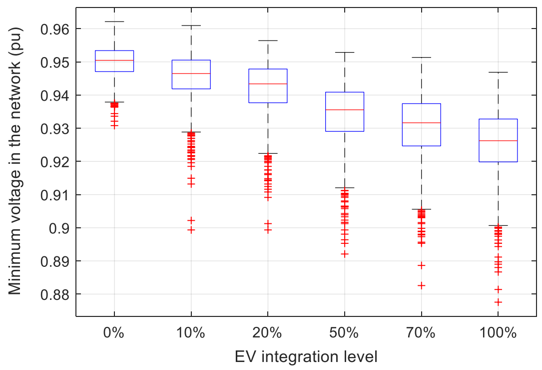

Fig. 5 Minimum voltage level in the network, for different penetration level of EVs

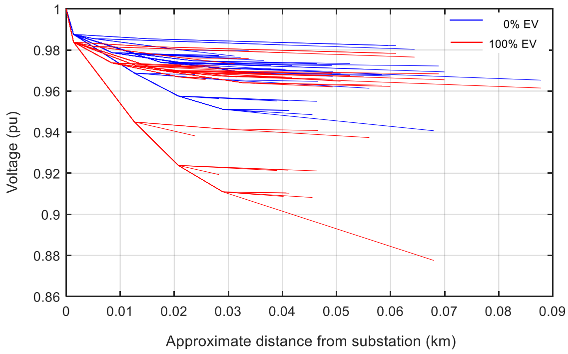

Fig. 6 Worst case scenario from 1000 simulations, at hour 20:00

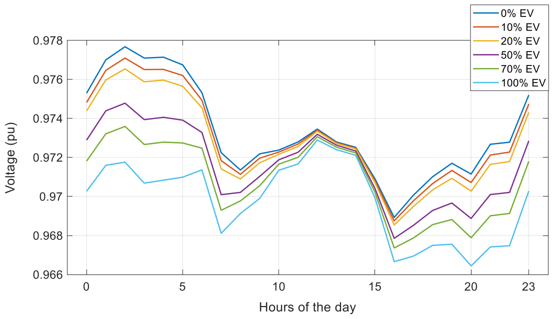

Fig. 7 Average voltage of all nodes for one winter day with different EV levels

For the case of EV impact analysis; EV type ownership, charging time (arrival at home and plugin), charging period (mileage driven) and charging station type are variables with certain probability distribution (see Fig. 4). After developing the probabilities for the aforementioned variables based on statistical data, Monte Carlo simulation is carried out for stochastic analysis of the impacts of the different penetration levels of EVs on the power distribution network. After attaining the EV profiles the simulation randomly selects 53 households out of the 99 households with actual smart metered hourly kWh consumption data to create various cases of EV integration level. The MCS runs with 1000 simulation iterations where all the random variables are randomly selected using uniform distribution and the respective probability distribution.

In the base case scenario, out of the 53 households in the network, it is assumed that none of them possess electric cars. The other case scenarios are associated with 10%, 20%, 50%, 70% and 100% penetration level of EVs. In the simulation, the EVs are replacing existing cars and higher penetration levels (say 20%) are developed on top of existing ownership in the 10% penetration level. The impact on voltage level is presented in Figs 5, 6 and 7.

Fig. 5 illustrates the box plot for 1000 simulations of the different penetration level of EVs. In the boxplot the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles. As one can see in Fig. 5, certain customers may already begin to experience voltage limit violations with only 10% EV integration level.

Based on the current loading scenario in households the worst case presented in Fig. 6 shows clear violation of the LV limit. Fig. 6 is a tree plot illustrating the voltage profiles and their location in the network at specific point of time where the lowest voltage level is experienced. The average winter day voltage profiles for the nodes in the network after 1000 simulations are plotted in Fig. 7. In all the simulations the grid voltage (i.e. voltage level at the secondary substation) is set to be 1 pu. Hence, with lower grid voltage the low voltage limit violations can be encountered earlier as the EV penetration level increases.

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A. *Future Trends and Impact of EVs*

According to smart meter measurement data of about 100 households from 2007 to 2015, the kWh/hour consumption of an average hour of an average household has been increasing by 0.03846 kWh/hour [15]. This is illustrated in Fig. 8 and the measurement data is temperature corrected. Hence, this trend is assumed to increase for the next 10 years and the simulation is repeated after 10 years with 100% penetration rate of EVs. With new energy efficiency measures the estimated load growth rate may be lower or even negative upon which the results of this analysis need to be re-evaluated.

In Fig. 9, the impact of the different integration level of EVs is assessed using the load growth figure mentioned above. According to the result, 100% EV integration level will not be acceptable without additional corrective measures. There are also rare scenarios where voltage limit violations can be encountered even at the level of 20% EV integration.

IV. THE IMPACT OF PVS IN LV NETWORK

In 2017, 18 MWp solar energy capacity has been installed in Norway. This one-year installation alone increased the total installed capacity in Norway by 59% (see Fig. 10). This impressive growth happened while there is still low power prices and weak support mechanism for solar power installations [3]. Hence, in the coming years one can expect exponential growth of solar panel installations in Norway especially in domestic sector which is still in a relatively early phase. The support offered by the Norwegian government to customers planning to install new solar panels is channelled through Enova SF. Enova SF is a Norwegian government enterprise responsible for promotion of environmentally friendly production and consumption of energy. An example subsidy for 3 kWp installation of solar panel is detailed in Table III.

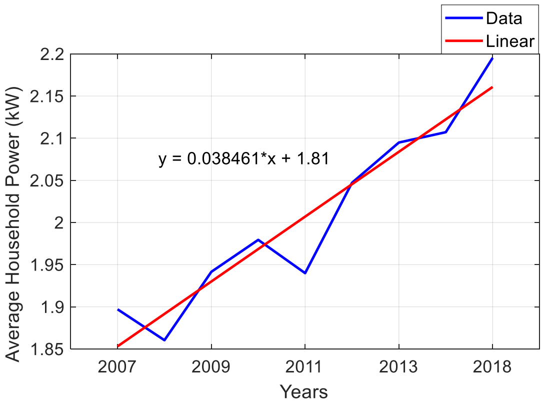

Fig. 8 Trend of average hourly kWh for average household (from approx. 100 households), temperature corrected

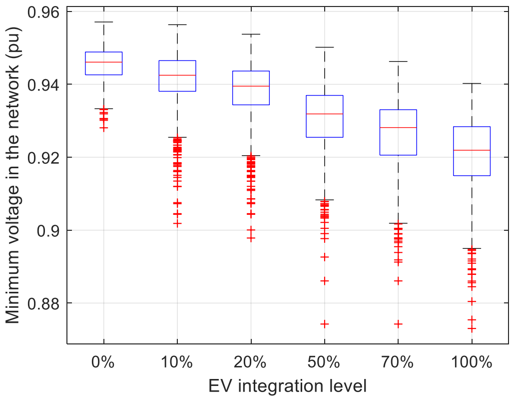

Fig. 9 Impact of EV integration level on the minimum voltage level after 10 years

There are certain technical challenges reported in the literature in association with PV integration in the LV grid. Some of the problems are violation of the thermal rating of grid equipment, violation of the permissible voltage range, interfering with the fault level rating of grid equipment and other issues such as power quality, grid reliability and network protection [16]. In this section, Monte Carlo simulation based probabilistic power flow is presented to study the impact of PV integration level on voltage quality. To estimate the number of panels per roof, Solarkart.no [17] is used and the probabilistic distribution for number of panels are presented in Table IV. Solarkart.no is a solar map of Norway and is based on data from PVGIS, together with roof angles, roof sky orientation and the area of the roof.

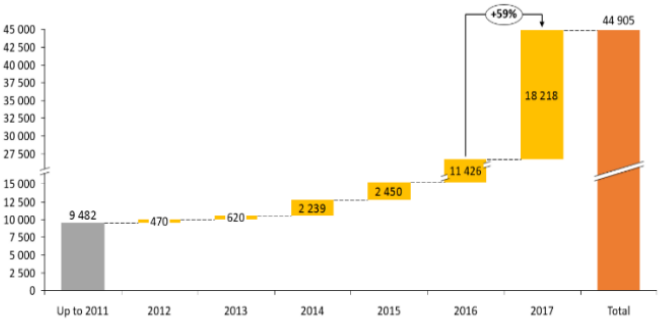

Fig. 10 Development in installed solar panel installations in Norway (2012-2017) *[3]*

TABLE III EXAMPLE OF CALCULATION OF INSTALLATION COSTS FOR SOLAR SYSTEMS AT PRIVATE HOMES [3]

Installation	
Meter square	22
Number of panels	12
Wp per panel (W)	265
WP of construction (W)	3086
Cost per watt including VAT	18.13 NOK
Present values of operating cost	6000 NOK
Costs	
Total installation cost including VAT	61942.28 NOK
Subsidies (Enova and others)	13858 NOK
Net investment cost	48084 NOK

TABLE IV THE PROBABILITY DISTRIBUTION OF NUMBER OF PANELS AND POWER PER PANEL FOR ROOFTOP INSTALLATION

Number of panels	**Proba bility**		**Solar panel type**	**Watt**	**Proba bility**
8	0.1		Premium Black (W)	310	0.4
10	0.1		Premium Black (W)	300	0.3
20	0.1		Standard Blue (W)	275	0.3
22	0.1		*Based on observation on https://solkart.no around the location of the test network		
24	0.1				
30	0.1				
32	0.1				
36	0.1				
40	0.1				
42	0.1				

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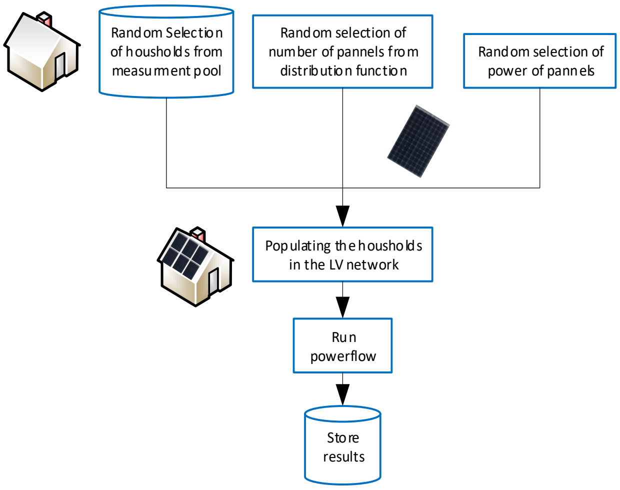

Fig. 11 Analysis method for PV

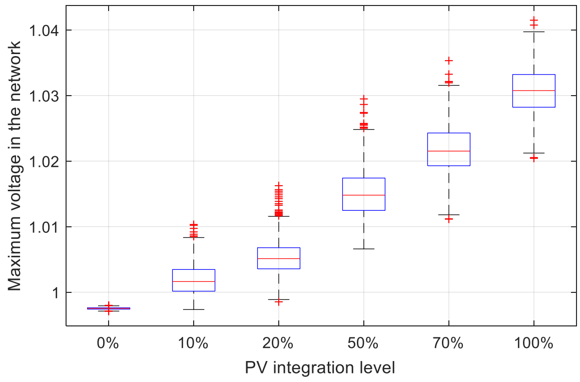

Fig. 12 Maximum voltage level in the network, for different penetration level of PVs

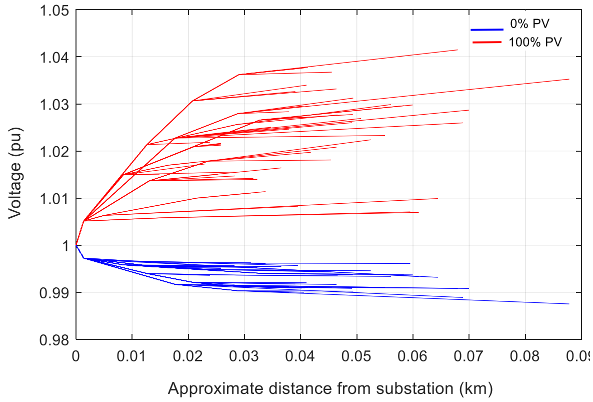

Fig. 13 Worst case scenario from 1000 simulations, at hour 10:00

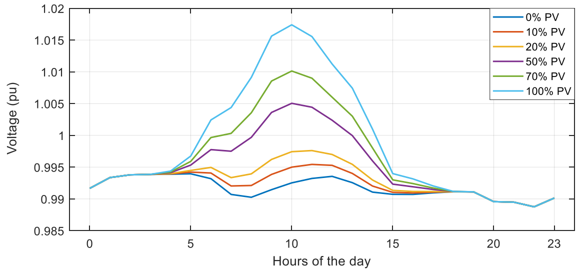

Fig. 14 Average voltage of all nodes for one winter day with different PV levels

Similar to the EV impact analysis, the household consumption profiles are randomly selected from database of hourly kWh consumption profiles of 100 households. The PV output is generated using the location information and PV system specification information in the Photovoltaic Geographical Information System (PVGIS). PVGIS is developed by the European Commission Joint Research Centre [18]. The MCS process is illustrated in Fig. 11.

Fig. 12 illustrates the box plot for 1000 simulations of the six cases of PV integration level. Fig. 13 is a tree plot illustrating the voltage profiles and their location in the network at specific point of time where the highest voltage increase is experienced. The average one day hourly voltage level in the network for all simulations and all cases are presented in Fig. 14. The results in general show that the higher integration of PV in LV distribution network is unlikely to create sustained overvoltage problems. For PVs to create such problems, the high output of PV shall coincide with the low loading in the network. Other issues not discussed in this paper are potential flicker problems in association with the frequent variability of solar irradiation.

V. IMPACT OF ACTIVATION OF FLEXIBILITY RESOURCES

In this section, activation of shiftable atomic loads to mitigate possible overvoltage caused by increase PV integration is demonstrated. A data-driven flexibility potential estimation method has been developed for shiftable non-interruptible loads (Cloth washing machines, Dish washing machines and Dryers) and presented in [19]. Using the developed method, the potential impact of shiftable loads in alleviating potential voltage problems is simulated.

As the flexibility potential of the shiftable loads are estimated based on the probability of use data extracted from real measurements in Norway, the Monte Carlo simulations of the shiftable load profiles will fit with the PV impact analysis method presented in this paper. Hence, 1000 scenarios for all the 53 households are generated and coupled with the rest of the simulations to conduct the power flow analysis. The shifting is implemented by changing the starting times for all cloth washing, dish washing and drying activities between 12:00-17:00 to earlier hours between 08:00-13:00. The shifting impact on average 24 hour dish washer related consumption profiles for average house of the 53 households after 1000 simulation is plotted in Fig. 15.

The impact of activating the flexibility potential for the shiftable loads alone are presented in Fig. 16 and 17. In Fig. 16, one can see that the shifting operation resulted in reduction

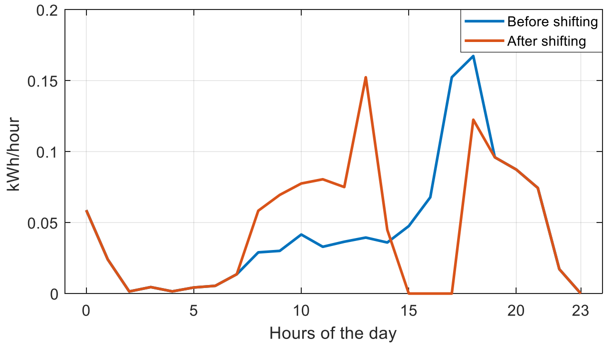

Fig. 15 Dishwashing related consumption profile for average household of 53 households after 1000 simulation

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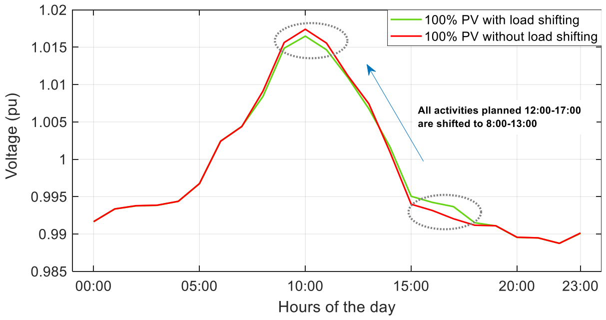

Fig. 16 Average voltage profile of all the nodes with 100% PV integration with shifting and without shifting

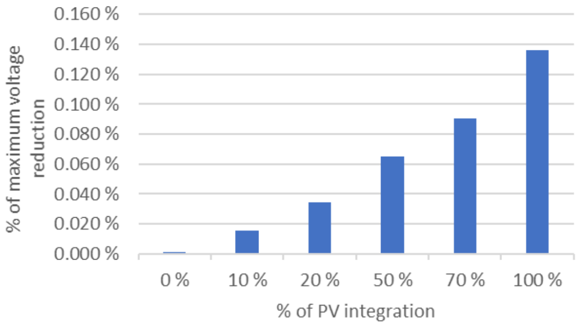

Fig. 17 Reduction in median voltage of the 1000 maximum voltage values with different level of PV integration and after shifting is applied

of the maximum voltage level while the voltage level in the periods from which the flexibility resources are shifted from, increased. The estimation of the flexibility potential from the resources is very close to realistic scenarios as the actual probabilities of operation of the appliances are considered. In Fig. 17, the reduction of the maximum voltage due to shifting of atomic loads, increases as the penetration level of PV increase although the same flexibility resource is activated. At 100% PV integration in the LV network, it is likely that the maximum voltage level can be reduced by 0.16% by activating flexibility potentials of shiftable atomic loads alone.

VI. CONCLUSIONS

This paper presents methods to evaluate the impacts of EVs and PVs in LV network by using the probabilistic distribution of the various parameters. The probabilities of the parameters needed for simulation study are attained mostly from publicly available statistical data and survey data. According to the LV network analysis, the occurrence of undervoltage problem caused by increased integration of EVs is very likely. The fact that EV consumption is high at hours of low consumption from other appliances makes it difficult to solve the problem by activating flexibilities from household appliances. In another analysis, the experience of overvoltage due to increased PV integration in the network is very unlikely. Moreover, if there is overvoltage problem due to PV integration, flexibility resources can be considered as reliable solutions.

The inclusion of other flexibility resources such as battery storage, V2G systems, hot water tankers and others in the analysis with the aim of solving the foreseen distribution network challenges is left for the next activities of this work.

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REFERENCES

[1] E. Lorentzen, P. Haugneland, C. Bu and E. Hauge, “Charging infrastructure experiences in Norway-the worlds most advanced EV market.,” in *In EVS30 Symposium*, Stuttgart, Germany, EN., 2017.

[2] H. Sæle and I. Petersen, “Electric vehicles in Norway and the potential for demand response, DOI: 10.1109/UPEC.2018.8541926,” in *2018 53rd International Universities Power Engineering Conference (UPEC)* , 2018.

[3] Viak, Multiconsult and Asplan, “Solcellesystemer og sol i systemet,” Mars 2018.

[4] S. Elphick, P. Ciufo and S. Perera, “Supply current characteristics of modern domestic loads.,” in *In Power Engineering Conference, 2009. AUPEC 2009. Australasian Universities (pp. 1-6). IEEE,* 2009.

[5] Ø. Sagosen, “Analysis of large scale integration of electric vehicles in Nord-Trøndelag (Master's thesis, Institutt for elkraftteknikk),” 2013.

[6] H. Ureh, “ Impacts of Plug-In Electric Vehicle on Residential Electric Distribution System using Stochastic and Sensitivity Approach.,” MSc. theisis, California Polytechnic State University,, 2011.

[7] M. R. Mozafar, M. H. Moradi and M. Amini, “A simultaneous approach for optimal allocation of renewable energy sources and electric vehicle charging stations in smart grids based on improved GA-PSO algorithm,” *Sustainable Cities and Society,* vol. 32, pp. 627-637, 2017.

[8] A. Nikoobakht, J. Aghaei, R. Khatami, E. Mahboubi-Moghaddam and M. Parvania, “Stochastic flexible transmission operation for coordinated integration of plug-in electric vehicles and renewable energy sources.,” *Applied Energy,* vol. 238, pp. 225-238, 2019.

[9] H. Markiewicz and A. Klajn, “Standard EN 50160-voltage characteristics in public distribution systems,” *Voltage Disturbances.,* 2004.

[10] “Forskrift om leveringskvalitet i kraftsystemet,” [Online]. Available: https://lovdata.no/dokument/SF/forskrift/2004-11-30-1557.

[11] S. Habib, M. Khan, F. Abbas, L. Sang, M. Shahid and H. Tang, “A Comprehensive Study of Implemented International Standards, Technical Challenges, Impacts and Prospects for Electric Vehicles.,” *IEEE Access,* 2018.

[12] Y. Gu, X. Zhang, J. Myhren, M. Han, X. Chen and Y. Yuan, “Techno-economic analysis of a solar photovoltaic/thermal (PV/T) concentrator for building application in Sweden using Monte Carlo method.,” *Energy Conversion and Management,* vol. 165, pp. 8-24, 2018.

[13] “Norwegian EV owners survey,” Association of Norwegian Electric Vehicle, 2017. [Online]. Available: www.elbil.no.

[14] “EV-database,” [Online]. Available: https://ev-database.uk/search/?q=hyundi.

[15] M. Z. Degefa, H. Sæle, J. Foosnaes and E. Thorshaug, “Seasonally variant deployment of electric battery storage systems in active distribution networks.,” in *CIRED-Open Access Proceedings Journal,*, 2017.

[16] B. Bayer, P. Matschoss, H. Thomas and A. Marian, “The German experience with integrating photovoltaic systems into the low-voltage grids.,” *Renewable energy,* no. 119, pp. 129-141, 2018.

[17] “Solkart,” Sivilingeniør Carl Christian Strømberg AS og Norkart AS, [Online]. Available: https://solkart.no.

[18] “PVGIS,” JRC EC, [Online]. Available: http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP.

[19] M. Z. Degefa, H. Sæle, I. Petersen and P. Ahcin, “Data-driven Household Load Flexibility Modelling: Shiftable Atomic Loads,” in *Data-driven Household Load Flexibility Modelling: Shiftable Atomic Loads,* Sarajevo, Bosnia Herzegovina, 2018.

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