Influence of decentralization and sector coupling on the load profiles of the remaining grid demand for private household sector in Germany

Rohith Bala Krishnan, Viktor Wesselak, Theresa Reinhardt, Christoph Schmidt

Institut für Regenerativ Energietechnik, Nordhausen University of Applied Sciences, 99734 Nordhausen (Germany)

Abstract

Since Germany has embarked on a journey to transform its energy supply, the share of the renewable energies and decentralized energy supply has been increasing. The proposed German energy market for the year 2030 consists of 29% and 39% share from renewable energies and decentralized supply respectively, which is almost triple the share compared to the year 2010 (KPMG, 2015). The private household sector receive a constant electricity supply according to the standard load profiles developed by German Association of Energy and Water Industries (BDEW, 2018). This paper focuses on the effects of the decentralized energy supply and sector coupling in private households on the standard load profiles. The electricity, heat and e-mobility load profiles are developed for the state of Thuringia in Germany and the effects of decentralized energy supply are analyzed. The prosumer load profiles are published in hourly resolution in the same format as standard load profiles.

Keywords: Energiewende, energy transition, load profiles, grid analysis, decentralized energy supply, photovoltaics, prosumer load profiles, demand, household sector, system analysis

1. Introduction

The German energy transition goals require a drastic change to the existing power supply system. In electricity sector, it is important to achieve affordable and clean electricity (BMWK, 2017). Decentralized energy supply is an increasing trend in private households, due to the high inflation rate on the energy prices. A household can consume up to 30% of energy obtained from the photovoltaic system on rooftop and almost 60-70%, if the system is accompanied with a battery. At the moment, due to high costs of the PV-Battery systems most household have systems without storage, which means the remaining 70% of energy produced by the PV system is fed to the electricity grid. The excess unused energy may have an influence on the constant supply of electricity from energy suppliers. Therefore, the energy suppliers should adjust the standard load profile to prosumer load profile and supply energy to the grid. Standard load profiles (SLPs) are time-resolved representative load profiles and used for power estimation and power gradients, as well as for the simulation of energy systems. A new method proposed to develop the electricity load profiles using bottom-up stochastic model to neglect the disadvantages of SLPs (e.g. constant flow and similar seasonal pattern) (Bala Krishnan, R.K. et al., 2022). This paper shows the way to overcome these disadvantages and analyzing the effects of raising decentralized PV power and storage capacity.

2. Development of load profiles

2.1 Electricity load profile

The load profile for the electrical devices in the household is developed using the open-source tool RAMP. RAMP uses stochastic algorithm to reproduce unpredictable, random consumer behavior (Lombardi, F., 2019). It is necessary to define the users and the appliances in RAMP to generate the desired profiles. The users are classified according to the family type living in a household, as the yearly consumption depends on the no. of person living in a household. The table 1 represents the classification of households according to family type in Thuringia. The state Thuringia is classified into four regions to differentiate the demand.

Tab. 1: Classification of user group according to family type living in a household (TLS, Thüringer Landesamt für Statistik, 2014)

User category	North thuringia	Middle thuringia	East thuringia	Southwest thuringia
EP - Single person	62608	123977	129333	60447
POK - Couple without children	54107	95644	103697	54757
AE - Single parent	17392	29317	28624	18622
PMK - Couple with children	52298	70105	73565	54357
MP - Big family	4090	8679	8694	3504

The common household appliances like indoor/outdoor lighting, television, office materials (PC, Laptop, etc.), refrigerator, deep freezer, washing machine, dishwasher, cooking devices (toaster, induction stove, air fryer, and oven), circulation pump, warm water and miscellaneous devices. The circulation pump is responsible to circulate warm water to the heaters and simulated (not in RAMP) depending on the ambient temperature. The circulation pump is mostly not used during summer season due to less heat demand. Figure 1 represents various information to the simulated electrical devices: i) The inner circle represents the yearly energy consumption (in kWh) for each user category, ii) the pictograms represents the appliances simulated, and iii) The bar plots represents the share of each appliance (in percent) on the total yearly energy consumption for the individual user categories (Stefan Peter, 2013).

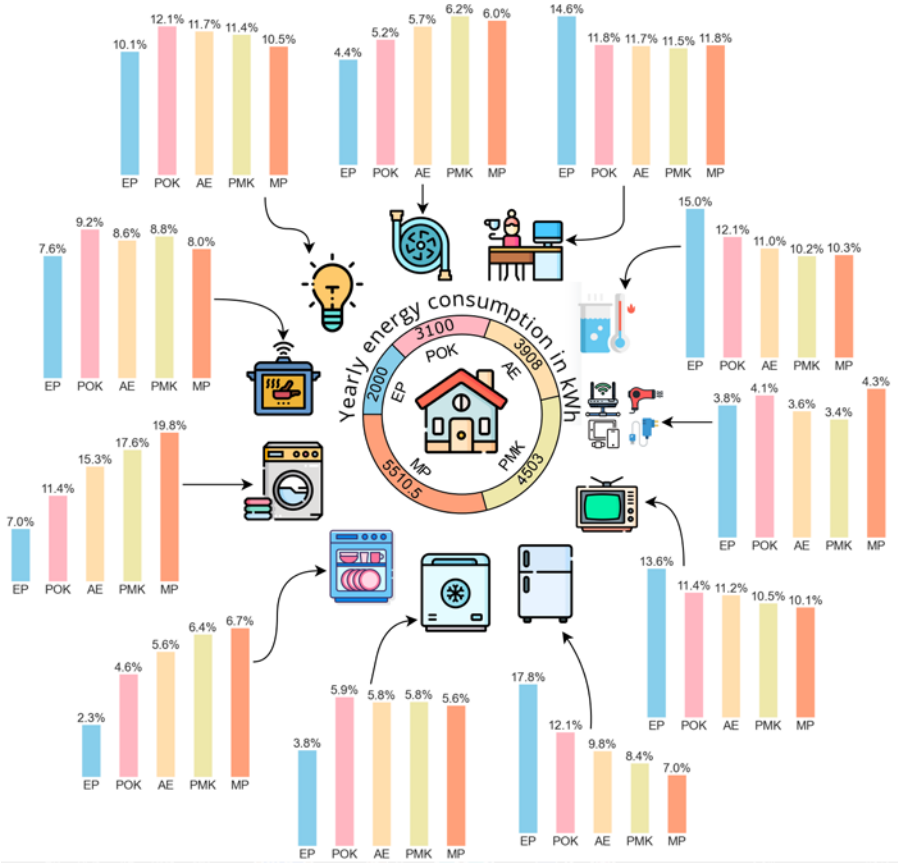

Fig. 1: Defined appliances and their share on the yearly energy consumption

All these devices are simulated with respective total usage time and operating timeframes. The total usage times are obtained from various energy survey reports. Due to insufficient information about the operating timeframes in Germany, the data are more or less obtained from UK energy survey report (EFUS, 2021). The documented total usage time and the operating timeframes are uploaded to the Institute's GitHub profile (in.RET, 2023) profiles are developed and compared with the SLPs for validation. All load profiles are simulated for the calendar year 2050, to have same holiday pattern. To compare, the RAMP profile and the SLP (Household profile - H0) are scaled to a same annual consumption of 1000 kWh/a. Figure 2 shows the comparison of the profiles in daily resolution and clearly represents the RAMP profile overcomes the disadvantages of the SLP and have similar course.

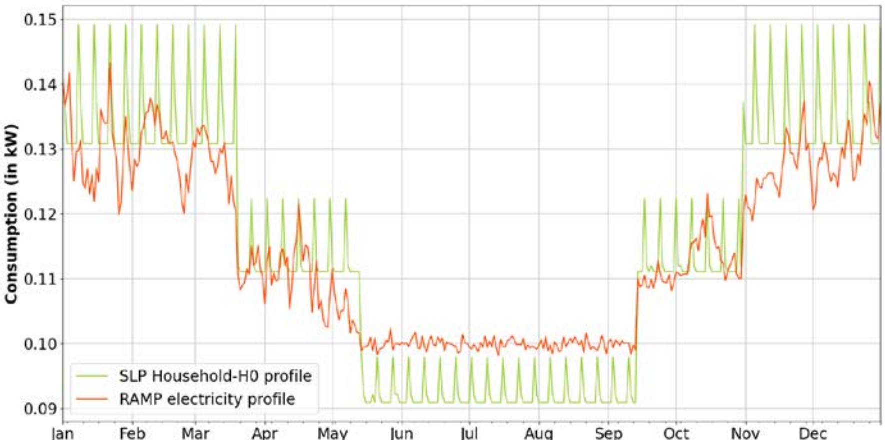

Fig. 2: Comparison between RAMP profile and the SLP in daily resolution

It is necessary to compare the annual load duration curve to make a more sensible comparison. The annual load duration curve represents the course with peak, main, transition and base load periods. Figure 3 shows the comparison between the annual load duration curves between the two profiles and can be clearly interpreted that the RAMP profile load curve has similar course in comparison with the SLP. Henceforth, the dynamic load profile can be substituted for future energy system modelling without interrupting the load course.

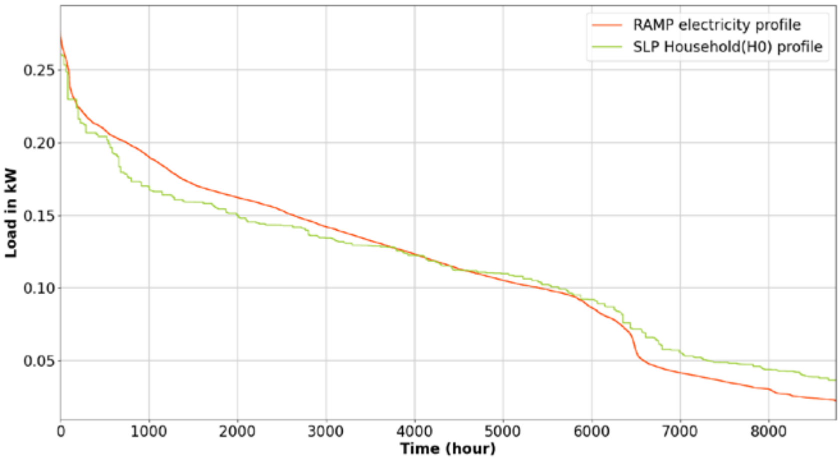

Fig. 3: Comparison of annual load duration curve between RAMP profile and the SLP

2.2 Heating load profile

Heating load profiles are determined by three factors: weather condition, building properties and habitation. The heat load profiles can be either developed using statistical or physical model approach. Due to less availability of data for the Thuringia region, the German statistical measurement methodology (BDEW, 2016) normally used to calculate standard gas load profiles is preferred for further calculations. The standard gas load profile methodology uses sigmoid curve/sigmoid function to calculate the daily heating requirement, which is later scaled up to the calculated annual demand for space heating and domestic warm water. To calculate the annual heat demand, the living area determined by the Thuringia state office for statistics (TLS, 2022) is multiplied with the specific heating requirement (including the demand for warm water) depending on the construction year of the building (Manteuffel B., 2013). Furthermore, it is also necessary to know the share of each building type and the year of construction to calculate the total heating demand for the specific building category. Figure 4 (a) represents the share of the detached houses (EZFH) and apartment buildings (MFH) for the four regions in Thuringia and figure 4 (b) shows the share of the household with respective construction year in Thuringia (TLS, 2022).

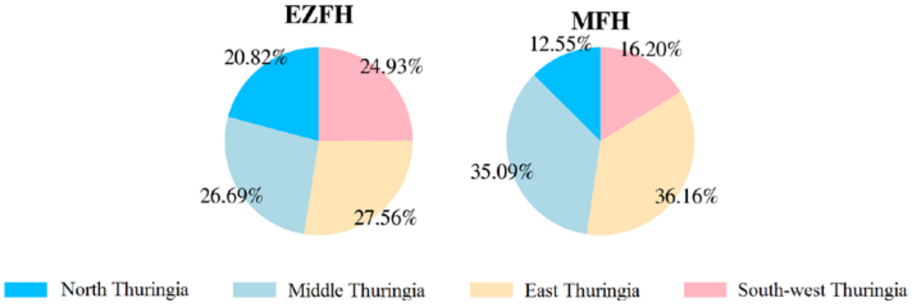

Fig. 4 (a): Share of detached houses and apartment buildings in Thuringia

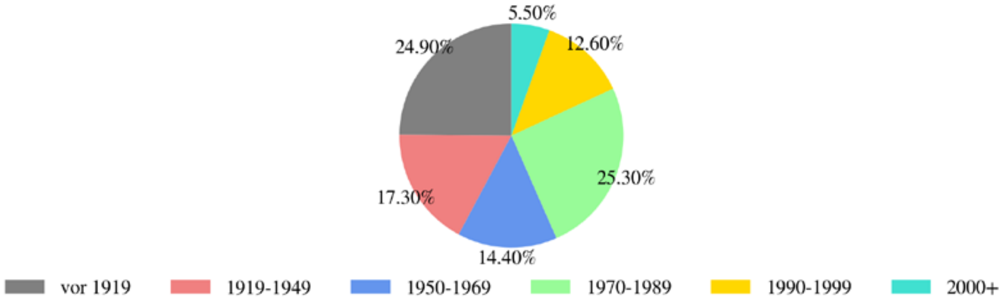

Fig. 4 (b): Share of Household according to the respective construction year in Thuringia

Furthermore, the Federal Association of the German Gas and Water Industry (BGW) presents the hourly demand factors for different building categories and for ten temperature ranges. These factors are multiplied with the respective daily demands to develop daily load curves.

2.3 E-mobility load profile

The expected increase of electric cars in the future will lead to an increased demand for electricity in both residential and commercial sectors. It is assumed that almost 80% of the charging process for electric cars takes place at home, as it can be done more efficiently in the long term and the remaining 20% in public parking's or commercial buildings. In residential building, the peak load is expected to occur in the late afternoon and evening hours when residents returning from work. If the building fails to have the smart charging management installed, the electric vehicles are charged immediately upon arrival and the charging power drops through the night depending on the maximum charging power. Due to lack of information regarding the user charging behavior specifically in private households, presently it is impossible to develop the load profiles stochastically. For the analysis, the e-mobility load profiles for residential building are obtained from a web-based planning tool known as nPro (Wirtz, 2023). Figure 5 shows the e-mobility load profile for residential building according to user behavior during weekday, Saturday and Sunday.

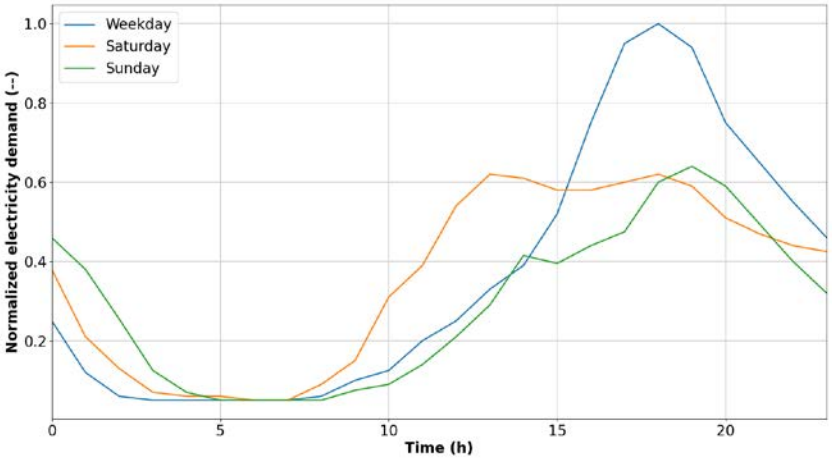

Fig. 5: E-mobility load profiles in the residential buildings according to the day type

2.4 Composition of the load profiles

The above-mentioned load profiles are scaled to the predicted annual electricity consumption (Tab.2) for Thuringia published by the Institute for renewable energies (Wesselak, 2023).

Tab. 2: Predicted final electricity demand for private households in Thuringia until 2045 in TWh

	2030	**2040**	**2045**
Electrical devices	2.1	1.9	1.8
Heat pump	0.622	0.85	0.828
Heating rod	0.303	0.234	0.131
E-Mobility	0.924	1.88	1.87
Total electricity demand	3.95	4.86	4.63

3. Energy system modelling

3.1 Predicted PV System Capacity in Thuringia

To analyse the effects of rooftop photovoltaic system on the remaining energy in the grid, it is necessary to predict the installed PV system capacity until 2045. Prognos AG, Öko-Institute e.V., and Wuppertal Institute made an energy system analysis for the whole of Germany and presented the results to achieve the climate-neutral future. The results also show the amount of PV capacity which has to be built by the year 2045 to achieve the energy transition goals (Prognos & Öko-Institut, 2021). The recent report from Fraunhofer Institute for Solar Energy Systems shows the percentage of annual installed capacity by size and the relative share of the federal states in the annual capacity increase in Germany over the past 20 years (Fraunhofer ISE, 2022). It is observed that the small segment PV system on rooftops (<10 kW_p) contributes a relative constant average share of 18.4% over the past ten years. The federal state Thuringia contributes a relative constant share of around 3% on the total installed PV capacity in Germany over the past ten years. It is assumed that the relative shares remain constant in the future and figure 6 represents the predicted capacity of rooftop PV systems (<10 kW_p) (green line) in private household sector in Thuringia.

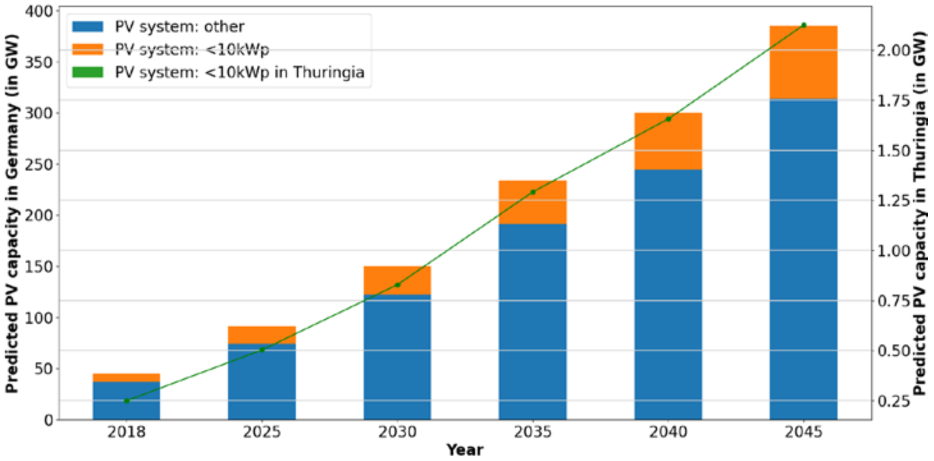

Fig. 6: Predicted capacity of rooftop PV system (<10 kWp) in Thuringia (left y-axis: green line) until 2045

3.2 System Analysis

An average PV feed-in profile is developed for the four planning regions with approx. 1005 kWh/kW_p full load hour. The energy produced by the PV systems significantly reduces the afternoon peak/load, resulting in reducing the utilization of the electricity grid. Before analysing the effects of PV on the electricity grid, it is necessary to compare the theoretically calculated PV capacity (fig. 6) with the optimum PV capacity. A small system is modelled in Open energy modelling framework (oemof) with the following components:

Photovoltaic system (with investment costs), electricity grid (with variable costs of 35 ct/kWh) as source and electricity demand as sink. Oemof.solph translates the energy system into mathematical equation using pyomo and optimizes the system with the help of a mixed-integer linear programming solver (Krien, 2020). The optimizer (cost optimization) suggest having a PV capacity of 2.196 GW by 2045, which is nearly close to our theoretical value (2.31 GW). The electricity demand from the grid is optimized with help of the theoretically predicted PV system capacity.

3.3 Influence of PV system without storage on grid

A self-consumption PV system without storage can consume approximately around 30% of the produced energy and the remaining energy is stored in the grid. People in Germany still prefer to store energy in the grid, as now they receive the feed-in tariff (approx. 8ct/kWh). The feed-in tariff encourages more people to build PV system on rooftops and to relieve the stress on the grid. However, this will change in the future and the feed-in tariff will decrease gradually over time. The people who consume only 30% and store the remaining 70% of the energy produces makes them *Prosumer* (producer + consumer). Hence, it is necessary adjust the SLPs for future energy system analysis or potential estimation and substitute it with the prosumer profile. Figure 7 represents the daily average prosumer demand profile for the year 2030, 2040 and 2045 in comparison with the normal reference load profile (dotted red line). The noticeable peak over the evening course is due to the increasing trend in E-mobility and the afternoon peak reduces significantly due to high PV energy production.

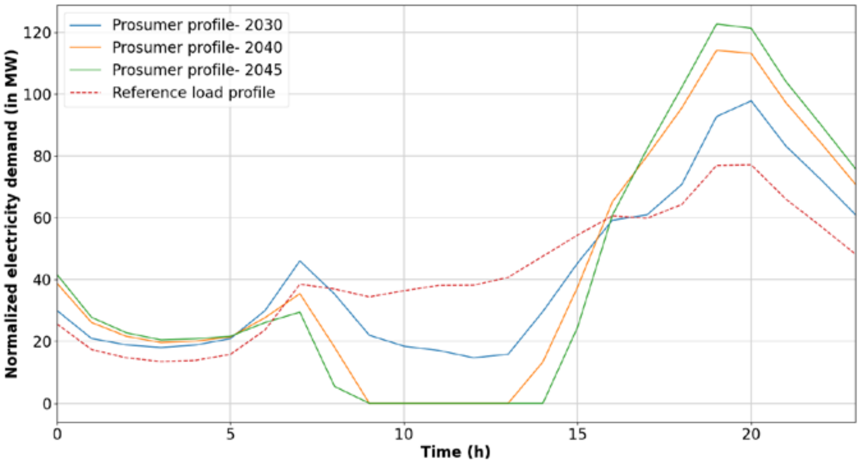

Fig. 7: Average prosumer electricity demand profile for one day in comparison with reference load profile

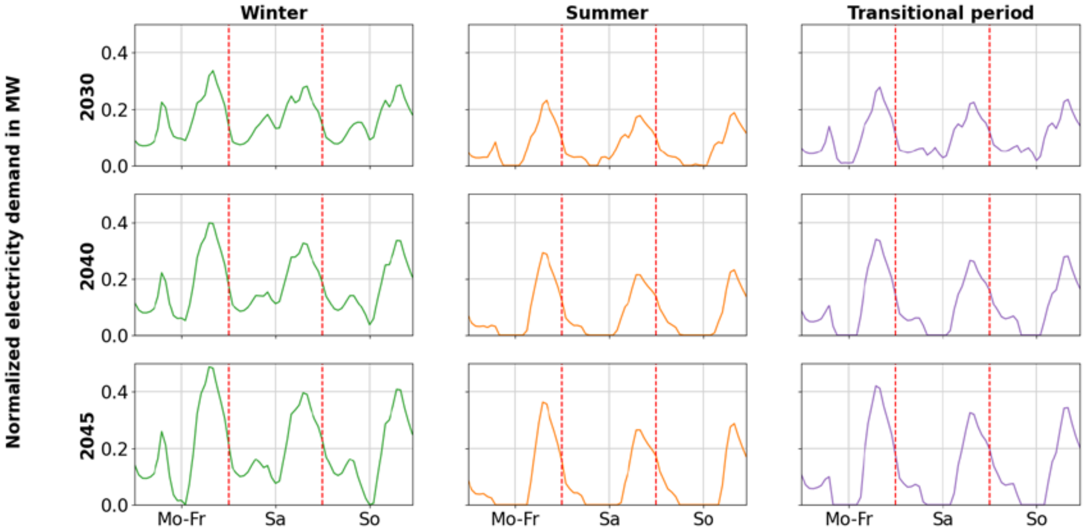

Fig. 8: Average prosumer electricity demand profile (with only PV system) for Weekday (Mo-Fr), Saturday (Sa) and Sunday (So) during winter, summer and transitional period

The yearly electricity demand profile was normalized to 1000 MWh/a and the profile was sorted according to the season and day type (similar to SLP). An average profile is developed for the each sorted profile to show the variation in the prosumer's electricity demand profile depending on the days of the week and season. The figure (Fig. 8) shown above represents a clear comparison between the profiles. In winter, it is noticeable that there is a demand for electricity during daytime due to less power produced by the PV system and in summer, there is almost zero electricity demand.

3.4 Influence of PV system with storage on grid

In contrast to the PV system without storage, the PV systems with battery storage can consume around 65-75% of the energy produced and stores only 35-25% of energy in grid. High electricity prices make the battery storage a more attractive option for the PV system owners, as higher self-consumption rates can be achieved and reduces the dependency on the grid. In Germany, the annual expansion of battery storage has increased significantly in the recent years and has achieved a total installed capacity of 3521 MWh until 2021. In the period 2014 – 2021, the proportion of battery storages installed with low capacity (≤ 5 kWh) continues to decline and lies around 7% of total installed capacity in 2021. On the other hand the storages with a capacity (between 5 -10 kWh) contributes a large share of the total capacity increase and contribute an average share of 40.3% over the past six year (Fraunhofer ISE, 2022). However, it is difficult to predict the total installed battery capacity in Thuringia. The required capacity of the battery can be optimized using oemof with investment model. For the optimization the battery's capex is taken as 80€/kWh. Table 3 shows the optimal battery capacity to be installed to increase the self-consumption rate.

Tab. 3: Optimized battery capacity for the respective predicted PV capacity until 2045 in Thuringia

	2030	**2040**	**2045**
Predicted PV capacity	828 MW	1656 MW	2125 MW
Optimized battery capacity	226 MWh	935 MWh	1467 MWh

Figure 9 shows the electricity demand curves from the grid with battery storages combined with PV systems. In comparison with the demand curves only with PV systems, it is noticed that the evening peaks are reduced with the battery system significantly during summer and transition periods. The excess PV energy is stored in the battery and retrieved during the evening's to reduce the grid dependency. It is observed that in 2045, the increase in the installed battery capacity has a significant change in the demand curve. The demand curves during winter looks almost similar in both systems, due to less energy produced and lack of PV excess energy, which can be stored in the battery storage.

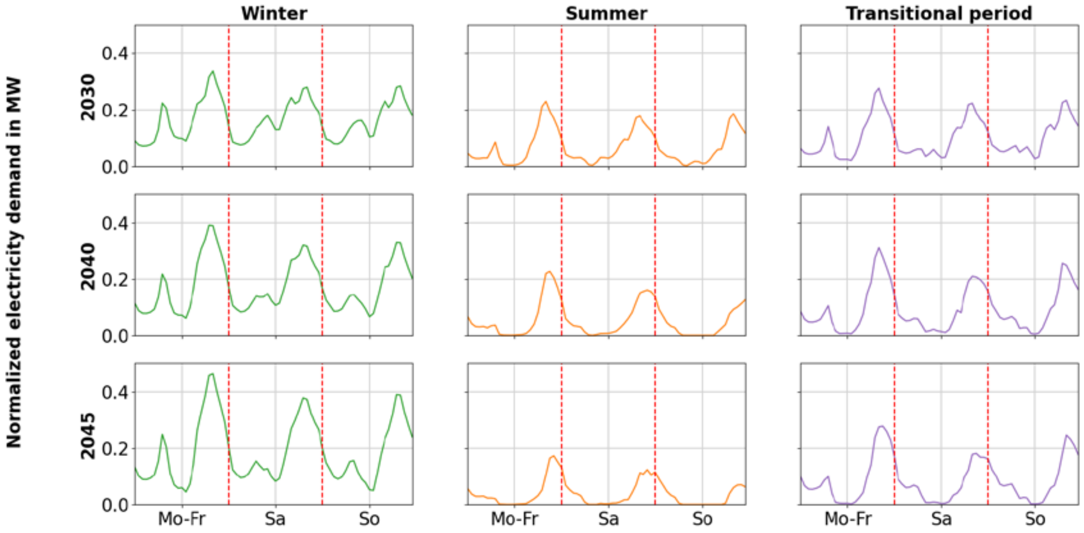

Fig. 9: Average prosumer electricity demand profile (PV + Battery system) for Weekday (Mo-Fr), Saturday (Sa) and Sunday (So) during winter, summer and transitional period

3.5 Annual Load duration curve

The annual load duration curve defines the curve between the load (electricity demand) and time in which the ordinates representing the load, plotted in the order of decreasing magnitude. From the load duration curve (Fig. 10), the total grid usage time (eq.1) and the load factor (eq.2) are calculated using the following equations. The load factor defines the measure of the utilization rate; a high load factor indicates that electricity grid is utilized at a high rate. In addition, the grid usage time represents the total time the electricity grid is used to satisfy the demand.

$$\text{Grid usage time (T)} = \frac{\text{Total energy consumption in a year (MWh)}}{\text{Peak load (MW)}} \qquad \text{(eq.1)}$$

$$\text{Load factor (LF)} = \frac{\text{Average load (MW)}}{\text{Peak load (MW)}} \qquad \text{(eq.2)}$$

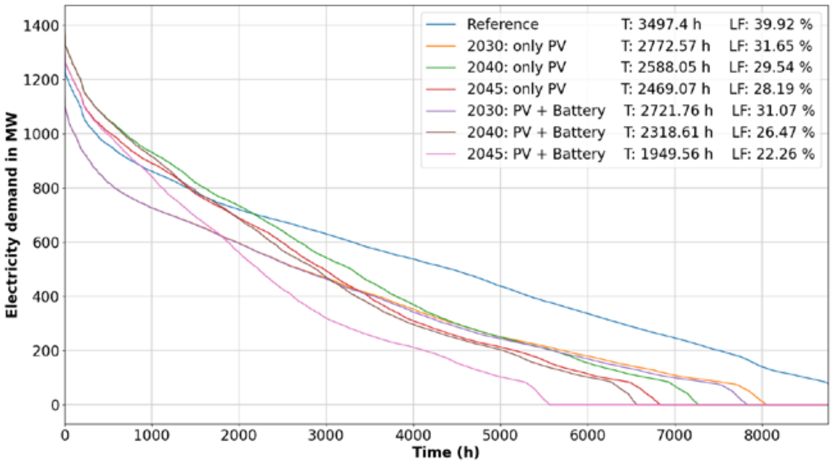

Fig. 10: Load duration curve for different scenarios with respective total electricity grid usage time (T)

The reference curve is the average demand curve of the three simulations (2030, 2040, and 2045). By 2045, the load factor reduces by almost 25% with only PV system and by almost 45% with PV-Battery system and the grid usage time decreases by approx. 29% with only PV system and by approx. 44% with PV-Battery system. The utilization rate can be reduced by almost 20% by complimenting a PV system with a battery storage. The analyses shows that the grid utilization rate is minimized eventually by continuous expansion of the installed capacity of decentralized energy supply system. Therefore, the CO_2 emissions can be minimized by not producing and making the availability of electricity on the grid according to the current SLP used by energy suppliers, and substituting it with the Prosumer load profiles to achieve the estimated political goals.

4. Summary

The effects of the decentralized energy supply on the load profiles were analyzed. As example, the federal state Thuringia in Germany was chosen for analysis, but the similar method can be used for other regions with respective datasets. The PV capacity was predicted until 2045 and the respective battery capacity was optimized using oemof. It was found that increase in the installing of PV system in household sector can significantly reduce the grid utilization rate and the PV system with battery storage can reduce the grid dependency. The prosumer electricity demand profiles were developed and forwarded for analysis. The load factor of electricity grid reduces by almost 25% with PV system and by 45% with PV-Battery systems. The grid dependency decreases largely during summer as well as transition period and slightly during winter, i.e. the grid utilization rate depends on the PV energy produced. Moreover, the excess energy produced from PV system in household sector can also be transferred to other sector (e.g. commercial or industry sector).

The dynamic electricity load profile developed using RAMP is compatible also for other regions in the same time zone. The RAMP profile for each user category is available for scaling to the respective no. of households in the particular region of analysis. The prosumer load profiles are sorted according to similar format as SLP for reference and further analysis. At the moment, the prosumer load profile are available only in hourly resolution but will be updated later with 15-minute resolution. The profiles are uploaded to the Institute's

GitHub handle and can be accessed using the link in the reference section (in.RET, 2023).

5. Acknowledgments

This work was a part of our main project Zero Carbon Cross Emission (ZORRO) and supported by the Thuringian Ministry of Environment, Energy and Nature Conservation.

6. References

Bala Krishnan, R. K., et al., (2022). Auswirkungen dezentraler Energieversorgung auf Standardlastprofil im Stromsektor.Tagnungsband 29th Energy-Symposium REGWA 2022, pg 9-17.

BDEW (Bundesverband der Energie- und Wasserwirtschaft), (2018)., Standardlastprofile. Retrieved from https://www.bdew.de/energie/standardlastprofile-strom/. Date of access: 05.09.2023

BDEW. (2016). Abwicklung von Standardlastprofilen Gas. Berlin: Bundesverband der Energie- und Wasserwirtschaft.

BMWK (Bundesministerium für Wirtschaft und Klimaschutz), (2017). Strom 2030: Langfristige Trends – Aufgaben für die kommenden Jahre.

EFUS. (2021). Lights, appliances, and smart technologies*:* An energy survey report. London: Department for Business, Energy & Industrial Strategy (BEIS).

Fraunhofer ISE. (2022). Photovoltaik- und Batteriespeicherzubau in Deutschland in Zahlen: Auswertung des Markstammdatenregister. Freiburg.

In.RET (Institut für Regenerativ Energietechnik), (2023). Electricity load profile development using RAMP: https://github.com/in-RET/RAMP; Prosumer load profile: https://github.com/in-RET/Prosumer-load-profile Date of Access. 06.10.2023

Krien, U. et al., (2020). oemof.solph- A model generator for linear and mixed-integer linear optimisation of energy system. Software Impacts, Volume 6, https://doi.org/10.1016/j.simpa.2020.100028.

KPMG, 2015. Decentralised energy industry: Opportunity or threat to energy companies?, pg 2. Retrieved from https://assets.kpmg.com/content/dam/kpmg/pdf/2015/06/decentralised-energy-industry.pdf. Date of access: 06.04.2023

Lombardi, F. et al., (2019). Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model. Energy, 2019.

Manteuffel B., et al., (2013). Der Gebäudereport Thüringen: Langfassung. Thüringer Ministerium für Wirtschaft, Arbeit und Technologie.

Prognos, & Öko-Institut, W. I. (2021). Towards a Climate-Neutral Germany by 2045. How germany can reach its climate targets before 2050. Executive Summary conducted for Stiftung Klimaneutralität, Agora Energiewende and Agora Verkehrswende.

Stefan Peter, U. (2013). Modellierung einer voll-ständig auf erneuerbaren Energien basierenden Stromerzeugung im Jahr 2050 in autarken, dezentralen Strukturen (Nr. 14/2013). München, Dessau-Roßlau: Umweltbundesamt (UBA), ISSN 1862-4359.

Thüringer Landesamt für Statistik (TLS) (2014). No. of households by household family type in Thuringia. Retrieved from: https://statistik.thueringen.de/datenbank/TabAnzeige.asp?tabelle=gs040001%7C%7C. Date of Access: 15.09.2023

Thüringer Landesamt für Statistik TLS. (2022). Bestand an Wohnungen in Thüringen im Jahr 2021. Erfurt. Retrieved from: https://statistik.thueringen.de/presse/2022/pr_133_22.pdf. Date of Access. 12.09.2023

Wesselak, V. (2023). Entwicklung des Thüringer Energiebedarfs bis 2045. Nordhausen. Retrieved from: https://github.com/in-RET/Prosumer-load-profile. Date of Access. 04.10.2023

Wirtz, M. (2023). nPro: A web-based planning tool for designing district energy system and thermal network. Energy, 126575, 2023. DOI: 10.1016/j.energy.2022.126575.