OPTIMAL INTEGRATION OF ELECTRIC VEHICLES, PV, HEAT PUMPS IN EXISTING DISTRIBUTION GRIDS IN THE NETHERLANDS

Louise DE VOS
Tractebel – BELGIUM
louise.devos@tractebel.engie.com

Niels LEEMPUT
Tractebel – BELGIUM
niels.leemput@tractebel.engie.com

Nazir REFA
ElaadNL - NETHERLANDS
nazir.refa@elaad.nl

Raoul BERNARDS
Enexis – NETHERLANDS
raoul.bernards@enexis.nl

Henk FIDDER
Stedin – NETHERLANDS
henk.fidder@stedin.net

Frans DE RIJKE
Liander - NETHERLANDS
frans.de.rijke@alliander.com

ABSTRACT

This paper analyses the future impact of photovoltaic solar panels (PV), electric vehicles (EV), and heat pumps (HP) on the distribution grid and how these technologies can be used as smart grid solutions to resolve the future distribution grid bottlenecks. AC optimal powerflow simulations are used to analyse the grid bottlenecks and the effectiveness of smart grid solutions compared to traditional grid reinforcements. These solutions are finally techno-economically assessed and compared.

INTRODUCTION

Distribution system operators (DSOs) are currently confronted with the rise of distributed energy resources, such as photovoltaic solar panels (PV), the expected strong uptake of electric vehicles (EV), and heat pumps (HP). The impact of PV, EVs, and HPs on the distribution grid is not to be underestimated. This paper analyses how these technologies can resolve the self-induced distribution grid bottlenecks by using them as smart grid solutions. A trade-off between these smart grid solutions, including grid batteries, and traditional grid reinforcements, such as cable or transformer replacement, is techno-economically assessed. The following elements are analysed and assessed in this paper:

1. Future distribution grid bottlenecks because of the uptake of PV, EVs and HPs.
2. Techno-economic analysis of the smart grid solutions and traditional grid reinforcements

METHODOLOGY

A distribution grid simulation tool, called Smart Operation, is used to study the operation and planning of the distribution grids. This tool uses a multi-period AC Optimal Power Flow (AC OPF) model [1], [2]. Smart Operation uses the available flexibility in the grid to obtain the optimal energy dispatch with minimization of the operation costs and losses. The future grid bottlenecks are identified by analysing when, i.e. at what level of PV and/or EV integration, and where in the grid these occur, e.g. at the level of the low voltage (LV) feeder, transformer or at the medium voltage (MV) grid level. A bottleneck in the grid is the location where the grid issue, such as a capacity issue or voltage issue, occurs with different gradations of frequency and severity.

CASE STUDIES

To assess the distribution grid of the Netherlands as

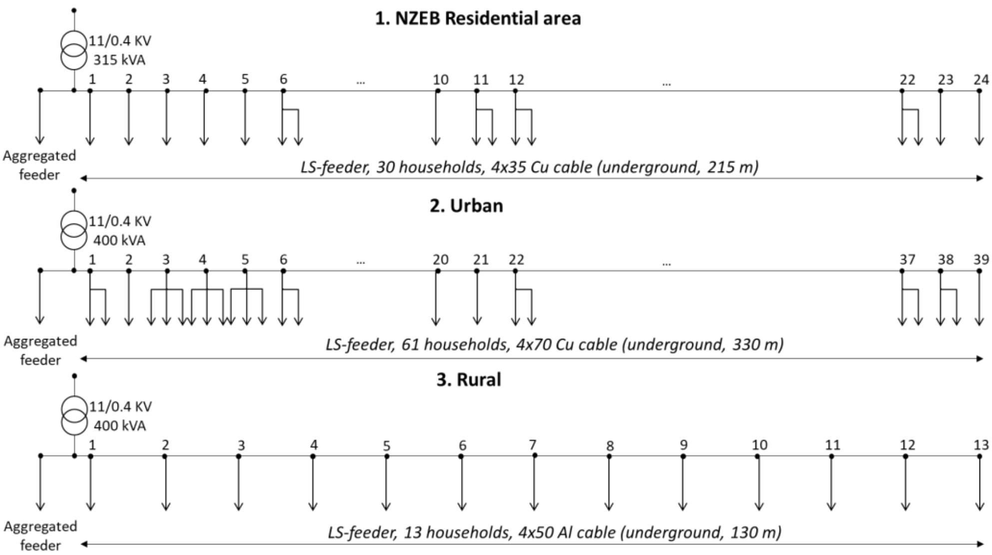

Figure 1: The three modelled LV feeders of three different distribution grids in the Netherlands.

realistically as possible, three different existing distribution grids in the Netherlands are modelled and analysed. The consumers/prosumers connected to the LV grids are all modelled individually and have different technologies (PV, EV, HP) associated to them.

Distribution grid modelling

The following three distribution grids from the Netherlands are analysed:

1. **Residential area with Net Zero Energy Buildings (NZEB) (based on realistic grid in Liander area)** with good insulation, installed HPs and solar panels for each house, with a gradual increase of EVs. Consequently, this type of distribution grid has a very high PV penetration grid early in the timeline.
2. **Old urban residential area (based on realistic grid in Stedin area)** with gradual increase of PV and EV. Since it is an urban residential area, the density of connections is higher.
3. **Rural residential (based on realistic grid in Enexis area)** area with gradual increase of PV and EV. The density of connections is lower, since it is a rural area.

The three distribution grids are analysed by modelling a single LV feeder in detail, with the remaining feeders connected to the same MV/LV transformer represented as aggregated loads, as can be seen in Figure 1. The modelling is done in this manner to reduce the complexity and calculation time of the simulations. All the grid assets are modelled as they are in the actual grid to correctly identify the possible future grid bottlenecks in the three distribution grids.

Prosumer/Consumer modelling

Each household is modelled with the following profiles:

1. **Purely electric load profiles** are generated with the current yearly electricity demand of each grid connection and the residential synthetic load profiles (SLP) of residential consumers in the Netherlands. [3]
2. **Heating load** are generated by a combination of the SLPs and degree heating days, related to its specific region in the Netherlands [3]-[4]. The heating load is converted to an electricity demand, with an assumption that the Coefficient of Performance (COP) of the HPs is equal to 3. This heating load is only dimensioned for the NZEB residential area distribution grid, since the HPs are not considered for the urban nor rural grid.
3. **PV profiles**: Each rooftop PV installation is sized according to the house's electricity consumption, using a power production profile coming from an existing PV installation in the Netherlands. The PV size ranges from 1 up to 10 kW for the three feeders modelled.

EV modelling

The EV electricity consumption profiles are based on probabilistic EV data from ElaadNL. Following assumptions were taken:

- Every EV connects and disconnects at least once a day to the LV feeder
- The maximal charging power is dependent on the type of feeder, with a maximum of 11 kW
- All EVs consume 7.5 kWh per day.

For the simulation model, the electricity consumption from the battery while driving is modelled, while the electricity consumption of the grid, during the charging of the battery is optimized by Smart Operation.

The charging method is an input of Smart Operation. When the charging method is traditional, the EV starts charging immediately the moment it connects to the distribution grid. With smart charging on the other hand, Smart Operation will optimize the charging of the connected EVs to reduce grid losses and minimize operation costs.

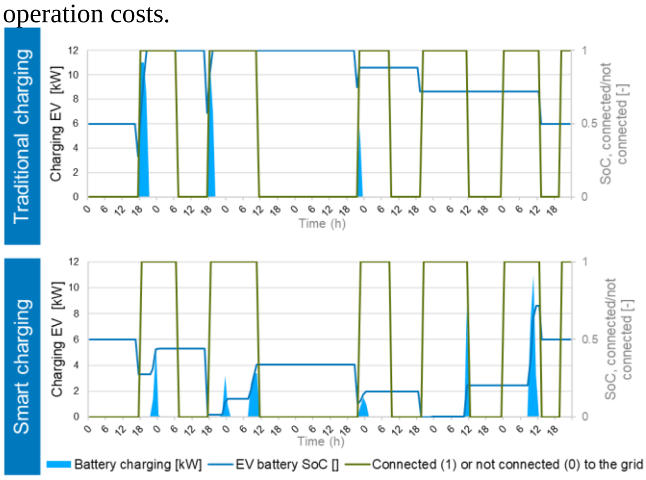

Figure 2: Traditional charging compared to smart charging profile for an EV, optimized by the simulation tool.

Scenarios

For the three different DSOs, different assumptions were made regarding the uptake of PV and EV in the LV distribution grid, which can be found in Table 1. These represent the share of households connected to the same MV/LV transformer with PV and/or EVs. The year 2040 has only been analysed for the urban area.

Table 1: Overview of the assumptions taken for the three different DSOs.

	NZEB area		Urban area		Rural area	
Year	PV (%)	EV (%)	PV (%)	EV (%)	PV (%)	EV (%)
2020	100	3	19	6	35	3
2025	100	14	28	18	50	14
2030	100	33	36	30	70	33
2040	/	/	59	65	/	/

The future grid bottlenecks are found by simulating the described grids in Smart Operation, with the EVs and HPs as traditional loads. EVs start charging their battery when they connect to the grid, and the HPs will consume

electricity at the moments that there is heat demand.
For the cases described in Table 1 where grid bottlenecks occur, the impact of different solutions will be analysed, these include traditional grid reinforcements, on-load tap changer (OLTC) transformers and smart grid solutions (smart management of EVs, HPs, and grid connected batteries). The impact of these solutions is assessed with AC OPF simulations and an economic analysis.
With this analysis, critical tipping points of the LV distribution grid will be identified, meaning when and which investment in the grid or smart grid solution is needed to avoid grid bottlenecks due to an increase in penetration of PV and EV.

RESULTS AND DISCUSSION

Grid bottlenecks

Grid constraints can be in the form of voltage issues, when the voltage goes over or under the voltage limits. For LV, the voltage limits are between -6 % for undervoltage and +1.5 % for overvoltage. Also capacity issues are grid constraints, where the power rating of the transformer or cable is not enough for the load connected to it.

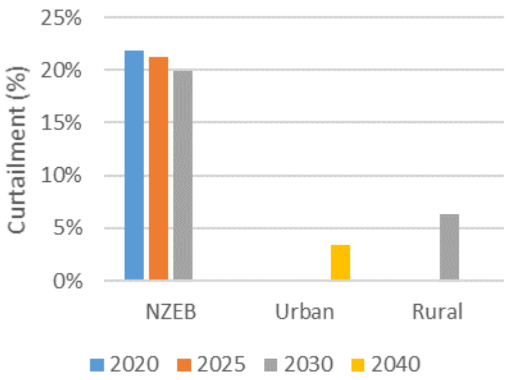

Figure 3: PV curtailment (% of production) for the three analyzed LV grids, without grid reinforcement or smart grid solutions.

NZEB Residential Area

For the NZEB residential area, early on (in 2020), the PV penetration is equal to 100%, meaning that all households have rooftop PV. This results in a simultaneous power production peak on the LV feeder, which causes grid bottlenecks in the form of overvoltage issues. Therefore, without smart grid solutions, solar curtailment will need to take place to reduce the voltage to an acceptable level. The yearly curtailment is around 20% of the PV production. As can be seen in Figure 3, the curtailment decreases slightly from 2020 to 2030 due to the increase in EVs in the grid.

Urban grid

For the urban grid, the PV penetration increases gradually. When the PV penetration exceeds 50 %, overvoltage issues occur, resulting in a yearly curtailment of around 4% of the PV production, as illustrated in Figure 3. This occurs in 2040 for the urban area, as summarized in Table 1. Additionally, in 2040 load shedding occurs due to undervoltage issues and capacity problems at the level of the transformer, due to the high EV penetration of 65%.
Furthermore, congestions occur in 2040 on the MV grid at the beginning of the MV feeder, also due to the high EV penetration rate.

Rural grid

The PV penetration also increases gradually for the rural grid, albeit faster than for the urban grid. Therefore, grid bottlenecks already occur in 2030 with a PV penetration of 70%. No grid issues occur due to the EVs, since the EV penetration remains quite low, even in 2030, see Table 1.

For each of the grid bottlenecks identified, several grid solutions will be identified, analysed and techno-economically compared:

Traditional grid reinforcement

Cable replacement

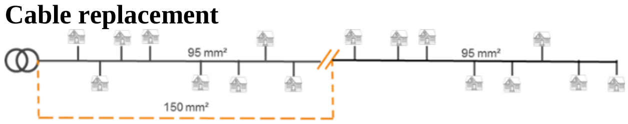

Figure 4: Traditional grid reinforcements with a 4x150 mm² Aluminum (Al) cable.

The cable replacement is separating the cable into two parts and connecting the most distant cable to a new cable, in this paper being a 4x150 mm² Al cable, schematically represented in Figure 4. All LV feeder bottlenecks can be resolved with a cable replacement. Dependent on the severity of the grid bottleneck, possibly two cables are needed for the grid reinforcement, as is the case for NZEB, see Figure 5. The bottleneck is considered to be resolved when PV curtailment is less than 3%.

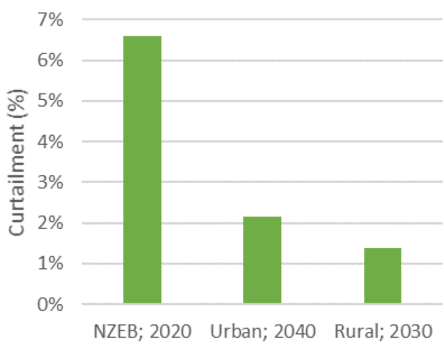

Figure 5: PV curtailment for the three analyzed grids with cable replacement (1 cable).

OLTC transformer

An OLTC transformer is a MV/LV transformer that can change the voltage ratio and resolve under,-and overvoltage issues, as can be seen in Figure 6. By replacing the transformer with an OLTC transformer with a higher capacity, it can additionally resolve capacity issues, such as is the case for the urban scenario.

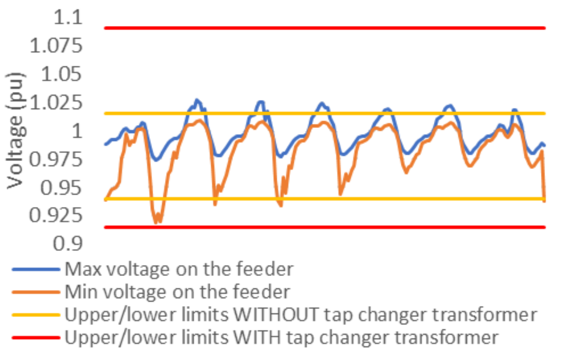

Figure 6: Voltage variations during 1 week in May for the urban LV grid.

Smart grid solutions

The flexible smart grid solutions (EVs, HPs, and batteries) resolve grid bottlenecks by changing the load curve. Consequently, contrary to traditional grid reinforcement and the OLTC transformer, flexible smart grid solutions can as well resolve grid issues on MV level, due to the resulted peak shaving effect by changing the load curve.

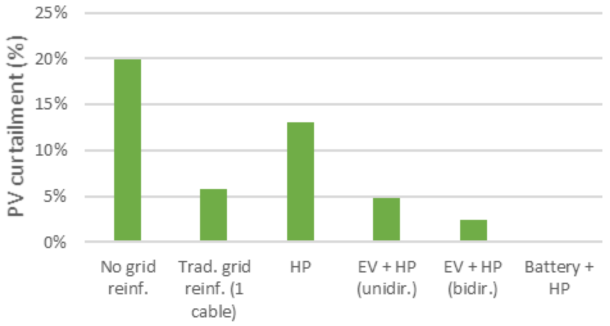

Figure 7: Impact on the PV curtailment of different solutions for the NZEB residential area in 2030.

Electric vehicles

The smart charging of EVs changes the charging patterns of the EVs, meaning they will charge (if connected to the grid) during times when there is a high amount of PV electricity production in summer or at another time than the load peak during the evening in winter. As a result, the voltage variations on the LV feeder will be smaller compared to traditional charging, since it will resolve both overvoltage and undervoltage issues. A certain level of EV penetration (above 30 % in the simulations) is needed to resolve the grid issues in a satisfactory manner, as enough EVs need to be available for charging during times of high PV generation. The difference between uni-, and bi-directional charging proves to be small.

Batteries

Batteries connected to the LV grid, of which the charging and discharging patterns are optimized by Smart Operation to resolve grid issues and minimize the grid losses, can resolve 100% of the grid issues if correctly sized. The batteries are optimized to be used mostly in summer, during solar production peaks to reduce over voltage issues for the three distribution grids analysed. However, for the urban feeder scenario, the battery is used the entire year for the 2040 scenario, to reduce the consumption peaks of the EVs that do traditional charging. The added benefit of batteries is that they are always connected to the distribution grid, opposed to EVs.

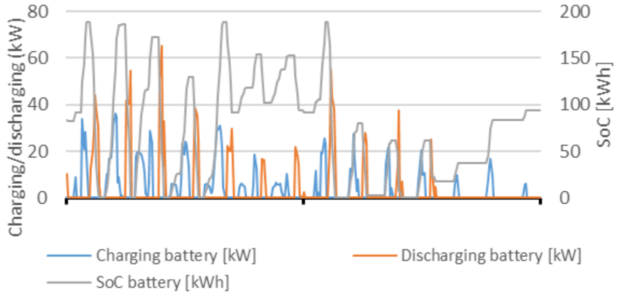

Figure 8: Charging, discharging pattern, and the State of Charge (SoC) of a neighborhood battery on the urban LV feeder in 2040.

Heat pumps

The HPs can partly resolve the grid bottlenecks, but less so than batteries or EVs in this scenario. There are two reasons resulting in a low amount of electrical energy available for shifting:

- The analysed residential area is NZEB, meaning with a high level of insulation. Therefore, the overall annual heat demand is low.
- The grid bottlenecks related to PV production occur mainly in summer when the heat demand is low compared to winter.

Cost analysis

A cashflow analysis was conducted for each solution, with the assumption that the investment costs for batteries will reduce with 50% by 2030 to 175 €/kWh.

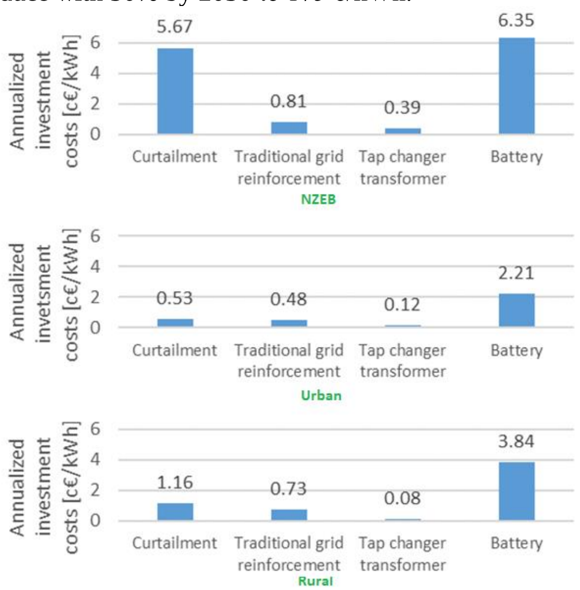

Figure 9: Results of cashflow analysis for the annualized investment costs of the three analyzed distribution grids for 2030 and 2040 for the urban case

The total annualized investment costs are analysed on a per-kWh basis, meaning that the costs are scaled to the cost related to the consumption on the LV feeder analysed. This allows to compare the solutions across the different grids. The following conclusions can be made:

- **Reimbursing the needed curtailment** at 0.25 €/kWh to resolve the grid bottlenecks is excessively expensive for the NZEB residential area, due to the high PV penetration rate. For the other two grids, this option is feasible, but more expensive than traditional grid reinforcement.
- **Traditional grid reinforcement** is one of the least expensive solutions. This is also if two cables are needed for the grid reinforcement, since the largest part of the cost is related to the excavation costs. Reinforcement is the cheapest for the urban LV feeder, due to the high density of grid connections.
- The **OLTC transformer** is for all scenarios the least expensive solutions, with the simplified assumption that the OLTC transformer doesn't cause additional grid bottlenecks on the other feeders. The probability is low in case that all feeders are residential feeders, and thus have similar load curves with a simultaneity in the load peaks. The costs are low because the total investment cost of the OLTC transformer is shared over all the connected LV feeders.
- The costs of the **battery** solutions are much more expensive than the other solutions, in case the battery is only used by the DSO. A possible value stacking of the batteries could reduce the costs for the DSO services.
- The investment costs for the traditional grid reinforcement and OLTC transformer can be converted into an annual budget to be spent for using the **flexibility of the EVs and HPs**. To be cost competitive to an OLTC transformer, the available yearly budget would be 3-10 €/EV or HP, and 24-102 €/EV or HP for the traditional grid reinforcement, depending on the scenario. If the flexibility could be made available within this budget, these solutions would be a cost-effective solution. The rural scenario reaches the highest cost-competitive budget, due to the lower density of grid connections, meaning that the traditional grid reinforcements are more expensive per kWh consumed on the LV feeder, compared to the non-rural feeders.

CONCLUSION AND DISCUSSION

This paper shows that the flexibility of EVs can solve grid bottlenecks, at LV and MV level. However, it will be difficult to become cost-competitive with traditional grid reinforcements or OLTC transformer. A possible stacking of other services from other parties than the DSO, such as the TSO or BRPs, can increase the cost-competitive budget for the EV user. Another possibility is an adjusted capacity tariff for the charging of EVs to incentivize a change in charging patterns and delay or avoid grid reinforcements.

The OLTC transformer is identified as the cheapest solution to solve LV grid voltage issues. In case of capacity problems on the LV feeder, other solutions need to be taken into account, such as smart charging of EVs.
Another part of the solution for grid bottlenecks is to consider a grid bottleneck solved if less than 3% of PV curtailment is needed, as is already the case is some European countries. Today, no curtailment in the Netherlands is allowed.

ACKNOWLEDGEMENTS

We would like to thank Netbeheer Nederland, and ElaadNL for supporting and funding this project.

NOMENCLATURE

AC OPF	Alternating Current Optimal Power Flow
BRP	Balancing Responsible Party
COP	Coefficient of Performance
DSO	Distribution System Operator
EV	Electric Vehicle
HP	Heat Pump
LV	Low Voltage
MV	Medium Voltage
NZEB	Net Zero Energy Building
OLTC	On-Load Tap Changer
PV	Photovoltaics (solar panels)
SoC	State of Charge
TSO	Transmission System Operator

REFERENCES

[1] F. Geth, S. Leyder, C. Del Marmol, S. Rapoport, 2016"The PlanGridEV Distribution Grid Simulation Tool with EV models", *CIRED Workshop*, Brussels, 2016

[2] P. Chittur Ramaswamy, C. Czajkowski, R. R. Sanchez, C. Chardonnet, G. Westnetz, I. G. Arriola, S. Rapoport, 2016, "Impact of Electric Vehicles on Distribution Network Operation: Real World Case Studies," *CIRED Workshop*, Brussels, 2016

[3] NEDU, Synthetic Load Profiles (SLP). Available: https://www.nedu.nl/documenten/verbruiksprofielen / Accessed on 04/12/2018

[4] BizEE, Degree Days.net - Custom Degree Day Data Available: https://www.degreedays.net/ Accessed on 04/12/2018