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REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 4e2 Deployment recommendation for large penetration of PV and distributed storage

Demo site: Rolle

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Nomencl	ature	OPEX	Operational Expense	
ACRONYM	S	PV	Photovoltaic	
APC	Active Power Curtailment	PVH	PV Hosting	
CAPEX	Capital Expenditure	PVP	PV Penetration	
DG	Distributed Generation	REel Demo	Romande Energie ELectric net- work Domonstrator	
DPP	Discounted Payback Period		Renewable Energy Sources	
DSM	Demand Side Management	ILDO	Renewable Energy Sources	
DSO	Distribution System Operators	SC	Self-Consumption	
FURIES	Future Swiss Electrical Infrastruc- ture	SS	Self-Sufficiency	
GHI	Global Horizontal Irradiance	SYMBOLS		
GU	Grid Usage	$P^{ ext{cur}}$ $P^{ ext{Exp}}$	Curtailed PV generation Exported	
HPC	High-Performance Computing		electricity power from the building to the grid	
IRENA	International Renewable Energy Agency	$P^{ m IMP}$	Imported electricity power from the grid to the building	
IRR	Internal Rate of Return	$P^{ m LOAD}$	Uncontrollable electricity power	
LCOE	Levelized Cost Of Electricity		consumption of the building	
LP	Linear Programming	$P^{\rm PV}$	PV power generation	
LV	Low Voltage	$t^{\scriptscriptstyle \mathrm{EXP}}$	Feed-in/export electricity tariff	
MILP	Mixed Integer Linear Program- ming	$t^{ m IMP}$	Retail/import electricity tariff	
MPC	Model Predictive Control	SUBSCRIPT	SUBSCRIPTS/SUPERSCRIPTS	
MV	Medium Voltage	b	Building	
NPV	Net Present Value	t	Time	

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1 Description of deliverable and goal

1.1 Executive summary

This report aims at providing some guidelines for the deployment of PV and distributed storage in low voltage grids, considering the economic aspects for the investors and the safety of the grid operation when facing a high PV penetration. This report proposes a novel approach imposing feed-in limits that are tailored on the load characteristic of the individual systems rather than based on the PV capacity. It is shown that this grid regulation is effective in preventing over-usage of the transformer but come with a cost for the system owners. A long term planning simulation, taking into account this grid regulation scheme and maintaining the distribution system operator's revenues, shows that a PV penetration of almost 150 % is achievable by 2050 without the need of replacing grid components while ensuring that all systems have an internal rate of return greater than 6%. To maintain the grid operator's revenue the electricity tariff shall increase from 21 to 28 cts/kWh.

1.2 Research question

A large deployment of distributed photovoltaic (PV) is one of the requirement to achieve decarbonization of the Swiss energy sector. The current trend in Switzerland is to install between 250 and 300 MW additional PV capacity per year (see figure 1). This is approximately 15 times higher than the 2010 level. The current total installed PV capacity is around 2 GW generating close to 2 TWh of energy per year. To meet the objective of the energy transition for 2050 which are to cover about 18% of the Swiss electricity demand, it requires to increase the PV generation to 11 TWh. Even more recent political call to aim an objective of 50 GW of PV to balance the increasing electricity demand for multiple sectors such as heating and mobility. This implies a consequent increase of the PV penetration in all areas of Switzerland. In other words, unless a new trend appears in building large MW scale PV plants (which is unlikely due mostly to space constraints), this deployment will mostly occur in local districts, i.e in low voltage distribution networks. A high PV penetration can cause multiple issues in the distribution network like over-voltage, line ampacity breaking and reverse power-flow. To mitigate these issues while ensuring a fair return on investment of PV investors, there is a need to guide the PV deployment and to develop new techno-economical frameworks.

This report aims to present how to guide the PV deployment in distribution networks to push as far as possible the PV penetration while ensuring the economic viability of the investments in PV energy systems. The use of additional technologies such as batteries to increase the flexibility of PV systems is investigated. However, their usage shall be guided in order to benefit to the grid operator and not to increase the pressure on the infrastructure. This report will hence present key concepts to capture both the operational aspect of PV and battery energy system usage and the planning aspect of these technologies. In particularly, it will focus on the operational constraints required to ensure a safe operation of the distribution grid.



Figure 1: Additional and cumulative PV capacity in Switzerland (data from [1])

1.3 Novelty of the proposed solutions compared to the state-of-art

Energy planning is a vast research area. In the following, we will focus specifically on the planning of distributed energy sources at the district scale. A common approach for energy planning is to generate scenarios such and select the most appropriate path for growing capacities from the initial situation up to the final target scenario (as in [2]). Our distinct approach consists in successively solving, for each year in the planning horizon, an optimization problem that aims to minimize the total cost of ownership. This approach allows us to account for the yearly price decrease of PV and batteries.

The planning of the electrical grid infrastructure is very relevant when dealing with high PV penetration as shown by Saad and Van der Weijde [3]. For this reason, our model integrates a grid usage constraint, that ensures that carrying out the deployment scenarios doesn't lead to an overloading of the local transformer. This constraint can be understood as a smartcurtailment as proposed in [4], mixing PV active power curtailment and battery energy storage to limit the power injected into the grid. Contrarily to the approach of Ricciardi et. al [5], Masuta et. al [6] or Luthander et al. [7], our approach does not try to define a grid-based feed-in limit, i.e. the feed-in limit is set according to what the grid can sustain, but rather assume that the grid as been design to sustain at least the maximum current withdrawn by each building with the reference power demand. If more current flows through the line in front of each building, this means that the grid usage has actually increased. The feed-in limit is hence defined so that the ratio between this new maximum power (or current) and the maximum reference power is the same for all buildings. We claim that this approach is more fair in the sense that it prevents the analysis from being dependent from the grid sizing. The operation of the PV battery systems is solved with a mixed-integer linear formulation of the control problem. Although this approach assumes a perfect forecast of the load and the generation, it enables to quickly solve the operation of all systems in the considered network in an acceptable time. Considerations on energy managers, as proposed in [8], [9] and [10] is outside the scope of this report. Indeed the time resolution for considering control algorithms

for such problem is in the range of a second as this report aims to deal with a broader time-scale, typically 15min for the operation part up to a year for the planning part.

Our work is original in two folds, first it investigates the financial burden of operational constraints that would limit the usage of the grid, second the long-term planning highlights how it is possible to reach almost a full PV hosting without having to replace the current transformer and also highlights how the retail electricity price should evolve to maintain the revenue of the DSO.

1.4 Description

This report is divided into three parts, section 2 and 3 describe the achievement and the impact of the deliverable. Section 4 describes the proposed grid operation constraint and its impact on both the profitability of PV-battery system and the network impact. Leveraging on the result of the latter, section 5 presents the results of a long-term planning study in which the evolution of the PV and battery capacity from 2020 to 2050 is presented along with the related consequence on the grid operation, financial impact and retail tariffs. Finally, section 6 summarizes the findings of this report and open for new studies.

2 Achievement of Deliverable

2.1 Date

This deliverable is handed in April 2020.

2.2 Demonstration of the Deliverable

This deliverable shows the existence of a path to high penetration of PV and battery in lowvoltage networks, ensuring at the same time a safe grid operation without reinforcement, high profitability for the prosumers and constant revenues for the grid maintenance. It provides a methodology to assess the possibility of maximizing PV deployment with minimal grid impact.

3 Impact

This works done in the context of the work package 4 *Planning and operation of Distributed generation and MW-class distributed storage systems.* The deliverable leverage on the previous deliverables of the REeL and JARED projects. The complete list of reports from these two

projects can be found in table 1. Part of the work achieved in this scope has already been published [11, 12]. The present deliverable aims to provide guidelines based on scientific approach for decision makers to accompany the energy transition.

Table 1: List of JARED and REeL deliverables on which is built the current deliverable.

REeL	WP5	D1.4.1a	Design of Sizes for Buildings Energy Systems as a Function of the Grid Evolution	[13]
REeL	WP4	D1.1.4b	Determination of the flexibilisation potential of the electricity demand	[14]
REeL	WP4	D1.4.4d	Deployment recommendation for large penetra- tion of PV and distributed storage	
JARED	WP1	D1.2.1	Description of the multi-energy demonstration system in the RE demo site	[15]
JARED	WP1	D1.2.2	Detailed evaluation of the grid operation bottle- necks and load shifting potential for the refer- ence system	[16]
JARED	WP1	D1.2.3	A list of possible ancillary services for enhanced grid operation and implementation of the most effective ones at the RE demo site	[17]

4 Regulation to mitigate the impact of distributed PV and battery systems

4.1 Introduction

High PV penetration in low-voltage grids may lead to over-voltage and lines or transformer overloading. To mitigate these issues, we investigate how an operation regulation could ensure safe grid operation while enabling building owners to recover their investment in a PV and storage system. Operation regulation already exists for PV in some countries. For instance, in Germany, plants with less than 30 kWp are required by law to have a feed-in power limit of 70% or to use remote control power limitations, which means that the injected power to the grid cannot be higher than 70% of the nominal DC power of the PV installation. This doesn't mean that all energy produced above this limit is curtailed since self-consumption of the PV generation is reducing the injection. As a reminder, the following figure gives an illustrative definition of the self-consumption (SC), as well as the self-sufficiency (SS) and PV penetration (PVP) in the case of simple PV system with a load but without any storage means.



self-consumption :
$$SC = \frac{A}{A+B}$$

self-sufficiency : $SS = \frac{A}{A+C}$
PV penetration : $PVP = \frac{A+B}{A+C}$

Figure 2: Illustration of the daily electricity consumption and PV generation.

Consequently, the economic burden caused by this kind of regulation can be lightened by increasing self-consumption when the generation would have been curtailed. This can be done either by using demand-side management (DSM) measures or by storing the PV excess. Assuming the PV levelized cost of electricity (LCOE as defined in [18]) is between the feedin and retail tariff, a battery can help to minimize operating costs in two ways. First, by increasing self-consumption in general, which means storing excess PV when it is higher than the load. This avoids selling the energy at a feed-in tariff lower than the production costs (i.e. LCOE). Secondly, by avoiding PV curtailment due to regulation such as with the enforcement of a feed-in limit. The latter should be prioritized since the curtailed energy is lost, i.e this is lost money. This analysis aims to reply to the following two research questions :

- Which operation constraint (regulation) would ensure a safe grid operation ?
- What is the cost (for prosumers) of this regulation ?

This kind of regulation presents the advantage not to require any communication between the systems and with the grid operator. Advanced electricity tariff structures have the same benefit and have been already investigated [12].

4.2 Methodology

The aim here is not to evaluate a complete list of possible regulations and find the most appropriate one. We want to assess if a selected regulation could ensure a safe grid operation for a low-voltage network in which all roofs are covered with PV while maintaining a reasonable payback period for all distributed PV and battery system owners. This problem requires to find out the optimal operation of those systems under the constraint of the regulation and assess the resulting impact on the network.

The optimal design and operation of a PV and battery system is formulated as Mixed Integer Linear Programming (MILP) problem whose main inputs and outputs are listed in figure 3.



Figure 3: Main inputs and outputs of the design and operation optimization of the PV and battery system.

Given a set of parameters such as the electricity consumption profile P^{LOAD} , PV potential capacity bounded by the roof areas, PV, battery and electricity costs, the optimization returns the optimal design and operation of the system considering both investment and operation costs in the objective function. The optimal design consists in the PV and battery capacities, whereas the optimal operation consists of the power profile of the battery operation and PV curtailment. By conservation of energy, the import power profile P_t^{IMP} and export P_t^{EXP} can be calculated. This optimization is typically executed on a full year at a resolution of 15 min. The complete description of the optimization problem can be found in the article [11]. In this paper, we defined a performance indicator named Grid Usage (GU) which is defined as :

$$GU^{\rm IMP,EXP} = \frac{\max(P_t^{\rm IMP,EXP})}{\max(P^{\rm LOAD})}$$
(1)

This GU basically gives how high is the export or import peak relative to the original peak of the consumption. A GU higher than one means that operation of the PV and battery system potentially requires a more important grid connection than the one needed to meet only the demand. Thus, if we assume a proportionality between the maximum consumption and the ampacity of the line connecting the system to grid, this GU can serve a possible regulation that takes into account the local grid property. It is very similar to the feedin limit discussed above, with the difference that the exchange power is not normalized by the nominal PV DC capacity but by the maximum consumption. It gives the advantage to possibly avoid imposing curtailment in the case of a small PV system with high power demand. This performance indicator GU can be converted into a constraint by adding the following equation to MILP optimization problem.

$$P_t^{\text{IMP,EXP}} < GU \cdot \max(P^{\text{LOAD}}) \qquad \forall t$$
 (2)

Depending on the value of GU, this constraint can make the problem not solvable. Indeed it is always possible to decrease the export power by curtailing the PV generation, but it is not always feasible to decrease the import power. In particularly a GU equals to zero means no exchange with the grid which is never feasible since the battery state-of-charge (SOC) should be identical to the initial SOC at the end of the year.

To assess which operation constraint is sufficient to ensure a safe grid operation, the methodology consists in iterating on the GU constraint from no constraint ($GU = \inf$) and decrease until no grid exchange (GU = 0). When the optimization problem becomes not solvable, the last feasible value of GU is kept for GU^{IMP} and GU^{EXP} is reduced step by step until zero. As shown in the workflow in figure 4, for each GU, the optimal operation of each building of a low-voltage network is resolved. The optimal design is done only once per building without considering any GU constraint and the values are then set as constraints in the following operation optimizations. It implies that for a given GU the design is sub-optimal however, a fixed design allows for a better comparison of the operation metrics between each GU scenarios. Moreover, a full design and operation of each building for each GU would be computationally very demanding.



Figure 4: Workflow to assess the impact of regulation on the grid operation

To assess the effectiveness of the proposed method, the load duration curve at the transformer is used as an indicator for the grid operation. The load duration curve is basically a cumulative probability density function where the axes have been flipped and the probability replaced by the number of hours in a year. An illustrative example is provided in figure 6. Since the transformer of the selected low-voltage network framework is the main bottleneck [12], this indicator is sufficient to assess the grid operation. To assess the operation of each system, two indicators will be used, the PV curtailment ratio and the battery usage. The PV curtailment ratio is defined as the fraction of the PV generation that has been curtailed (see equation 3), as illustrated in figure 5. The battery usage is the ratio between the total amount of energy stored in the battery under a given grid usage constraint and the same quantity under the reference case, without grid constraints, as defined in equation 5. Financial indicators to assess the economic burden of the current grid constraint are the total loss, i.e the sum of the difference between the new operating cost of each building and the reference operating without any constraint as formulated in equation 6, the levelized cost of electricity served, LCOE, as derived from [18] and adapted by replacing, in the denominator, the PV production by the total energy demand, as shown in equation 8.



Figure 5: Illustration of curtailed PV generation

PV curtailment ratio
$$PV_b^{CUR} = \frac{\sum_t P_{b,t}^{CUR}}{\sum_t P_{b,t}^{PV}}$$
(3)

PV penetration
$$PVP = \frac{\sum_{b,t} P_{b,t}^{\rm PV}}{\sum_{b,t} P_{b,t}^{\rm LOAD}}$$
(4)

battery usage
$$Bat_{GU}^{usage} = \frac{\sum_{t} P_{t,GU}^{cHA}}{\sum_{t} P_{t,GU=\inf}^{cHA}}$$
(5)

financial loss
$$\log_{GU} = \sum_{b} \left(OPEX_{b,GU} - OPEX_{b,GU=\inf} \right)$$
(6)

$$NPV = \sum_{t}^{L} \operatorname{CF}_{t} / \left(1+r\right)^{t} \tag{7}$$

levelized cost of electricity
$$LCOE = \frac{NPV}{\sum_{t}^{L} \frac{\left(\sum_{t} P_{t}^{\text{LOAD}} \cdot TS_{t}\right)}{(1+r)^{t}}}$$
(8)

where $P_{b,t}^{\text{CUR}}$ is the curtailed power, $P_{b,t}^{\text{PV}}$ is the power generation without considering active curtailment of building *b* at time *t*. *OPEX* are the operating costs, CF_t is the net cash flow (investment + maintenance cost + operational cost, including battery replacement) at time *t*, *r* the discount rate, *L* the system lifetime, \sum_b indicates a sum over the buildings, if no subscript *b* is indicated it means that the indicator is calculated for each building, but omitted to improve readiness.

net present value



Figure 6: Upper plot : power measurement at the transformer of the low-voltage network HÔPITAL-TR3716 (see section below). Lower plot : corresponding load duration curve

4.3 Framework

The presented methodology is applied to a selected low-voltage network in Rolle, HÔPITAL-TR3716. The selection of this network, in particular, is explained in a previous deliverable [15]. This network, illustrated in figure 7, is composed of 71 buildings with 41 grid connections. All buildings under the same connection point are considered as one system, which means that all roofs from those buildings contribute to the potential PV capacity of the system. Moreover, if the system is composed of multiple households, their electricity consumption profiles are aggregated. We are therefore considering and optimizing 41 energy systems. Original data sources reference can also be found in deliverable [15]. The electricity consumption profiles have been allocated with the method presented in deliverable [16].



Figure 7: Selected low-voltage network HÔPITAL-TR3716 in Rolle. The black line represents the grid. Roofs belonging to building connected to this grid are colourized according to the annual incident irradiance.

	Parameter	Value	Description
TIME	T TS	35040 900 s	number of time steps time steps
PV	$C^{ ext{MOD}} \ \mathbf{C}^{ ext{PV}}_F \ \gamma^{PV}$	$0.83 { m CHF/W} \\ 10049 { m CHF} \\ 0.5\%$	PV configurations, specific costs PV fixed cost annual maintenance specific cost
BATT	C_F^{BAT} C_F^{BAT}	$182 \mathrm{CHF/kWh}$ $0 \mathrm{CHF}$	battery specific cost battery fixed cost
TARIFF	$t^{ m IMP} \ t^{ m EXP}$	$\begin{array}{c} 21.02\mathrm{cts/kWh}\\ 8.16\mathrm{cts/kWh} \end{array}$	retail electricity tariff feed-in electricity tariff
OTHER	$L \ L^{ m BAT} \ r$	25 years 9 years 3%	system lifetime expected battery lifetime discount rate

Table 2: Optimization parameters, expected costs for 2030 [11]

4.4 Results

To cope with the GU constraint, import peaks can be reduced by discharging the battery if this one is not empty. Export peaks, on the other hand, can also be reduced by charging the battery if not full or by curtailment if economically more attractive. Indeed storing each PV excess can require a large battery capacity, involving high investment cost and can be more expensive in the end than simply curtailing the PV excess. Such a strategy is illustrated in figure 8, which shows two days of operation of a selected system. Without regulation, a high share of the PV generation is injected into the grid. A small battery is here use to increase selfconsumption, which is, in this configuration, the only measure that minimizes operating cost. With a GU constraint set to 0.5, meaning for this particular system a maximum exchange power of about 8 kW, a high share of the generation is curtailed.



Figure 8: Operation of the same building, without any constraint (up), with a GU constraint set to 0.5 (down).

In general, the lower the grid usage constraint, the higher the PV curtailment. Figure 9 shows this relation with a boxplot for each value of GU, with a red line representing the median values over the 41 systems. Until a GU constraint of 0.7, PV curtailment is almost zero. Below, it is strongly increasing, reaching a maximum of 80% for a grid usage constraint set to zero, resulting in a self-consumption median to 20%. This quite low value can be explained by the high PV penetration shown in figure 10a. Excepting for two systems, all others have all available roofs covered with PV. As shown in figure 10b, the higher the PV penetration, the lower the self-consumption.



Figure 9: PV curtailment ratio in function of the grid usage constraint.



Figure 10: PV penetration

To cope with the operation constraint but to avoid the loss inherent to PV curtailment, figure 11 shows the batteries usage is increasing. The median of the relative increase of

the energy stored in the batteries compared to the scenario without regulation (GU = Inf), reaches 17% when GU is equal to 0.3. Surprisingly the battery usage is decreasing for a grid usage constraint below 0.3. Without regulation, batteries typically do one full charge and discharge per day to increase self-consumption. When the GU ranges from infinity down to 0.3, batteries usage increase by adding small cycles to meet the operation constraint. When the power feed-in limit becomes too low, batteries can't discharge during the day except if the load is close to the PV generation. This explains why, in the extreme case of forbidding exporting power (GU equals to zero), the battery usage returns close to one, which means that the amount of energy stored in the battery when no export power is allowed is equal to the amount of energy stored when there is no constraint to the export power.



Figure 11: Battery usage in term of energy stored compared to the scenario without regulation in function of the grid usage constraint.

To assess the impact of the regulation constraint on the grid operation, the load duration for each GU is shown in figure 12. The import part of all scenarios are quite similar. However, the aggregated peak export, which is the value on the left vertical axis decreases strongly with the decreasing GU value. In this particular framework, the transformer capacity is rated at 400 kW, which illustrated as a dashed black horizontal line. This implies that only a grid usage constraint set to about 0.3 or smaller would ensure a safe grid operation. The energy loss (kWh) due to a given grid constraint GU is here the area between its load duration curve and the one with no constraint (GU Inf).



Figure 12: Load duration curves of each value of the grid usage constraint.

This energy lost by the curtailment has a direct impact on the profitability of the PV and battery system for the prosumers. Before investing in a system, the LCOE of each consumer is the retail electricity tariff represented by a continuous horizontal black line in figure 13. This retail tariff is 21.02 cts/kWh which is considerably above the median LCOEof all systems operated without constraint (GU =Inf) calculated at 15 cts/kWh. Until a grid usage constraint of 0.6, medians of the LCOE remain close to the original median. Then the LCOE increases while staying below the retail tariff until a grid usage constraint of 0.2. With a GU of 0 or 0.1, more than 50% of the owners would lose money with their PV and battery system. This consideration presupposes the enforcement of the regulation during all the lifetime installation. If it was indeed the case, prosumers would invest in a different design than the one found without constraint. Probably that smaller PV capacity and/or higher battery capacity would be incentivized, which is not desirable at an early stage the energy transition. Finally, one outlier is clearly visible in figure 13. It is a prosumer with a large production, which would lose significantly more than the others with the decreasing GUvalue.



Figure 13: Boxplot of the Levelized Cost Of Electricity (LCOE) in function of the grid usage constraint.

This outlier is represented as a blue square in figure 14 that shows the annual consumption of each system in function of its installed PV capacity. Each square is a system whose colour indicates the relative increase of LCOE when GU is decreased from infinity to 0.3. The ones with the higher increase, shown with a lighter colour, are the ones that have a high PV capacity but only low consumption.



Figure 14: Annual consumption and PV installed capacity for all systems. Squares with lighter colour indicate a higher relative increase of the LCOE when an operation regulation is imposed (GU = 0.3).

If the grid operator had to compensate the shortfall of revenues caused by the introduction of an operation constraint, figure 15 gives how much it would pay to all systems over their lifetime. The sum of all these losses is then shown in figure 16 as well as the maximum power at the transformer in function of the grid usage constraint. This total loss is exponentially increasing with the decreasing GU constraint. It is expected that replacing the transformer would be more profitable at a certain point.



Figure 15: System losses due to the operation constraint.



Figure 16: Sum of the system financial losses and maximum of the power at the transformer in function of the grid usage constraint.

If the systems were optimally designed for each GU, it can be expected that losses would be much smaller. At the same time, the GU limit that would ensure a safe grid operation is also expected to be higher. Finally, it should be noted that the conditions of the initial design and operation optimizations don't incentivize investment in high battery capacity. Indeed, with flat retail and feed-in tariff, battery profitability relies only on the self-consumption enhancement. Although almost all prosumers invest in the maximum PV capacity available (figure 17a), the battery autonomy median is only 0.17, meaning that the battery can store in average 17% of the average daily consumption. However, this relatively low battery capacity doesn't help to mitigate the loss due to the operation constraint.



Figure 17: PV and battery design

4.5 Regulation potential conclusion

Results presented in the previous section have shown that it is possible to ensure a safe grid operation in low-voltage network with a high distributed PV penetration with the help of a regulation constraint. In the selected framework, a grid usage constraint slightly below 0.3 allows to limit the export peaks below the nominal transformer capacity. The operation constraint is met by each system of the low-voltage network by adapting both the battery operation and PV curtailment level. Since the reference flat electricity tariff and battery investment cost framework doesn't incentivize to invest in high battery capacity, the PV energy curtailed quick increase below a GU of 0.7. However, half of the system remain profitable with a LCOE below the retail tariff until a GU of 0.2. Over the 25 years of the system lifetimes, the loss due to regulation constraint is important. This emphasizes the need to properly design PV and storage systems before introducing this kind of operation regulation. Setting a strong regulation overnight doesn't appear as an acceptable solution. In this case, a high share of the systems designed before the regulation would become nonprofitable. One solution could be to introduce year after year a progressive constraint, allowing prosumers to eventually update their system design by increasing, for instance, their battery capacity. This approach will be studied in the following section.

Finally, as an improvement to properly assess the losses, a full design and operation optimization should be carried out for each regulation scenario. Others kinds of regulation could also be investigated using the same methodology. Reproducing the results in others frameworks (i.e. other distribution grids with various typologies) and adding power flow simulation based on optimization results to assess the save grid operation not only at the transformer level but also to ensure that line capacity and voltage constraint are satisfied, would reinforce conclusion of this study.

5 Long term PV and battery deployment in distribution grid

5.1 Introduction

Distribution System Operators (DSO) don't all have a positive view on the deployment of distributed generation. Indeed each household investing in a PV system will import less electricity from the grid, meaning less revenue for the DSO. As shown in figure 18, the cost for the grid maintenance, in particular, the local transport is just a fraction of the of what is paid by the consumer for the imported electricity. As a consequence, households that have invested in a PV system pay less for grid maintenance than households that haven't, even if they are expected to have a similar or high grid usage.



Figure 18: Typical division of the electricity cost for a household in Switzerland.

One legitimate reaction from DSO, could be to increase the retail electricity tariff to maintain their revenue. This will increase the gap between this tariff and the PV *LCOE*, giving a higher incentive to distributed PV generation. This can create a vicious circle, in which households that haven't invested yet are paying more and more for the grid maintenance, increasing unfairness between consumers and prosumers.

The current analysis aims to assess, in this circumstance, the evolution of the retail tariff, assuming the DSO can readjust the tariff year after year. The expected decrease in PV system investment cost is also expected to increase the PV adoption rate and in the same way, the retail tariff. However, this fast increase of the PV penetration could lead to over-voltage and line or transformer over-loading. In the continuity of the previous study (previous sections), to ensure a safe grid operation, a grid usage based operation constraint can be imposed in order to limit the export peaks and cope with the transformer capacity. This constraint should evolve year after year, in function of the PV deployment rate.

To sum up, the aim of the current analysis is to reply to the following two research questions :

- How the retail tariff should evolve to keep DSO revenue for grid maintenance stable ?
- How should regulation evolve to avoid grid reinforcement ?

5.2 Methodology

To assess the retail tariff and required operation regulation evolution, a yearly iteration is done from 2020 to 2030. The workflow in figure 19 illustrates this temporal loop as well as the main actions evaluated each vear. Each vear y, each prosumer of a low-voltage network can invest in a PV and battery system as long as they haven't invested yet. The design of the system is given by the design and operation optimization already introduced in the previous section. If the investment is not only profitable but has an Internal Rate of Return (IRR, defined in equation 9) higher than a given threshold, the prosumer invests in the computed optimal system design. The *IRR* depends not only on the electricity consumption, PV potential but also on the evolution of both battery and PV investment costs described in a preceding paper [11]. The design is fixed henceforth, only the operation of the system can be optimized the following years. Based on the aggregation of the optimal operations of all buildings, the power profile at the transformer level is calculated. If it exceeds the nominal transformer capacity, a more restrictive grid usage constraint is introduced. Taking into account this new constraint, the operation of each system is again optimized. This operation is repeated until the transformer constraint is satisfied. Based on the final optimized operations, the sum of the imported electricity from the network, $E_y^{\mbox{\tiny IMP}},$ is calculated . The network part of the electricity tariff $t_y^{\text{IMP,network}}$ is updated such that the revenue for the network remains unchanged (equations 10 and 11).

$$IRR = r$$
, such that: $\sum_{i}^{L} \operatorname{CF}_{i} / (1+r)^{i} = 0$ (9)

$$t_y^{\text{IMP}} = t^{\text{IMP, energy}} + t_y^{\text{IMP, network}} + t^{\text{IMP, tax}}$$
(10)

$$E_0^{\text{IMP}} \cdot t_0^{\text{IMP,network}} = E_y^{\text{IMP}} \cdot t_y^{\text{IMP,network}} \qquad \forall y \tag{11}$$

Where E_0^{IMP} is the initially imported electricity when all actors are simple prosumer and $t_0^{\text{IMP,network}}$ the initial network part of the electricity tariff. This process is repeated until reaching year 2050.



Figure 19: Flow chart of the long term planning methodology

5.3 Framework

The presented methodology is applied on the network already presented in section 4.3. The only additional parameter is the IRR threshold which is set here at 8%.

5.4 Results

Starting in 2020, the profitability condition implies that only two households are investing in a PV and battery system. The self-consumption of these two systems implies an increase in the retail tariff for 2021. This increase combined with a reduction of both the PV and battery costs contribute to increasing the IRR of a third investment just above the threshold. As shown in the first graph of figure 20, new investments are made year after year. In 2050, 35 amongst the 41 households have invested. All those new systems contribute to rising of the retail tariff, which reaches 27.8 cts/kWh. No regulation to ensure safe grid operation is required until 2026 during which the GU constraint is set to 0.9. This value decreases until 2041 to reach 0.2. Global PV penetration is continuously increasing until 2041 too, when it attains a value of 1.4, implying a PV generation of about 40% higher than the annual consumption of the low-voltage network.



Figure 20: Evolution of the number of investments, import electricity tariff, grid usage GU constraint and global PV penetration from 2020 to 2050.

It is not only the missing investments that explain a global PV hosting lower than one. As shown in figure 21, most systems make use of the full PV potential but not all. Households that invested at the beginning of the simulation period have usually invested in a system with the maximum PV capacity but a rather low battery capacity. Later, the decreasing GU value gives higher profitability to smaller PV systems with larger battery autonomy. The evolution of the global installed PV and battery capacity in the low-voltage network is shown in figure 22. Again, the PV capacity shows a strong growth in the first years and flattens later. Differently, the sum of the battery capacity only starts increasing since 2025 and then grows at a nearly constant rate until 2041, to finally reach a value of almost 400 kWh. This final capacity, assuming a C-rate of one means, incicates that batteries together have a nominal power equal to the local transformer's one.



Figure 21: PV hosting in function of the battery autonomy (battery capacity divided by the mean daily consumption) for each system. The colour of each point corresponds to the investment year.



Figure 22: Evolution of the installed PV and battery capacities.

One of the main idea presented in the methodology is to ensure high profitability for each household investing. In this case study, only investments with an IRR higher than 8% are realized. As shown in figure 23 only outliers are investing.



Figure 23: Internal rate of return of the potential investments. Only systems that haven't already invested in a given year are represented.

The IRR computed (initial IRR) to decided investing or not is unfortunately not the IRR that could be determined at the end of the system lifetime (real IRR). Indeed, the first one assumes the same import tariff and GU for the next 25 years, however, theses two variables are evolving after the investment during the following years. In particular, the increase of the tariff contributes to rising the IRR whereas the decrease of the GU value has an opposite effect. Figure 24 shows an histogram of the absolute difference between these two IRR. The real IRR values are within a 2% percent range around the initially computed IRR. This distribution of the differences is centred on zero and shows that the two effects are reasonably compensating each other.



Figure 24: Histogram of the difference between the real IRR that takes into account GU and t^{IMP} evolution and the initial IRR that supposes those parameters constant from the investment year.

As the rate of the variation of the GU value and t^{IMP} are not the same, we could expect that all first or last investments have, respectively, a lower or higher IRR than the initially computed one. However, figure 25 shows that such correlation doesn't exist. However, a correlation exists between the IRR deviation and PV penetration. Indeed, figure 26 shows a trend indicating an increase of the IRR for low PV penetration and a decrease for high PV penetration systems. This trend can be explained as follows: low PV penetration systems have a profitability that depends more on the tariff than the GU constraint. Consequently, the increase of the tariff makes those systems more profitable than what was initially computed. On the opposite, large PV penetration systems have a profitability that depends more on the GU value than on the tariff. The decreasing GU value makes those systems less profitable than what was initially computed.



Figure 25: Error on IRR in function of the investment year.



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5.5 Long term PV deployment conclusion

Results show a path to high PV hosting in a low-voltage network, ensuring at the same time a safe grid operation without reinforcement, high profitability for the prosumers and constant revenues for the grid maintenance. This path from 2020 to 2050 relies on a 30% increase of the retail tariff, incrementing from 21.02 to 27.81 cts/kWh and a severe operation regulation with a grid usage constraint ending to 0.2 in 2041. It should be clear that the presented methodology gives a path which is sufficient in the sense it ensures all the conditions listed above. However this path in particular is not optimal if optimality is given by the total costs for all actors of the energy transition. As shown in the previous section, imposing a very severe grid usage can lead to high losses that could be avoided by upgrading the transformer at the right time. Obviously in the current framework, line overloading or over-voltages could become the new grid bottleneck, which makes combining energy and grid planning an interesting but complicated task.

The investment condition of our approach is based on an internal rate of return threshold. We shown that the initially computed one is inexact due to the evolution of both the tariff and GU. However, the real value remains in 2% absolute range around. The effects on the profitability of those two parameters evolution are counter interacting with each other, although low PV penetration systems have a higher probability to finally get a higher *IRR* than what was initially estimated.

One improvement, toward a more optimal path, would be to allow an update of the system designs. Indeed, the evolution of the operation constraint is expected to incentivize investment in higher battery capacity. This means that system owners should probably upgrade their system by either installing more PV modules, adding a new battery or replacing an old battery with a larger one. Since it is unlikely that households update their energy system design each year, a new optimal design and operation optimization could be executed after a few years after the last investment. This solution would allow systems to evolve in time and also limit the number of design optimization that are computationally demanding.

Others methods to ensure safe grid operation could be investigated. In this analysis a regulation was chosen, but an advanced electricity tariff structure could maybe at the same time ensure this condition and a constant revenue for grid maintenance.

6 Conclusions

In the context of the current Swiss energy transition, this deliverable gives deployment recommendation for large penetration of PV and distributed storage. In the first part, it has been shown that, even with a high PV penetration, an appropriate operation regulation can be used to ensure a safe grid operation without grid reinforcement. This operation regulation imposes to each system to harvest the flexibility provided by the battery and PV curtailment to limit their feed-in power below a given level. This flexibility, while beneficial for the grid operator, has a cost for the prosumers, and this cost can be particularly high if the system designs don't take into account the introduction of such operation constraint. Fortunately, a high PV penetration at a low-voltage network-level won't occur in one day. A continuous deployment over decades is expected depending on local investment resources, potential profitability and consumer sensibility to sustainable development. This progressive PV deployment suggests that a progressive regulation could be sufficient to ensure a save grid operation in all time. This aspect has been investigated in the second part of this deliverable, taking into account that higher PV penetration could lead to a lack of revenue used to maintain the electrical grid. By ensuring a constant revenue for the DSO through a progressive increase of the retail tariff, a path toward high PV penetration in distribution grids has been shown. The economical impact for prosumers of this assumed unforecasted evolution of the evolution of both operation constraint and tariff has been investigated in detail. These two parameters have a different impact depending on the local PV penetration, but on average seem to counter interact with each other, ensuring a final safe internal rate of return for all prosumers.

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