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Enhancing the economic benefit of fair PV curtailment with an improved remuneration mechanism

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Abstract. With the increase in the distributed renewable energy sources (DRES) in the energy system the problems connected with them have become a major factor. The paper focuses on the voltage control in the distribution network (DN) and on resolving the problem of DRES curtailment in the fairest possible way for the photovoltaic generation plant (PV) owners. Curtailment schemes – uniform and non-uniform implemented for using various PV control strategies (simple, local and overlaying control) are presented. An improved approach to fair economic remuneration for the PV operators for the curtailed energy is proposed. The energy difference between the local control (non-uniform curtailment) and overlaying control (uniform curtailment) is calculated. To increase the efficiency of curtailment and maximise the PV profits, the energy difference between the uniform and non-uniform curtailment can be sold on the balancing market, thus making an additional profit for the PV owners. Trading of this energy should be done by an independent external party with an access to the inverter control. In most cases that would be distribution system operator (DSO) or a third-party aggregator. Money gained by selling that energy on the short-term market would then be distributed to the PV owners using the proposed improved remuneration mechanism. Technical and administrative barriers as well as their solutions are discussed. At the end, simulation results for a typical distribution network are presented and the energy-economic potential of the proposed mechanism is analysed.

Keywords: distribution network, PV non-uniform curtailment, PV uniform curtailment, intra-day and balancing energy market, remuneration business model

Izboljšan način poplačila PV proizvajalcev, temelječ na pravičnem omejevanju PV proizvodnje

Z večanjem deleža obnovljivih virov energije v distribucijskem omrežju, postaja njihov negativni vpliv na kakovost napetosti in zanesljivost dobave električne energije čedalje večji. Članek se osredotoča na regulacijo napetosti v nizkonapetostnem distribucijskem omrežju, ki jo izvajamo z zmanjševanjem delovne moči in s tem proizvodnje električne energije fotovoltaičnih (PV) enot. Napetost v elektroenergetskem sistemu je lokalne narave, zato so PV enote v radialnem distribucijskem omrežju v neenakopravnem položaju. Tiste bolj oddaljene od transformatorske postaje namreč bolj vplivajo na napetost kot tiste, ki so nameščene bliže postaji. Zaradi njihovega različnega vpliva na napetost v članku vpeljujemo načelo enakomernega omejevanja proizvodnje PV virov. Predstavljamo vpliv dveh različnih regulacijskih strategij za zmanjševanje delovne proizvodnje PV virov, preprosto PV regulacijo ter lokalno regulacijo PV enot in ju primerjamo s strategijo enakomernega zmanjšanja proizvodnje PV.

Izboljšati želimo učinkovitost omejevanja delovne proizvodnje PV enot in optimizirati njihov dobiček. Zato privzamemo, da bi se razlika proizvedene energije PV enot, ki bi nastala zaradi spremembe regulacije PV enot, lahko prodala na izravnalnem trgu. Prihodek od te energije bi bil dodaten dobiček PV proizvajalcev, ki bi se pogodbeno razdelil med vse deležnike. Trgovanje z energijo bi izvajal zunanji deležnik, ki bi imel možnost izvajanja regulacije PV enot. V večini primerov bi bil za to najprimernejši sistemski operater distribucijskega omrežja ali upravljavec bilančne skupine, v katero bi spadale posamezne PV enote. Dobiček, ki bi nastal s prodajo energije na trgu, bi se nato med lastnike PV enot razdelil po novem mehanizmu poplačila PV virov, ki ga predlagamo v članku.

V članku se v razpravi dotikamo tudi tehničnih in administrativnih problemov pri uvajanju predlagane rešitve in predlagamo načine za odpravljanje teh težav. V zadnjem delu članka so predstavljeni rezultati izvedenih simulacij in pripadajoča ekonomska analiza.

1 NOMENCLATURE

V_{min}	inverter minimum operating voltage
V_{max}	inverter maximum operating voltage
V_{cpb}	inverter curtailment starting voltage
V_g	voltage at the generator
P_{ref}	max. instantaneous active power of the generator
G	generator
x	level of the overlaying control curtailment of G_1
y	level of the overlaying control curtailment of G_2

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z level of the local control curtailment of G_2

W maximum produced energy of the generator in the time interval

S contracted energy price of the generator

S_m balancing-market price

Π profit of the generator

D contractual profit sharing factor of the generator

2 INTRODUCTION

With the introduction of the 20-20-20 Climate and Energy Package all the EU states had committed themselves to reach by 2020 the goal of covering at least 20 % of the end energy use with electricity production from the renewable energy sources (RES), which has brought a big expansion of RES in the EU states. Especially the share of the photovoltaic (PV) installations has been increasing very rapidly due to the high feed-in tariffs (FIT) and quickly decreasing prices of the PV technology. In future, the expansion of RES will continue as the EU Council set EU-wide target of 27 % of generation from RES to be reached by 2030, [1]. With that, penetration of distributed RES (DRES) will continue to rise and require new control solutions and operating strategies in order to maintain the a safe and reliable power supply.

Transmission system operators (TSO) use ancillary services to ensure safe and reliable operation of the power system. The ancillary services are traditionally provided by the synchronous generation units and typically they control the frequency, active-power reserve, voltage and reactive power, black-start and islanding. Until recent by large fossil-fired generation units have been covering all the needs for ancillary services in the transmission and distribution system. With the increasing share of the DRES units installed in the distribution system, their negative impact on the operation distribution-system has been increasing. In future, they are expected to help providing the ancillary-services support to DSO and potentially even to TSO, [1], [2].

In the EU FP7 INCREASE project, innovative inverters enabling the DRES units to provide the ancillary services were developed. With their active power controlled through an INCREASE-developed multi-agent control scheme, these inverters enable a more flexible operation of the inverter-connected distributed generators (e.g. PV units), thus allowing for more DRES capacity to be installed with no excessive detrimental impact on the distribution network, while also postponing the need for an additional network reinforcement. The key ancillary services investigated in the INCREASE are: voltage control, voltage-unbalance mitigation, line-congestion mitigation and active-power reserve provision [3].

A large penetration of the PV generation can cause overvoltage and current congestions in the low-voltage (LV) distribution network, where most of the DRES units are allocated. Controlling the voltage in a distribution network can be done by focusing on controlling the reactive or active-power generation. Due to the reactive character of the transmission network, control of the reactive power is normally used to control the voltage. In contrast, in the LV distribution network the X/R ratio below 1 makes the voltage control using the active-power control through active-power curtailment a much more efficient solution, [4].

The paper focuses on the voltage control enacted through the active-power control of the PV plants, which mostly entails curtailment of the electricity production. This technology and the discussed strategies can later be expanded also to other DRES. In Section 2, different strategies of the PV generation curtailment are described which have mostly been developed in the INCREASE project. The hypothesis about the possible additional power provided by the PV units under different curtailment strategies is described in Section 3. Based on that hypothesis an improved remuneration mechanism is presented and proposed in Section 4. Section 6 provides a description of the technical and administrative challenges and solutions. In Section 7, a simulation platform and simulation scenarios are described. They provide basis for an economic evaluation presented in Section 8. The final conclusion are drawn in Section 9.

3 PV CURTAILMENT

Because of the R/X ratio in the LV distribution network and the radial operating topology of the network the PV units connected further away from the substation notably impact the local-voltage profile. Since their production results in a considarable voltage rise, the PV producers at the end of the feeder are curtailed more than those closer to the substation, [5], [6].

To control the voltage rise, several control methods can be employed to curtail the active power, leading to different curtailment outcomes for the PV units along the same feeder, Table 1. In this chapter we investigate their impact and consider their qualities.

Table 1:The investigated control strategies

Control type	Abbreviation	Uniform curtailment?
Simple	-	No
Local	LC	No
Overlaying	OC	Yes

A. Simple control

The simple control represents the current business as a usual active-power curtailment scenario. When the voltage level in a PV node exceeds the critical voltage (i.e. 1.10 p.u.), DSO disconnects the PV plant from the grid (lowering its production to 0). In the paper, the results of the simple control are used as a reference point in control-strategy added-value analysis.

B. *Local control*

The local control, also called the droop control in [7], is implemented in the hardware of the PV inverter. It reduces active-power injection of the PV inverter as soon as the voltage at the inverter connection point exceeds the critical value. Two different simulations in [5] and [7] show that this type of curtailment is the most efficient as less power is curtailed on a feeder than in any other control strategy. The local control reduces the active power according to the slope of droop characteristic, Figure 1, where V_{cpb} and V_{max} are the thresholds for activation of the active-power curtailment and for the complete cut-off of the power injection when the PV unit is disconnected. In Figure 1 and (1), V_{min} is the inverter minimum operating voltage and P_{ref} is the maximum instantaneous active power the PV unit can generate. In the simulations, the parameters V_{min} and V_{max} are set to [0.9, 1.1] p.u. according to the network operation limits and V_{cpb} is set to 1.06 p.u., [8], [6].

$$P_{inj} = \begin{cases} P_{ref} & V_{\min} < V_g < V_{cpb} \\ P_{ref} - P_{ref}\dfrac{\left(V_g - V_{cpb}\right)}{\left(V_{\max} - V_{cpb}\right)} & V_{cpb} < V_g < V_{\max} \\ 0 & V_{\min} \geq V_g \text{ or } V_g \geq V_{\max} \end{cases} \qquad (1)$$

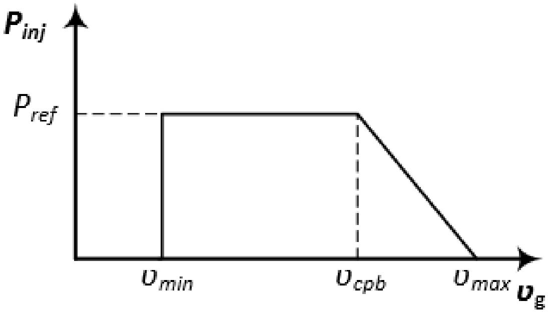

Figure 1: Typical droop curve of controllable PV units

C. *Overlaying control*

Using the local-control, the PV plants at the end of the feeder are curtailed most, which decreases their revenue. The curtailment fairness can be improved by splitting the necessary amount of the curtailed power among all the PV producers connected to the feeder. In [7], a curtailment scheme is presented complementing the local control with an overlaying control (OC). Such combination of the local and overlaying control is sometimes also referred to as integrated control, [7], [6].

In the overlaying control, the voltage is measured in various network points. If an overvoltage is detected, the overlaying control ensures all the PV plants in the feeder to be uniformly curtailed by curtailing the active-power generation of each inverter to the same level. The energy amount that needs to be curtailed is calculated by using the network sensitivity matrix, [7]. In our investigation, the overlaying control always has the local control running in the background as a safety control when an overvoltage is detected as a result of an overlaying-control control error or any other unexpected event, [7], [6].

4 ADDITIONAL POWER FROM DIFFERENT CURTAILMENT SCHEMES

The effect of different curtailment schemes can be evaluated by comparing the total produced energy from the PV units in a LV network in a selected time interval. The amounts of the energy generated in different curtailment schemes described in [7] are taken as a basis for a comparison. Table 2 presents the curtailed-energy levels assumed by the control strategies for two equal PV generators, G_1 and G_2, connected to the same radial feeder. The scenario with no control is included only as an illustration, as it assumes that the voltage constraints are not respected is therefire not a realistic one.

Table 2:The assumed curtailed energy over control strategies

Control	**W_{G1} (%)**	**W_{G2} (%)**	**Total (%)**
No control	0	0	0
Simple control	0	100	100
Local control	0	25	25
Overlaying control	20	20	40

While the overlaying-control strategy improves the curtailment fairness for both generators, G_1 and G_2, compared to the local control strategy, the cost can be expressed as the difference of the total curtailed energies (i.e. 15%). Using our remuneration mechanism, the market value of this energy difference is determined. The market value can be used to propose a fair remuneration scheme for the PV units joining the fair-curtailment scheme.

To determine the market value, a suitable wholesale energy market is selected. The period of the control actions of the advanced PV inverters to enact overlaying control is 15 min, corresponding by with the shortest time interval of the balancing energy market in several EU countries operated by TSO, [15]. We assume that for each 15-minute interval, the energy difference between the local control and overlaying control can be sold on the balancing market. This additional energy is regarded as a short-term upward active power reserve ancillary service provided to TSO.

The main idea of the proposed remuneration mechanism is that DSO that controls the voltage of an LV grid and hence curtails the PV generation effectively uses the local control and only curtails G_2, however, some of the profit the non-curtailed G_1 receives is shared among the two PV producers in the scheme, G_1 and G_2. In this case PV producer payment is composed of two parts: a payment by their retailer for the energy supplied, calculated by the overlaying control under a uniform curtailment scheme, and an additional payment by the ancillary services.

The amount of the additional payment equals the value of the energy difference between the local and the overlaying control sold on the balancing market. This way, there is no need for a complex economic profit-sharing scheme of the PV producers enjoying different retailer purchase prices for the PV energy. No matter which PV producer is curtailed, the price is always tied to the balancing-market price at a given time interval. The scheme can also be coordinated by another commercial entity like an aggregator operating the portfolio of the PV plants and acting as a trader on the balancing market on their behalf.

If for a given time interval it is not possible to sell the energy on the balancing market (e.g. no buying bids) it is assumed that the voltage control is done by an overlaying-control algorithm, and all generators are curtailed uniformly.

5 AN IMPROVED REMUNERATION MECHANISM

To illustrate the improved mechanism, three different scenarios of the energy production and profit shares are presented. Scenario A uses the local control, scenario B uses the overlaying control, and scenario C uses the proposed profit-sharing scheme. For Scenario A, Figure 2 shows the energy production of the two PV generators, G_1 and G_2, for a given time interval. The local control is used to maintain an appropriate voltage level. While G_1 operates at a full power, G_2 is curtailed to level *z*, and has therefore a reduced profit. The profits of generators π_{G1} and π_{G2} are calculated with equation (2).

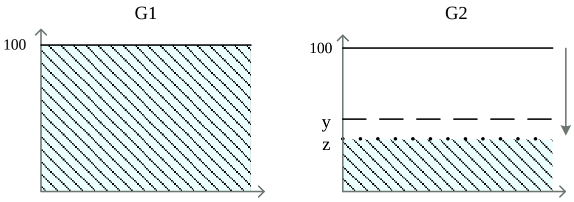

Figure 2: Scenario A – Local-control energy curtailment

$$\begin{aligned} \Pi^{A}_{G1} &= W_{G1} \cdot S_{G1} \\ \Pi^{A}_{G2} &= z \cdot W_{G2} \cdot S_{G2} \end{aligned} \tag{2}$$

Variables W_{G1} and W_{G2} are the maximum produced energy in that time interval, S_{G1} and S_{G2} are their contracted energy prices, and *z* is the energy production of G_2 after the local-control curtailment.

Figure 3 shows dividing the energy production between the two generators using the overlaying control in Scenario B. The PV production is curtailed uniformly to achieve an equal production and income rate. Production of G_1 is lowered to *x*, and G_2 operates at *y*. Although fairness is achieved, with this control, less total energy is injected in the grid. In general, x = y when the generators are the same or when their power is expressed in p.u., while this is generally not the case with different generators.

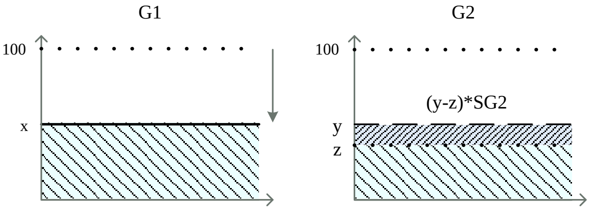

Figure 3: Scenario B – Overlaying-control energy curtailment

The generator profit are calculated as shown in (3), where *x* and *y* are the generator energy productions as a result of the overlaying-control curtailment.

$$\begin{aligned} \Pi^{B}_{G1} &= x \cdot W_{G1} \cdot S_{G1} \\ \Pi^{B}_{G2} &= y \cdot W_{G2} \cdot S_{G2} \end{aligned} \tag{3}$$

The energy that can be sold on the balancing market within the proposed remuneration mechanism under Scenario C is illustrated in Figure 4. While G_1 operates at a full power, G_2 operates at curtailed level *z*, as in Scenario A. Production of G_2 is lower than in Scenario B, but the lost profit is reimbursed from the income made by selling the additional energy from G_1 on the balancing market. Profit π_K that is available for covering the lost profit of G_2 and that is to be shared between G_1 and G_2 comes from G_1. Profit π_K will result if the energy difference between the overlaying and local control is actually sold on the balancing market.

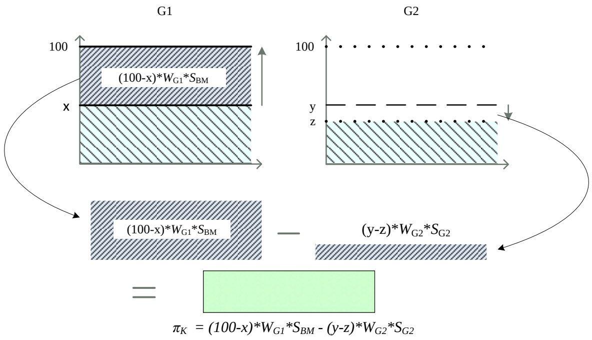

Figure 4: Scenario C - Available energy for the proposed remuneration mechanism

In (4) and (5) the calculation of the profit for each generator in Scenario C is shown.

$$\Pi_K = (100 - \mathrm{x}) \cdot W_{\mathrm{G1}} \cdot \mathrm{S}_{BM} - (\mathrm{y} - \mathrm{z}) \cdot W_{\mathrm{G2}} \cdot \mathrm{S}_{\mathrm{G2}} \tag{4}$$

$$\begin{aligned} \Pi^{C}_{\mathrm{G1}} &= x \cdot S_{\mathrm{G1}} + \Pi_K \cdot D_{\mathrm{G1}} \\ \Pi^{C}_{\mathrm{G2}} &= y \cdot S_{\mathrm{G2}} + \Pi_K \cdot D_{\mathrm{G2}} \end{aligned} \tag{5}$$

In the above equations, S_{BM} is the balancing market price at which the energy difference is sold, and D_{G1} and D_{G2} are the contractual profit-sharing factors that G_1 and G_2 negotiated beforehand, with their sum equalling $D_{\mathrm{G1}} + D_{\mathrm{G2}} = 1$.

In order for the remuneration scheme to operate as foreseen in Scenario C, the following energy assumption must apply:

$$(100 - \mathrm{x}) > \mathrm{y} - \mathrm{z} \tag{6}$$

In (6) it is assumed that the amount of the energy that can be sold on the balancing market is larger than the amount of the energy produced with the uniform curtailment scheme. Profit sharing must also be eligible from the economic aspect, which is checked with (7):

$$S_{BM} \cdot W_{\mathrm{G1}} \cdot \left(100 - \mathrm{x}\right) > W_{\mathrm{G2}} \cdot \left(\mathrm{y} - \mathrm{z}\right) \cdot S_{\mathrm{G2}} \tag{7}$$

The profit from selling the energy difference on the balancing market in Scenario C must be greater than the lost profit of G_2 which it makes in Scenario B with OL. Like in (4), S_{BM} is the energy price on the balancing market and varies with the current energy demand and supply in the system.

When profit $\pi_{\mathrm{K}} = 0$, the conditions for the minimal price on market S_{BMmin} are met. If DSO or the third-party aggregator achieves a higher price on the balancing market, the system is eligible for the Scenario C scheme of profit sharing. From (4), the minimal price is determined as:

$$\mathrm{S}_{BM\,,\,\min} = \frac{\left(\mathrm{y} - \mathrm{z}\right) \cdot \mathrm{S}_{\mathrm{G2}}}{100 - \mathrm{x}} \tag{8}$$

To access the balancing market, a sufficient amount of energy needs to be aggregated beyond the minimum-bid requirement (usually 1 MWh/h). Therefore, aggregation of the generators into a group is required. So, the minimal price for any generator group is defined as:

$$S_{BM\,,\,\min} = \frac{\sum\limits_{\mathrm{i=k+1}}^{\mathrm{n}} \left(\mathrm{x} - \mathrm{z_i}\right) * S_{\mathrm{G,i}}}{\sum\limits_{\mathrm{i=1}}^{\mathrm{k}} (W_{\mathrm{max,\,i}} - \mathrm{x})} \tag{9}$$

where n is the number of all the curtailed generators, k is the number of the less curtailed generators, x is the fair curtailment energy level, z is the energy level of a more curtailed generator, $W_{\max}$ is the production level of a less curtailed generator, and S_{g} is the contracted price of a more curtailed generator.

The entire process is shown in Figure 5. On the start of a 15-minute time block, the power flows are calculated with the forecast data of the demand and supply and possible voltage violations. If there are no voltage violations, production proceeds as planned, while in case of voltage violations, different control strategies are compared regarding the profit gained. The minimal market price required for the remuneration scheme in Scenario C to work is also determined. If the energy can be sold on the balancing market, then the local control is enacted and profit π_{K} is split among the generators, otherwise the generators are uniformly curtailed with the overlaying control.

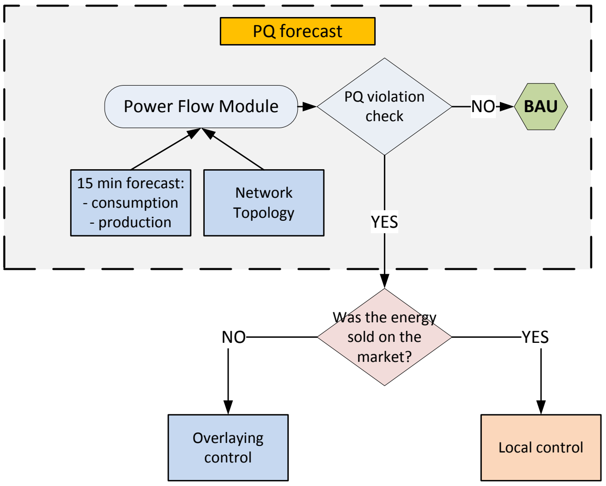

Figure 5: Remuneration-mechanism decision tree

The action timeline-flow chart is presented in Figure 6. We can see that the local control on the generators is always running in the background and acts as a safety mechanism for a possible overvoltage as a result of forecast error or a sudden change. These time intervals were chosen due to the forecast accuracy of production and consumption in the LV network which also affects the overvoltage and curtailment calculations.

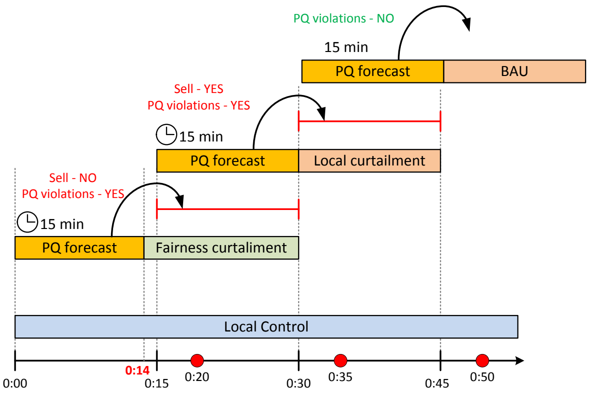

Figure 6: Time schedule of the remuneration mechanism

Determination of the profit-sharing parameters is a matter of a business model. Profit sharing factors D_i are either equal for all generators i or are calculated in accordance with the generator installed power, type and costs at different power rates. For example, for the aggregated wind turbines, their changing efficiency rate and the associated costs with respect to the operating level are taken into account. This kind of the profit-sharing analysis is beyond the scope of this paper.

6 CHALLENGES AND SOLUTIONS FOR THE PROPOSED REMUNERATION MECHANISM

In this section a short overview of the technical and regulatory specifications for the proposed remuneration mechanism is presented.

6.1 *Real measurements*

Every PV producer needs to have a flexible inverter to allow for intelligent control of the output power and a smart meter, to measure the real power production. The measurements are used for calculating the load flows. The load-flow calculations can be used by the aggregator executing the trading to determine the amount of the reserve power that can be potentially sold on the balancing market.

6.2 *Accounting measurements*

For energy accounting and remuneration among the partner PV units in Scenario C, Figure 4, the aggregator needs the "accounting energy values”. They can be obtained by calculating the energy production of different curtailment schemes and by comparing them with real measurements. These calculated accounting energy values are then used for the final remuneration of the PV producers.

6.3 *Forecasting demand challenges*

One of the most important tasks in predicting the curtailment events is forecasting the demand. Forecasting the aggregated demand on the transmission system level has a long tradition and has very reliable forecasting results. Unlike the transmission-level demand, the nature of the demand on a radial LV distribution network is highly local. To forecast the curtailment events on the LV level, a local -emand forecast of a small number of consumers on a single feeder down to a single household is needed. To improve the curtailment-event forecast, the forecasting horizon needs to be very short, from 15 min to 1 hour. So far, only a few researches have been done in the direction of short term forecasting of the household demand. In [9] and [10], it is shown that by using of smart metering data it is possible to forecast local demand with a sufficient accuracy for the needs of predicting the curtailment events.

6.4 *Forecasting PV production*

The PV production on the LV network is very local and weather-dependent, and for long time horizons very hard to predict due to the variability of weather patterns. But to predict a curtailment event, a short-term forecast (from 15 min up to 1 h) of the PV production is sufficient. Contemporary short-term forecasting methods for this time horizon, especially when supported with measurements, are already of the accuracy levels adequate for this purpose, [10].

6.5 *Distribution-network topology and curtailment calculation*

In addition to the demand forecasts and PV generation, a detailed distribution network model is used to calculate the power flows of a LV distribution network as accurately as possible. The power-flow calculation indicates the bottleneck areas where curtailment is most likely to be necessary. After DSO runs a voltage-violation check and calculates the necessary curtailment for that area, the curtailed-energy values for all PV generators are known. From them, the amount of the reserve energy that can be used in the proposed remuneration scheme is calculated as a difference between the uniform and non-uniform curtailment schemes.

6.6 *Regulatory changes*

Currently, in most of the EU countries the DRES curtailed energy is fully remunerated through FIT and is also preferentially dispatched. DSOs have to buy all of the DRES generation, and also remunerate the DRES owners for any energy curtailed. The DRES owners therefore don’t care whether their generation is curtailed or not. For the proposed remuneration mechanism to work, the below three basic regulatory changes need to be affected:

- The DRES generators should not receive any remuneration for the curtailed energy.
- All DRES generators should be capable of executing the local control and overlaying-control control.
- Uniform curtailment scheme with the overlaying-control control should be a mandatory primary control option.

With this changes adopted, the DRES owners would be in favour of participating in the proposed remuneration mechanism as this would increase their profit.

7 SIMULATION SETUP

The proposed remuneration mechanism was tested using a simulation model with a part of the LV network modelled in OpenDSS, [12]. The model resembles a small part of the network of the Slovenian DSO Elektro Gorenjska. The basic network parameters are listed in Table 3 and the topology is shown on Figure 7. The six green dots represent the already installed PV plants in the real network and the red dots represent the locations of new PVs that were added in order to simulate the RES development scenarios.

Table 3: The parameters of the simulation network

Object type	Value
Number of branches	10
Number of nodes	77
Number of loads	70
Number of PV base scenario	6 (already installed)
Transformer	250 kVA (21kV/420V)

To evaluate the technical potential of the controls and economics of the proposed remuneration mechanism, simulations with different parameter settings were tested. The simulations were done using a combination of the Matlab code for different control types and OpenDSS model for the power-flow analysis. Most of the PV production and load profiles used for the simulation of the base-case scenario were taken from the real measurement data provided by Elektro Gorenjska. The additional load and PV profiles added for the RES development scenario were derived from the original data with a 10 % MAPE variation.

Each of the control strategies was simulated with different parameters of the PV unit shares, different loads and different PV production profiles as a result of the seasonal variations. The scenarios were defined as a combination of the control type, number of the PV units and seasons, as shown in Table 4. The number of the combinations and tested scenarios is therefore 3*9*4=108, and the main parameters of the DRES development scenarios are shown in Table 5.

Table 4: The scenario building matrix for technical evaluation

Control type	Nr. of PV units	Season
Simple	6, 9, 12, 15, 18, 21, 24, 27, 30	winter spring summer autumn
Local		
Overlaying		

The installed power of the PV units in Scenario 2 exceeds the installed transformer power by 50 kWh, and in Scenario 9 by 900 kWh, Table 5. This way, the simulation results show that with the proposed remuneration scheme new connections are still possible without upgrading the network, of course, with a significant curtailment. The PV penetration is calculated by dividing the number of the PV units with the nodes in the network.

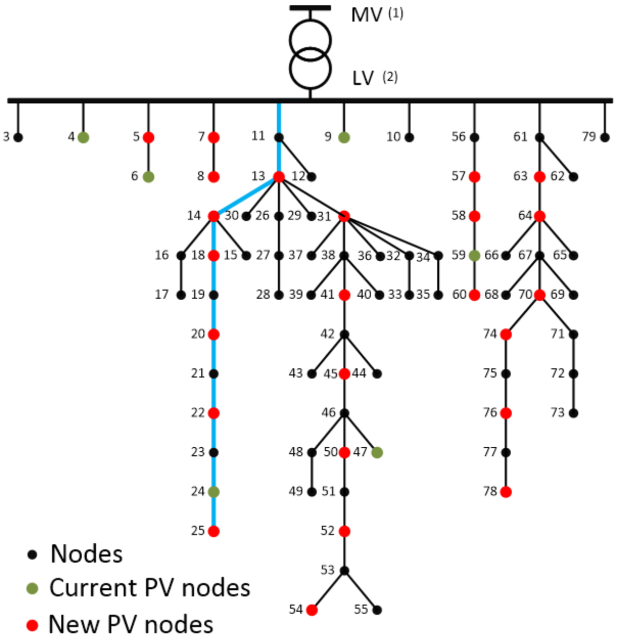

Figure 7: Simulation network topology

Table 5: The DRES development scenarios

Scenario	Number of PV	Installed power [kW]	PV penetration [%]
1	6	209	7.79
2	9	304	11.69
3	12	418	15.58
4	15	513	19.48
5	18	627	23.38
6	21	722	27.27
7	24	836	31.17
8	27	931	35.06
9	30	1045	38.96

8 RESULTS

The simulation scenarios were made for the time period of one week for each season. To calculate the yearly values, the weekly results of the seasons were multiplied by 13. To present the results, we chose the summer scenario because of the high PV production, expected voltage problems and therefore the expected noticeable effect of the control strategies.

8.1 Technical analysis results

The results of the summer scenario for different PV penetration levels are shown in Figure 8 and Figure 9. In Figure 8, the energy sum of all the PVs production is shown by different control strategies. In the graph, no control represents the maximum PV production as if there were no network limits. In the scenarios with up to 15 PVs, there is no curtailment. From the scenarios with 15 PVs to 21 PVs, it's interesting that with the local control strategy we get lees RES electricity fed into the system than with the simple-control strategy. This results from the local-control curtailment which starts at 1.06 p.u., while the simple control shuts down PV at 1.1 p.u. . It is important to note that congestion issues with the MV/LV transformer were not ignored in order to demonstrate the merits of the proposed scheme in none of the simulations and analyses,

With an increased number of PVs, the scenarios with 24 PVs to 30 PVs, the local-control strategy feeds in more RES electricity than the simple-control strategy and this difference proportionally increases with the number of PVs. The overlaying-control strategy always results in lower RES generation than the local control which is expected and can be considered as the cost of fairness. The overlaying-control strategy breaks the barrier of being more effective than the simple control in the scenario with 30 PVs.

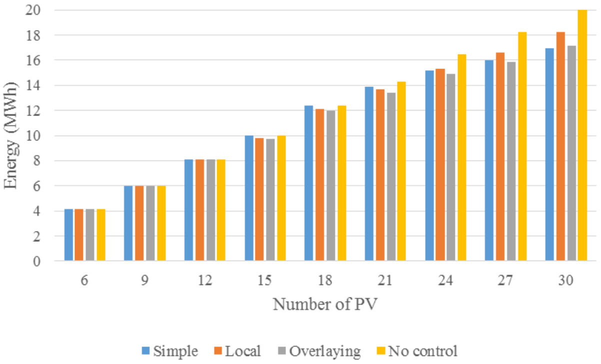

Figure 8: Energy production in the summer simulation per PV scenarios and different control strategies

The energy difference between the control strategies which represents the energy potential for the proposed remuneration mechanism, is presented more clearly in Figure 9 and Figure 10. In Figure 9, we can see that the curtailed energy increases with the PV penetration, and that the difference between the control strategies follows the same trend.

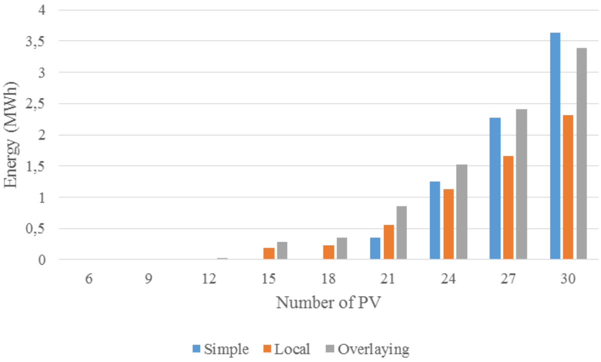

Figure 9: Curtailed energy in the summer simulation per scenarios and different control strategies

In Figure 10 a "turning point" where the local-control and the overlaying control strategies become more effective than the simple control is clearly seen.

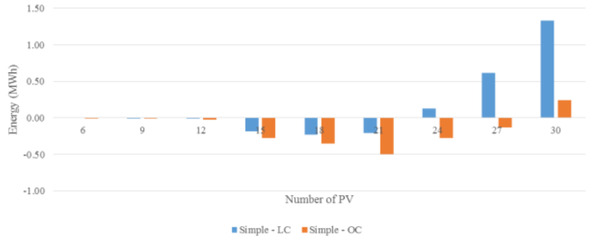

Figure 10: Energy difference between local control and overlaying control against the simple control in the summer simulation over the PV scenarios

Table 6: The energy difference of curtailment between the control strategies

Nr. of PV: 30	**Simple vs. LC**	**Simple vs. OL**	**LC vs. OC**
Winter	6,34	2,83	3,51
Spring	19,91	4,51	15,40
Summer	18,66	3,44	15,22
Autumn	-0,25	-1,76	1,51
Total Year:	**44,65**	**9,01**	**35,64**
Nr. of PV: 27			
Total Year:	**22,92**	**-2,40**	**25,32**
Nr. of PV: 24			
Total Year:	**4,05**	**-10,53**	**14,58**

The simulation results expanded for the yearly values are presented in numerical way in Table 6. The large variations between the seasons can be attributed to the varying solar irradiation, [13].

8.2Economic value analysis

To determine whether the proposed remuneration mechanism would be economically attractive for the PV generators, we compared it with the status quo where all the generators are remunerated by the Feed-in Tariff. For the economic-value analysis, two different approaches were compared, with the energy difference remunerated as if:

- sold on the balancing market, or
- paid by FIT.

Because of the uncertainties of the balancing-market prices, we took a structured approach. As most of the solar energy for the proposed remuneration mechanism is available in spring and summer, we used the average price of the Slovenian balancing market, the BSP Southpool energy balancing market price for July 2015, i.e. 41.44 €, [14]. This price was used as a balancing-market price for the whole year.

In the second case, the average price of FIT in Slovenia from 2009 until December 2014 was used, i.e. 151,7 €. The average was taken because of the PVs different time entries into the FIT scheme, the first PV got a higher support than the new ones, and would still be included in the remuneration schemes.

In the economic-potential assessment in Table 7 a without taking which doesn’t take into account the interest rates or changing the market or FIT prices.

Table 7:The economic potential of proposed remuneration mechanism

Nr. PV:	**1-year profit (€)**		**15-year profit (€)**	
LC- OC	**FIT**	**Market**	**FIT**	**Market**
30	5406	1476	81097	22153
27	3840	1049	57604	15736
24	2211	604	33173	9062
LC- simple				
30	6773	1850	101607	27756
27	3476	949	52149	14245
24	613	167	9206	2514

As seen from Table 7, the values of the profit obtained through the balancing market are quite small and by adding the costs of the inverter, they would probably be hardly profitable even for a high PV penetration.

The FIT evaluation shows a different picture, especially when considering the energy difference between the local and simple control at a high PV penetration. The profit the PV owners would make by installing inverters and local control makes the investment a reasonable choice.

9 CONCLUSIONS

In the paper we investigate the possibility of voltage control in a low-voltage distribution network though the active-power curtailment of the PV units. Several control strategies are compared with regard to their impact on the curtailed energy in a network model, and two curtailment schemes, the uniform and the non-uniform are compared from the energy and economic point of view. The energy difference between the different control strategies is economically evaluated.

An improved remuneration mechanism for the PV generators is proposed that uses the electricity price on the wholesale balancing market to value the energy difference. The mechanism entails the uniform power curtailment and prices the energy difference when sold on the balancing market. This way, the market price of fairness in the uniform curtailment scheme is calculated.

The paper defines the conditions for having the proposed remuneration method efficiently introduced. A methodology for determining the quantity of the additional power under different control strategies is provided along with a methodology of determining its minimal selling price.

By simulating different control strategies on a model of a real LV distribution network, the remuneration concept of the energy difference is demonstrated. An important conclusion from the simulation results is that the simple-control strategy is more effective than the local and overlaying-control strategy in the RES energy infeed in the low PV-penetration scenarios. But this changes with the increasing the PV share where the local- and overlaying control strategies increase their effectiveness in RES electricity injection into the grid.

The results of a basic economical assessment show that using the proposed remuneration mechanism is profitable for high PV penetration scenarios. In the future research, additional assumptions and more detailed scenarios will be investigated in order to further improve the proposed remuneration concept

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