# Cost-effective integration of photovoltaics in existing distribution grids:

## *results and recommendations*

metaPV

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cost-effective integration of photovoltaics in existing distribution grids:
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## COORDINATOR:

### 3E

3E is a technology company in sustainable energy. It provides consultancy and software to improve the performance of renewable energy portfolios, to reduce energy consumption and to facilitate grid and market interaction. 3E's expertise covers solar energy, wind energy, sustainable buildings and sites optimisation, power infrastructure and energy markets.

3E's clients include project developers and investors, power utilities and grid operators, technology manufacturers, asset managers, maintenance companies and public authorities.

## PROJECT PARTNERS:

### AIT - Austrian Institute of Technology

The AIT Austrian Institute of Technology, Austria's largest non-university research institute is among the European research institutes a specialist in the key infrastructure issues of the future. AIT provides research and technological development to realize basic innovations for the next generation of infrastructure related technologies in the fields of health & environment, energy, mobility and safety & security. These technological research areas are supplemented by the competence in foresight & policy development.

### Infrax

Infrax cvba compiles the operational activities of four Flemish distribution system operators. Active in 110 municipalities in Flanders, Infrax manages and operates electricity grids, natural gas networks, cable TV and sewage and invests in the maintenance, improvement and expansion of these networks.

### LRM

As an impact driven Investment Company, LRM is the catalyst for the transition of Limburg's "production economy" towards an innovative and technological economy. Through a uniquely intertwined offer of venture capital and infrastructure, LRM helps to construct qualitative communities around the Limburg industry clusters. This way, the activities of LRM contribute to sustainable and inclusive job creation. LRM targets all sectors and companies, from starting companies to growing SMEs and larger businesses.

### SMA Solar Technology

SMA Solar Technology AG develops, produces and sells solar inverters and monitoring systems for photovoltaic applications. Based in Germany, SMA is the world's largest producer in this segment and the only vendor with a product range matching any module type in any power class.

University *of Ljubljana*
Faculty *of Electrical Engineering*

### University of Ljubljana

The Faculty of Electrical Engineering at the University of Ljubljana is the central research group for distributed energy sources in Slovenia. It focusses on research, development and innovation in the fields of power networks, distributed generation, ICT and energy policy.

## SUPPORTED BY

metaPV

### MetaPV Participants

MetaPV as a real-life demonstration project had not been possible without the engagement of 85 families in Lommel and Opglabbeek, 5 private businesses in Lommel, Heusden-Zolder and Sint-Truiden and 4 public services of the City of Sint-Truiden. MetaPV was successful thanks to their investments into a controllable PV plant and their cooperation during regular on-site interventions.

### European Union

The MetaPV project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 239511.
The project ran from October 2009 until March 2015.

## ACKNOWLEDGED BY

EEGI
EUROPEAN ELECTRICITY GRID INITIATIVE

### European Electricity Grid Initiative (EEGI)

The EEGI Label acknowledges that a specific project is in line with the spirit of the EEGI (i.e. knowledge sharing of results, system level innovation, etc.) and an EEGI Functional Objective as specified in the EEGI Research and Innovation Roadmap. It provides a methodology for identifying the list of projects that form part of the EEGI Roadmap.

# FOREWORD

**Geert Palmers**, CEO 3E

Solar photovoltaics is a no-regret option for Europe's energy policy towards security of supply, competitiveness and sustainability. Its costs declined with a factor of 5 in less than ten years, thereby becoming a competitive and strategic option in the power landscape. Already today, electricity from photovoltaics contributes 3.3% to the Union's electricity demand. Depending on national energy policies, it has substituted power from fossil and nuclear fuel and contributes to a reduction of wholesale prices for electricity.

At the same time, photovoltaics is increasingly facing limits intrinsic to our power system, which has grown historically to bring centrally generated power to the consumers. Decreasing wholesale prices are accompanied by increasing volatility. The decommissioning of thermal power plants may lead to a decline of generation adequacy. And some distribution networks are simply saturated. Without expensive reinforcements, they cannot accept any more power from photovoltaics already today. As a true no-regret option for Europe, photovoltaics needs to transform from being a troublemaker for the grid into a part of the solution. The MetaPV project has shown how this is possible.

MetaPV is the world's first project to show on a large scale and in historically grown distribution networks how photovoltaics can support the grid actively. We show that intelligent control of photovoltaic inverters can increase the capacity of a network for hosting distributed generation by 50%. This is possible at less than 10% of the costs of classical grid reinforcement. This report provides caveats, guidelines and recommendations on how this can be done in practice.

MetaPV owes its success to the engagement of citizens, private businesses and public services in the Belgian province of Limburg. They made their own PV installations MetaPV-compliant and participated in the demonstration. Without their engagement, what you can read in this report had not been feasible.

In order to ensure photovoltaics can further contribute to Europe's energy supply, we invite distribution system operators, industry and regulators to replicate and upscale the solutions we have presented. The MetaPV team is eager to share its experience with you.

**Geert Palmers**, CEO 3E

# EXECUTIVE SUMMARY

## Network Constraints for the Larger Deployment of Photovoltaics

### PHOTOVOLTAICS BECOME SIGNIFICANT

In 2014, electricity from photovoltaics (PV) contributed 3.3% to the European Union's electricity demand with approximately 8% of demand in Germany and Italy, and 3.5% in Belgium. For the Belgian municipalities where the current project took place, PV covered approximately 8% of demand. The share of solar generation in the electricity mix will continue to grow in the years to come. Since solar energy is an endless, indigenous and clean resource, this continued growth is very desirable.

### BOTTLENECKS ARE LOCAL

At the same time, this growth challenges the way distribution networks are planned and operated today. The first effects of increased PV penetration appear locally on the distribution network level: overvoltage on distribution feeders, overloading of feeders and transformers, and undesired exchange of reactive power. These phenomena indicate that the generation capacity a particular network can host is reached. When this so-called hosting capacity is reached, grid reinforcement is usually required before new generation units can be connected. Grid reinforcement usually requires long lead times and it is expensive. It should follow strategic planning rather than being a response to fast changing market dynamics as we have seen them in PV. However, there has been no proven alternative for increasing the hosting capacity of existing distribution networks up to now.

### INVERTER CONTROL IS AN ALTERNATIVE TO NETWORK REINFORCEMENT

Modern PV inverters can be used for grid control, thus increasing the hosting capacity of existing distribution grids. More concretely, controllable PV inverters can adapt their active and reactive power exchange with the grid to influence the grid voltage around the connection point. In addition, battery storage with bidirectional, controllable inverters can be connected to distribution feeders or transformer busbars and buffer PV electricity when active power control is applied. MetaPV has demonstrated this solution on a large scale and in real, historically grown distribution networks.

### METAPV SHOWS ON A LARGE SCALE
### HOW PV CAN SUPPORT THE GRID IN PRACTICE

The overall objective of MetaPV was to show how large amounts of distributed generation can be integrated in real, largely saturated, distribution networks. The project team wanted to investigate and show on a large scale how PV plants themselves can contribute to increasing the hosting capacity and thus substitute for expensive grid reinforcements. This ambition was accomplished with concrete and often quantitative conclusions and recommendations.

## MetaPV as a Real-life Demonstration Project

### THE METAPV DEMONSTRATOR

The MetaPV project is built around a demonstrator, developed for testing and demonstrating the contribution that controllable PV inverters can make for increasing the hosting capacity of distribution grids. The MetaPV demonstrator is distributed in nature. It is situated in the Belgian province of Limburg and extended over a selection of distribution grids within four municipalities. It covers residential-scale PV installations with controllable inverters of 428 kW peak power on low voltage (400 V) and commercial-scale installations with 2.4 MW on medium voltage (10 kV), with locally high concentrations of controllable PV and PV in general.

### CONTROL FUNCTIONS FOR TESTING

The inverters of these PV installations feature different control functions. These are first of all functions for *local control*: the inverter adapts its active and reactive power output as a function of a quantity measured at the point of connection. Examples are reactive power control as a function of voltage ($Q(V)$) or power factor control as a function of power injected to the grid ($PF(P)$). Any of the controllable PV inverters in the demonstrator can be addressed remotely in order to select one of the functions available and set the desired parameters for the chosen control scheme. Moreover, they can be controlled by a supervisory control system that sends them setpoints for active and reactive power output. Setpoints may be calculated centrally, based on broader network knowledge. We then talk about *coordinated or supervisory control*.

### TEST PROGRAMME

The overall objective of the MetaPV demonstration is to test and show how inverter control needs to be organised in practice in order to effectively contribute to extending the hosting capacity of these operational and historically grown grids. For this purpose, an extensive test and evaluation programme was run between 2012 and 2015. This programme essentially contained periodic measurements linked to the study of different control functions, alternating with periods without control for reference. The functions were tested alternately in different parts of the demonstration areas. Finally, the demonstrator also allowed for testing with different communication protocols, enabling us to learn about the practical side of inverter control in the field.

# Conclusions and Recommendations

## HOSTING CAPACITY AND OVERVOLTAGE

For the studied distribution networks, the voltage limit on distribution feeders turned out to be the most prominent constraint for PV. The maximum thermal loading of feeders and transformers and the contractual limit for the exchange of reactive power are much less important as a limit in practice.

In situations with unbalanced voltages over the three phases, reactive power-based voltage control is less effective than in balanced situations. When selecting measures for increasing the hosting capacity in practice, possible unbalanced network states must be taken into account. Smart meters may be used to identify heavily unbalanced feeders and thus concentrate the efforts on situations where they can yield a high benefit.

In general, the hosting capacity can be increased by applying three-phase instead of single-phase installations. The overall hosting capacity may be severely limited with PV power being unevenly distributed over the three phases. Particularly for very long low-voltage feeders, three-phase installations are advised.

## EFFECTIVENESS OF VOLTAGE CONTROL

The project team explored to which extent reactive power control alone or in combination with active power control can effectively do the job of substituting grid reinforcement. Simulations, lab tests and field tests confirmed that the proposed functions for reactive power control can generally operate stably under all network conditions.

Different voltage control strategies using reactive power from PV inverters have been evaluated through simulations and tests in the demonstration areas. For situations with high active power from PV and high voltage on the feeder, all reactive power control strategies succeed in reducing the voltage, often to similar extents. The specific choice of control function and parameter settings should therefore follow additional criteria, namely: efficiency, fairness and simplicity of implementation.

In distribution networks, the effect of reactive power on voltage is primarily proportional to the line reactance $X$, while the voltage increase due to active power is proportional to the line resistance $R$. Therefore, when evaluating the effectiveness for any of these solutions, distribution system operators should calculate the effect based on the ratio $R/X$ for the particular network.

Effective voltage control with reactive power requires as many PV plants on the feeder as possible to participate. If only few PV inverters contribute to voltage control, this will often be insufficient. When many inverters contribute, overvoltage will be mitigated more effectively and the reactive power contribution will be distributed more fairly among the inverters. In practice, this implies that all new inverters should be capable to support voltage control even if applied in a grid where no overvoltage is expected on short term.

## SELECTION OF VOLTAGE CONTROL FUNCTIONS

The selection of control functions is driven by these criteria: effectiveness, efficiency, fairness and simplicity. *Effectiveness* of a control measure in the MetaPV context denotes how well the measure can contribute to increasing the network hosting capacity. *Efficiency* relates to the effectiveness of a measure to the expense required for achieving the desired effect. The efficiency mainly depends on the amount of reactive power flowing over the network with the different control systems. This reactive power may cause electrical losses and additional costs. *Fairness* evaluates the distribution of reactive and active power control actions over different PV installations. By intuition, a control function may be considered fair when it ensures that the burden of voltage control is shared by all PV plants on a feeder in proportion to their active power outputs. *Simplicity* evaluates the effort required for implementing, operating and maintaining the voltage control approach on a large scale.

The results show that different local control functions offer a different trade-off between effectiveness, efficiency, fairness and simplicity (Table I). The best solution depends on the particular network and the local voltage conditions. For a simple and efficient solution, *PF*(*P*) and *Q*(*V*) with an appropriate deadband are the first choices. For a fair solution, *PF*(*P*) or coordinated control can be used.

**TABLE I:** QUALITATIVE COMPARISON OF REACTIVE POWER CONTROL SCHEMES
(++ CRITERION FULFILLED, + CRITERION APPROACHED, - CRITERION NOT FULFILLED)

| | Effectiveness | Efficiency | Fairness | Simplicity |
|---|---|---|---|---|
| Q(*V*) with small/no deadband | ++ | - | - | ++ |
| Q(*V*) with medium deadband | + | + | - | ++ |
| Q(*V*) with large deadband | - | ++ | - | ++ |
| Q(*V*) with location-based deadband | + | ++ | + | + |
| *PF(P)* without deadband | + | + | ++ | ++ |
| *PF(P)* with deadband | + | ++ | ++ | ++ |
| Coordinated control with uniform *Q* | ++ | + | + | - |
| Coordinated control with uniform *PF* | ++ | + | ++ | - |
| Coordinated control (hierarchical) | ++ | ++ | - | - |
| Constant *Q* / Constant *PF* | ++ | - | ++ | ++ |

*PF*: power factor, *P*: active power, *Q*: reactive power, *V*: voltage, *Q*( )/*PF*( ): *Q*/*PF* controlled as a function of

As a general trend, the most effective control functions cause a high local consumption of reactive power. Therefore, the ideal function for local voltage control meets but does not exceed the required effectiveness. It is efficient, i.e., it consumes reactive power mainly when this is needed. And it fulfils the grid operator's expectations in terms of fairness and simplicity.

Finally, hierarchical coordinated control is more efficient than any local reactive power control but more complex to implement. Therefore, coordinated control of PV inverters is mainly advisable for distribution system operators that have or plan to introduce a strong communication infrastructure. This way, the specific effort for introducing reliable, secure and scalable means of communication and data handling will be of relatively lower weight.

## IMPLEMENTATION AND STANDARDISATION

MetaPV and other projects showed that distribution networks are heterogeneous and that only some distribution networks pose a severe limit to PV integration, while the majority of them is able to host a large amount of PV generation. For networks approaching saturation, distribution system operators should consider reactive power control with PV inverters, on-load tap changers for the secondary substation and possibly local storage. These solutions may serve to substitute for a grid reinforcement or postpone it until the anticipated generation and load on the network have become clearer.

Local voltage control by inverters does not strictly need a communication link. However, when the inverters' controller settings would need to be updated, this needs to be done manually if no communication link is available. For this purpose, a common secured internet connection is sufficient. Hierarchical coordinated control by the distribution system operator will in any case require a communication link. For this purpose, the distribution system operator will probably apply a private connection for supervisory control and data acquisition (SCADA) as it is common in the power industry. In any case, the communication with the PV inverters needs to be reliable and secure.

In grid codes and standards, the requirements for active and reactive power control should be further harmonized in order to ensure that the available control functions can be applied broadly. This way, distribution system operators have access to the control of their choice and exchange their experiences. Standardisation is required in terms of hardware design, software design and communication. The parameter settings for different control functions should remain adjustable per country or per grid.

## ECONOMICS

The MetaPV team wanted to show whether the hosting capacity of a given network can be increased by more than 50% at the cost of 10% of traditional grid reinforcement. Based on the technical findings and cost figures from the MetaPV demonstration, this question was answered positively. For medium-voltage grids it is always possible. For low-voltage grids, it is possible as long as the costs of sophisticated features for communication do not eat up the savings from the substituted grid reinforcement.

The economics of voltage control depend on different aspects as shown in Figure I. The results on the ordinate show the lifecycle costs in net present value as they incur for achieving the increase in hosting capacity denoted on the abscissa. The different cases, as indicated by the legend, differ in whether the reactive power is controlled centrally or locally, whether it is complemented by either storage or intelligent curtailment and, in addition, the communication equipment used. They are compared to grid reinforcement by means of an additional distribution cable. To correctly read the figure, one has to look (i) at the targeted capacity, (ii) at the colour representing the voltage control solution and (iii) at the final cost indicated by the marker representing the type of communication.

Figure I was made for low-voltage grids. For medium-voltage grids, the quantitative results differ but point into the same direction. In particular, the costs for communication are relatively lower on medium voltage. As a consequence, on medium voltage, the solutions making use of a private SCADA network are also very competitive for a hosting capacity increase of 50% and more.

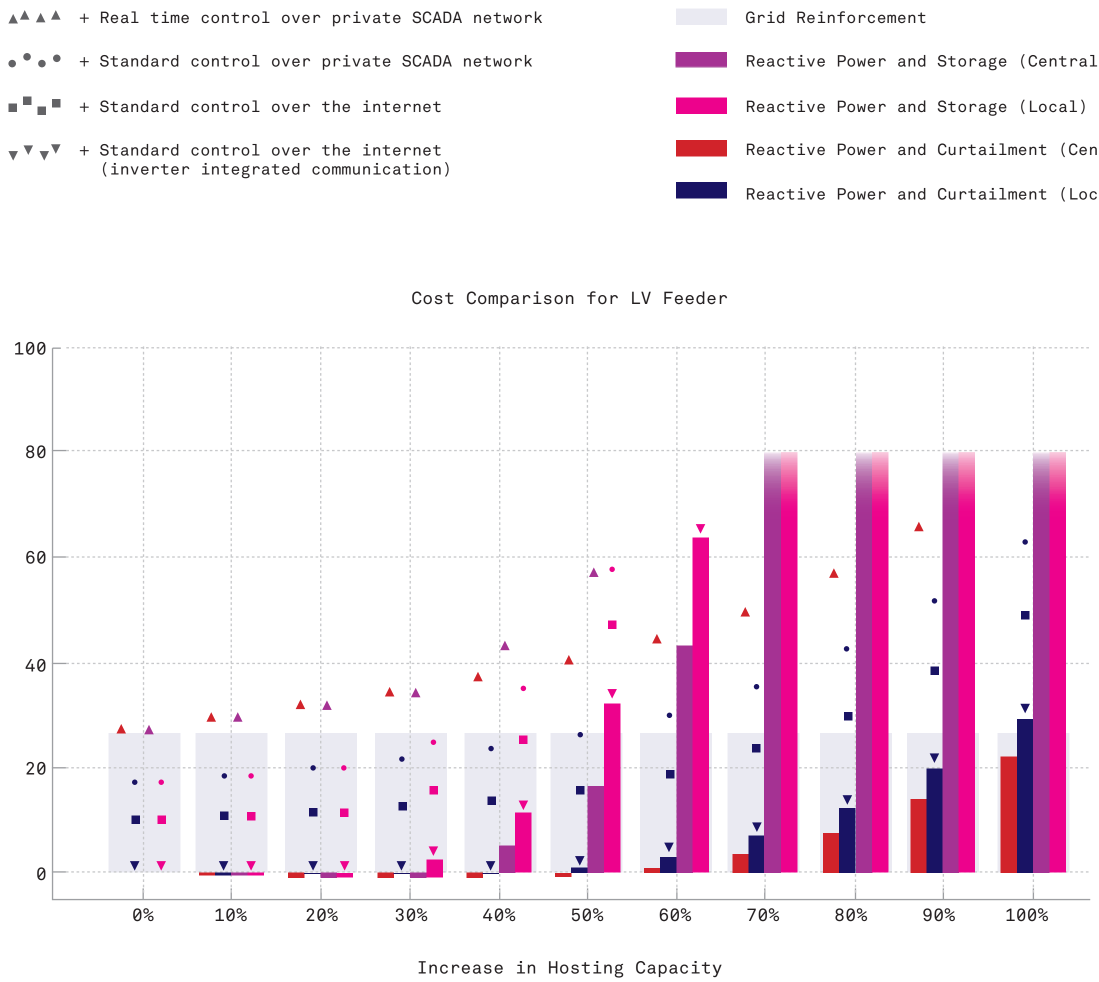


**FIGURE I:** COST COMPARISON FOR LOCAL OR COORDINATED (CENTRAL) REACTIVE POWER CONTROL AND GRID REINFORCEMENT, COMPLEMENTED BY EITHER STORAGE OR CURTAILMENT FOR DIFFERENT WAYS OF COMMUNICATION

### INTELLIGENT CURTAILMENT AND STORAGE

Intelligent curtailment refers to gradually limiting the PV power output before a grid constraint is reached. Intelligent curtailment is technically and economically suited to complement reactive power control. It can be used for reducing overload on feeders and transformers or controlling the voltage on distribution feeders. By accepting a very small decrease of the annual energy yield, active power control can contribute to significantly increase the hosting capacity of a network. Currently, in most parts of Europe, active power control is not foreseen as a common control action. If it should contribute in the future, several political questions need to be answered and translated into regulation.

Storage today is barely competitive with intelligent curtailment. In the future, its deployment will depend on costs and its ability to serve complementary use cases with a single storage system. For example, increasing the hosting capacity locally may be complemented by increasing the local self-consumption of electricity from PV or providing ancillary services to the transmission system operator.

## Overall Conclusion

The MetaPV project has shown and documented how PV can actively support the grid. The proposed solutions help to increase the share of variable renewables that can be integrated into the distribution grid. They can veritably complement network reinforcement on distribution level. They can reduce investment costs by introducing a more agile and stepwise solution for increasing the hosting capacity of our grids. As such, they contribute to keeping grid fees affordable in the future.

Most of the detailed project results are publicly available in project reports and scientific papers. Distribution system operators, industry and regulators are encouraged to build further on these results for improving, replicating and upscale the solutions presented here.

# Contents

# 00

# ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| **3G** | third generation technology for mobile telecommunication |
| **AC** | alternating current |
| **CHP** | combined heat and power |
| **const.** | constant |
| **DC** | direct current |
| **DSO** | distribution system operator |
| $f$ | frequency |
| **FTP** | File Transfer Protocol |
| **GPRS** | General Packet Radio Service |
| **HTTP** | Hypertext Transfer Protocol |
| $i$ | phase number |
| **LDB** | location-based deadband |
| **LV** | low voltage |
| **MicroSCADA** | small-scale SCADA |
| **MV** | medium voltage |
| **OLTC** | on-load tap changer |
| $P$ | active power |
| $PF$ | power factor |
| **pu** | per unit |
| **PV** | photovoltaic |
| $Q$ | reactive power |
| $R$ | electrical resistance |
| **SCADA** | supervisory control and data acquisition |
| **UPS** | uninterruptible power supply |
| $V$ | voltage |
| $V+$ | positive sequence voltage |
| $V-$ | negative sequence voltage |
| $VUF = V-/V+$ | voltage unbalance factor |
| **VREG** | Flemish Regulator of the Electricity and Gas Market |
| **Wp, kWp** | watt peak, kilowatt peak |
| $X$ | electrical reactance |

# INTRODUCTION

# 01

# 1 INTRODUCTION

## 1.1 Context

### PHOTOVOLTAICS BECOME SIGNIFICANT

At the end of 2014, approximately 180 GW of photovoltaic (PV) peak power generation capacity were operating world-wide. Half of this is installed in the European Union. There, within five years, the installed PV capacity increased from 16.9 GW at the end of 2009 to approximately 90 GW by the end of 2014. In 2014, electricity from PV contributed 3.3% to the Union's electricity demand with approximately 8% of demand in Germany and Italy, and 3.5% in Belgium [1]. For the Belgian municipalities where the MetaPV demonstration took place, PV covered approximately 8% of demand. The share of solar generation in the electricity mix will continue to grow in the years to come. Since solar energy is an endless, indigenous and clean resource, this continued growth is very desirable.

At the same time, this growth challenges the way distribution networks are planned and operated today. The first effects of increased PV penetration appear locally on the distribution network level: overvoltage on distribution feeders, overloading of feeders and transformers, and undesired exchange of reactive power.

## 1.2 Problem Description

### BOTTLENECKS ARE LOCAL

Local grid bottlenecks already appear today. In particular, PV installations at the end of long distribution cables and in areas with a very high connection density of distributed generation face such bottlenecks. Already with today's 3.3% of electricity from PV in the EU, local bottlenecks regularly hamper the deployment of PV when the amount of generation that a particular network can host is reached. Some distribution grids with a high density of PV are saturated already today. When this so-called hosting capacity is reached, grid reinforcement is usually required before new generation units can be connected. Grid reinforcement usually requires long lead times and is expensive. It should follow strategic planning rather than being a response to fast changing market dynamics as we have seen them in PV. However, there has been no proven alternative for increasing the hosting capacity of existing distribution networks up to now.

### THE CONCEPT OF HOSTING CAPACITY

According to Yang and Bollen [2], the hosting capacity of a network for distributed generation (DG) can be defined as follows:

> *"The hosting capacity is the maximum DG penetration for which the power system operates satisfactorily. The hosting capacity is determined by comparing a performance index with its limit. This limit is the limit of satisfactory operation of the power system. The performance index is calculated as a function of the DG penetration level. The hosting capacity is the DG penetration level for which the performance index becomes less than the limit."*

The chosen performance index depends on the type of bottleneck that is expected to become significant first, for example: voltage over the feeder, feeder loading or reactive power exchange. For the networks studied in MetaPV this was firstly the voltage on distribution feeders, and the project mainly focusses on so-called voltage hosting capacity. In one specific situation, without taking further measures, the installed PV plant would have caused the overload of the existing transformer of a medium voltage grid, thus exceeding the so-called current hosting capacity.

Notably, the concept of hosting capacity as we use it here does not account for other phenomena such as network losses, flicker or harmonics. Such indicators have been assessed as secondary performance indicators.

## INVERTER CONTROL AS ALTERNATIVE TO NETWORK REINFORCEMENT

Modern PV inverters can be used for grid control, thus increasing the hosting capacity of existing distribution grids. PV can actively provide “local ancillary services for network operation to improve its power quality, security and efficiency” [3] and, thus, actively contribute to system reliability. More concretely, controllable PV inverters can adapt their active and reactive power exchange with the grid to influence the grid voltage around the connection point. In addition, battery storage with bidirectional, controllable inverters can be connected to distribution feeders or transformer busbars in order to reduce losses of PV electricity when active power control is applied.

This way, instead of applying the classical approach (see box) of a stepwise grid reinforcement, every time a hosting capacity limit is attained, distribution system operators (DSOs) may opt for an evolutionary and more agile approach: to increase the hosting capacity by using distributed control facilities. Hence,  large investments in grid reinforcement can be deferred or even avoided.

**The classical approach of increasing the grid hosting capacity for PV**

When the hosting capacity limit is reached in a distribution grid, DSOs first check whether the limit can be extended by adapting the configuration of the existing grid. In some cases, this is possible without large investments. One solution may be a change of topology of the grid, which can often be done by adapting the normal position of some switches. Another solution may be to redistribute existing single-phase-connected PV generators more evenly over the three phases of the grid. This second solution particularly applies to the low-voltage level when the hosting-capacity limit is reached on one or two phases only.

When these measures are exhausted, the network should be reinforced. In practice, this means adding an asset to the grid, e.g., an additional cable in parallel to the congested one, or a new transformer.

Good knowledge of the real network situation as well as a reliable forecast of load and generation in the specific grid section are required for the right decision, technically and economically, in line with the DSO’s long-term network development strategy. When this knowledge or forecast are missing, the risk of either delays in the connection of new generators or the risk of inefficient investments is high.

### OUT OF THE LAB – INTO THE FIELD

Concepts for using PV inverters to provide ancillary services for grid support have been published in literature for quite some time [3]–[5]. Such features have been implemented into inverters and tested successfully in research labs and outdoor test sites. However, when MetaPV started in 2009, none of these devices had been applied in real grid operations at large scale. There was a wide gap between the scientific state of the art on one side and the application and market introduction on the other, leaving a long list of open questions for practical application. The missing step was a demonstration on a medium to large scale which would allow us to prove the technical and economic feasibility and identify the necessary improvements needed for a large-scale introduction. MetaPV contributed to closing this gap by demonstrating this solution on a large scale and in real, historically grown distribution networks.

## 1.3 Objectives

The overall objective of the MetaPV project was to show how large amounts of distributed generation can be integrated in real, largely saturated, distribution networks. The project team wanted to investigate and show on a large scale, how PV plants themselves can contribute to increasing the hosting capacity and thus substitute for expensive grid reinforcements. The team was looking for answers to the specific questions listed here.

The present report contains a brief description of MetaPV as a demonstration project and then focusses on conclusions and recommendations. A detailed description of the work including methodology and direct technical results is available in [6]. Additional reports and publications are available from the project website at http://www.metapv.eu.

### HOSTING CAPACITY AND OVERVOLTAGE

How is the hosting capacity of grids limited in practice? Which types of constraints are exceeded in reality: voltage limits on distribution feeders, maximum thermal loading of feeders and transformers, or contractual exchange of reactive power? In practice, the voltage limit on distribution feeders turned out to be the most prominent constraint and the MetaPV project showed how to mitigate this by means of controlling PV and also some storage systems. Based on the practical findings, particular attention was paid to low-voltage networks with unbalanced loading or generation.

### EFFECTIVENESS OF VOLTAGE CONTROL

How can reactive-power-based voltage control with PV inverters be effective in a historically grown network? In distribution networks, the effect of reactive power on voltage is primarily proportional to the line reactance, while the voltage increase due to active power is proportional to the line resistance. The project team wanted to explore to which extent reactive power control alone or in combination with active power control can really do the job of substituting for a grid reinforcement. How should reactive power control be executed and parametrized in order to be as effective as possible, preferably without curtailing active power?

## VOLTAGE CONTROL EFFICIENCY

When different functions for reactive power control are available, which is the best for a specific network? Besides effectivity of the control, the choice will depend on efficiency, i.e., the additional reactive power exchange over the network along with the associated losses. It also depends on the stability of the control system. For example, instable control systems might cause oscillations. Moreover, since the distribution system is a common infrastructure that links its different users with each other, DSOs and regulators may want to see the burden of reactive power control distributed fairly over the PV customers, according to their active power injection. And finally, the practical applicability of different solutions also depends on their technical complexity: the simpler a solution is, the lower its risk and up-front costs and the easier it can be rolled out as a substitute for grid reinforcement.

## IMPLEMENTATION AND STANDARDISATION

How can voltage control with PV inverters become a standard option for connection studies and network planning procedures at DSOs? Can communication with PV systems be established in an easy, reliable and secure way? In order to introduce competitive products for the European market and beyond, the features and functions for voltage control need to be standardized throughout Europe. MetaPV also wants to serve as a reference for standardisation committees and grid code working groups world-wide.

## ECONOMICS

Finally, the MetaPV team wanted to show whether the hosting capacity of a given network can be increased by more than 50% at the cost of 10% of traditional grid reinforcement. Based on the technical findings and cost figures from the MetaPV demonstration, this question was answered positively. For medium-voltage grids it is always possible. For low-voltage grids, it is possible as long as the costs of sophisticated features for communication do not eat up the savings from the substituted grid reinforcement. This techno-economic evaluation includes investment costs, ohmic and curtailment losses and also the alternative of storage versus intelligent curtailment. The detailed economic analysis made by the MetaPV team can serve policy and regulation to allocate costs and benefits to the different stakeholders involved.

## THE DEMONSTRATOR IN PRACTICE

The MetaPV team managed to achieve these objectives by means of theoretical study, modelling and simulation, practical testing and analysis of the results with the MetaPV demonstrator. The MetaPV demonstrator was designed by the project team and installed successfully in the Belgian municipalities of Lommel, Opglabbeek, Sint-Truiden and Heusden-Zolder. This was possible thanks to the engagement of 85 families, 5 private businesses and 4 public services in these municipalities who made their own PV installation MetaPV-compliant and available for the demonstration. During the past three years, the project team could rely on these installations for analysis and testing and so all project results presented inthis report are reality-proven.

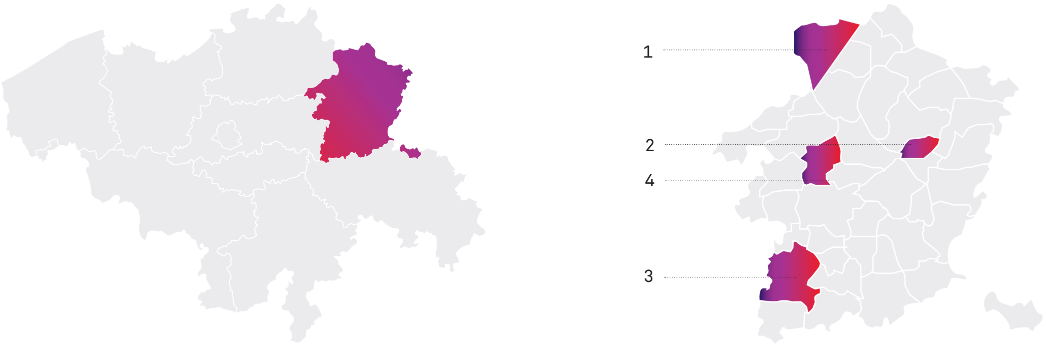
# WHAT IS METAPV

# 02

# 2 WHAT IS METAPV

## 2.1 The MetaPV Demonstrator

The MetaPV project is built around a demonstrator. This infrastructure was developed for testing and demonstrating the contribution that controllable PV inverters can make to increasing the hosting capacity of distribution grids. The MetaPV demonstrator is distributed in nature. It is situated in the Belgian province of Limburg and extended over distribution grids in the four municipalities of Lommel, Opglabbeek, Sint-Truiden and Heusden-Zolder (Figure 1). It covers residential-scale PV installations with controllable inverters of 428 kW peak power on low voltage (400 V) and commercial-scale installations with 2.4 MW on medium voltage (10 kV), with locally high concentrations of controllable PV and PV in general (Table 1).



(a) Province of Limburg in Belgium

(b) Municipalities in Limburg

**FIGURE 1:** THE DEMONSTRATION TOOK PLACE IN FOUR MUNICIPALITIES IN THE BELGIAN PROVINCE OF LIMBURG (1 TO 4: LOMMEL, OPGLABBEEK, SINT-TRUIDEN & HEUSDEN-ZOLDER)

By the end of 2014, the total PV capacity of controllable and uncontrollable installations in theses municipalities was approximately 42 MW[1]. In several sections of the grids being part of the demonstrator, the hosting capacity limits are reached and may even be exceeded from time to time.

The overall objective of this demonstrator was to test and show how inverter control needs to be organised in practice, in order to effectively contribute to extending the hosting capacity of these operational and naturally grown grids. For this purpose, an extensive test and evaluation programme was run between 2012 and 2015. This programme essentially contained periodic measurements with the different control functions studied, alternating with periods without control for reference. The functions were tested alternately in different parts of the demonstration areas. Finally, the demonstrator also allowed for testing with different communication protocols and learn about the practical side of inverter control in the field.

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[1] Based on data from the Flemish Regulator of the Electricity and Gas Market (VREG).

**TABLE 1:** OVERVIEW OF THE METAPV DEMONSTRATOR

| | Lommel | Opglabbeek | Sint-Truiden | Heusden-Zolder |
|---|---|---|---|---|
| Targeted grids | MV + LV | LV | MV | MV |
| Number of LV controllable PV systems | 45 | 40 | | |
| Capacity of LV controllable PV systems (kWp) | 215 | 213 | | |
| Capacity of LV total connected PV capacity (kWp) | 12 030 | 4 620 | | |
| Number of MV controllable PV systems | 2 | | 6 | 1 |
| MV controllable PV capacity installed (kWp) | 371 | | 1 617 | 396 |
| MV total connected PV capacity (kWp) | 10 380 | | 16 080 | 15 420 |
| Storage systems | 2 | 3 | 1 | |
| Storage system rating | 2 systems with inverters of 4.6 kW each | 3 systems with inverters of 4.6 kW each | 1 inverter 180 kVA; 60 kW charging, 100 kW discharging | |
| Storage capacity | 2 systems of 7.4 kWh each | 2 systems of 7.4 kWh each; 1 system of 14.8 kWh | 58 kWh | |

The PV installations in low-voltage (LV) grids are entirely installed at private households and owned by them. The PV installations in medium-voltage (MV) grids are installed at local businesses and public institutions, and owned partly by the businesses and third-party investors. These parties agreed to buy a PV installation with a controllable inverter offered by the MetaPV project at a discount price. In exchange, they allowed access to the inverter control and the measured data.

In addition, several households installed a battery system. These installations can be operated in support of voltage control or in order to minimize the grid injection of active power from these households. Moreover, in case of a blackout they ensure the household remains powered by functioning as an uninterruptable power supply (UPS).

Finally, the medium voltage PV installation connected at the municipal workshops of Sint-Truiden (called “Werkplaatsen”) is complemented with a large battery system. It serves as a buffer for electricity generated by PV at times when the medium voltage transformer of these workshops is fully loaded. Other control objectives are possible as well; however, no UPS function has been foreseen here.

## 2.2 Types of Grids

The demonstration takes place in different medium-voltage and low-voltage grids, which in terms of nominal voltage, topology and realisation are typical for distribution systems in Belgium.

### MEDIUM-VOLTAGE GRIDS

The three medium-voltage grids in the demonstrator have a nominal voltage of 10 kV, which is a common value for medium voltage in Belgium.

- The Lommel substation connects 33 feeders, some of which are very long. It has access points to industrial consumers directly connected to the 10 kV busbar, large renewable power plants and low-voltage grids. Around 16 MW of wind power generation is present here, along with a large amount of PV generation, some combined heat and power (CHP) plants and important loads. The Lommel substation has a peak load of 38.3 MW.

- The eastern part of the medium-voltage grid in Sint-Truiden is connected to the Brustem substation. The western part is connected to the Sint-Truiden substation. The Brustem substation connects 26 feeders. It has a peak load of 25.4 MW and a total installed PV capacity of approximately 15 MW. The Sint-Truiden substation connects 31 feeders. It has a peak load of 28.1 MW and a total installed PV capacity of approximately 10.5 MW.

- The medium-voltage grid in the municipality of Heusden-Zolder is connected to the Houthalen substation. The substation connects 30 feeders, including a direct access point (2 feeders) for a 6 MW CHP plant. The peak load of the substation amounts to 26.8 MW.

### LOW-VOLTAGE GRIDS

The low-voltage grids are a subset of all low-voltage grids in Lommel and Opglabbeek. They have a nominal voltage of 400 V.

- 104 low-voltage grids connected to the medium-voltage grid of the Lommel substation. These grids are estimated to connect to 1379 houses. The demonstration covers 13 of these grids.
- 105 low-voltage grids connected to the medium-voltage grid of the Opglabbeek substation. These grids are estimated to connect to 1187 houses. The demonstration covers 11 of these grids.

In the studied grids, for all secondary substations (also referred to as cabins), the electrical parameters voltage, current, active and reactive power are measured in high time resolution on the low voltage sides of the transformers. These data are returned to the distribution management system of Infrax where they are displayed to the operator and recorded.

The low-voltage grid cabins “Molsekiezel” in Lommel and “Lijsterstraat” in Opglabbeek contain nine and eight controllable PV installations, respectively, and each a storage system. The first cabin has specially been equipped with a voltage regulator, connected in series to one of the feeders, and the second cabin has been equipped with a transformer with on-load tap changer (OLTC). Both devices monitor and control the voltage locally, each in a different way. They are accessible to the DSO by using a MicroSCADA system. This setup allows to study the interaction of supervisory control via these network assets and the distributed voltage control via the PV inverters.

## 2.3 Types of Installations for Demonstration

As part of the MetaPV demonstrator, four different types of installations were installed:

- residential-scale controllable PV systems for direct connection to low voltage,
- commercial-scale controllable PV systems for connection to medium voltage via the transformer cabin of the grid customer or directly connected to the low-voltage busbar of a public transformer cabin,
- residential-scale controllable battery storage systems for direct connection to low voltage,
- a commercial-scale controllable battery storage system, directly connected to the low-voltage busbar of a public transformer cabin.

### RESIDENTIAL-SCALE CONTROLLABLE PV SYSTEMS

The residential-scale controllable PV systems are connected to the low-voltage grid via the electric switchboard of the grid customer. This is the most common connection scheme for residential and small-scale commercial PV in Europe. They consist of one or several single-phase PV inverters of the type SMA Sunny Boy 3000/4000/5000 TL 20, available for a nominal 3, 4 or 5 kW PV peak power, respectively. Communication for monitoring and controlling the inverters proceeds via an SMA Sunny Webbox and a GPRS router (Figure 2).

**FIGURE 2:** RESIDENTIAL-SCALE CONTROLLABLE PV SYSTEMS ARE BUILT WITH SMA SUNNY BOY 3000/4000/5000 TL 20 INVERTERS (1), AN SMA SUNNY WEBBOX DATALOGGER (2) AND A GPRS ROUTER (3); THE PHOTOGRAPH SHOWS A RESIDENTIAL SYSTEM IN OPGLABBEEK

## COMMERCIAL-SCALE CONTROLLABLE PV SYSTEMS

The commercial-scale controllable PV systems are connected to the medium-voltage grid via the transformer cabin of the grid customer or via a direct connection to the low-voltage busbar of a public transformer cabin. They consist of large numbers of medium-size three-phase inverters of the types Sunny Tripower 15000 TL and 17000 TL, which can be aggregated and controlled as one large system (Figure 3). These inverters have a unit size of 15 and 17 kW PV peak power, respectively. Again, communication for monitoring and controlling the inverters proceeds via an SMA Sunny Webbox and a GPRS router.

**FIGURE 3**: COMMERCIAL-SCALE CONTROLLABLE PV SYSTEMS ARE BUILT WITH SMA SUNNY TRIPOWER INVERTERS AND CAN BE AGGREGATED TO THE DESIRED PV PEAK POWER; THE PHOTOGRAPH SHOWS 15 INVERTERS MOUNTED BACK-TO-BACK ON A RACK AT THE MUNICIPAL WORKSHOPS

## RESIDENTIAL-SCALE STORAGE SYSTEMS

The residential-scale storage systems are built around a single-phase SMA Sunny Island converter. Via a special distribution panel, the converter can connect both to the grid and the electrical system of the house. This way, a backup functionality is available in case of power outage. On its DC side, the inverter is connected to a lead-acid battery pack (Figure 4). The system communicates over GPRS using the IEC 61850 protocol [7]. This way it can directly feed data into and accept data from the MicroSCADA system.

The converters have a nominal power of 4.6 kW and the standard battery pack has a capacity of 7.4 kWh. Depending on the location, double-capacity battery packs (14.8 kWh) are installed.

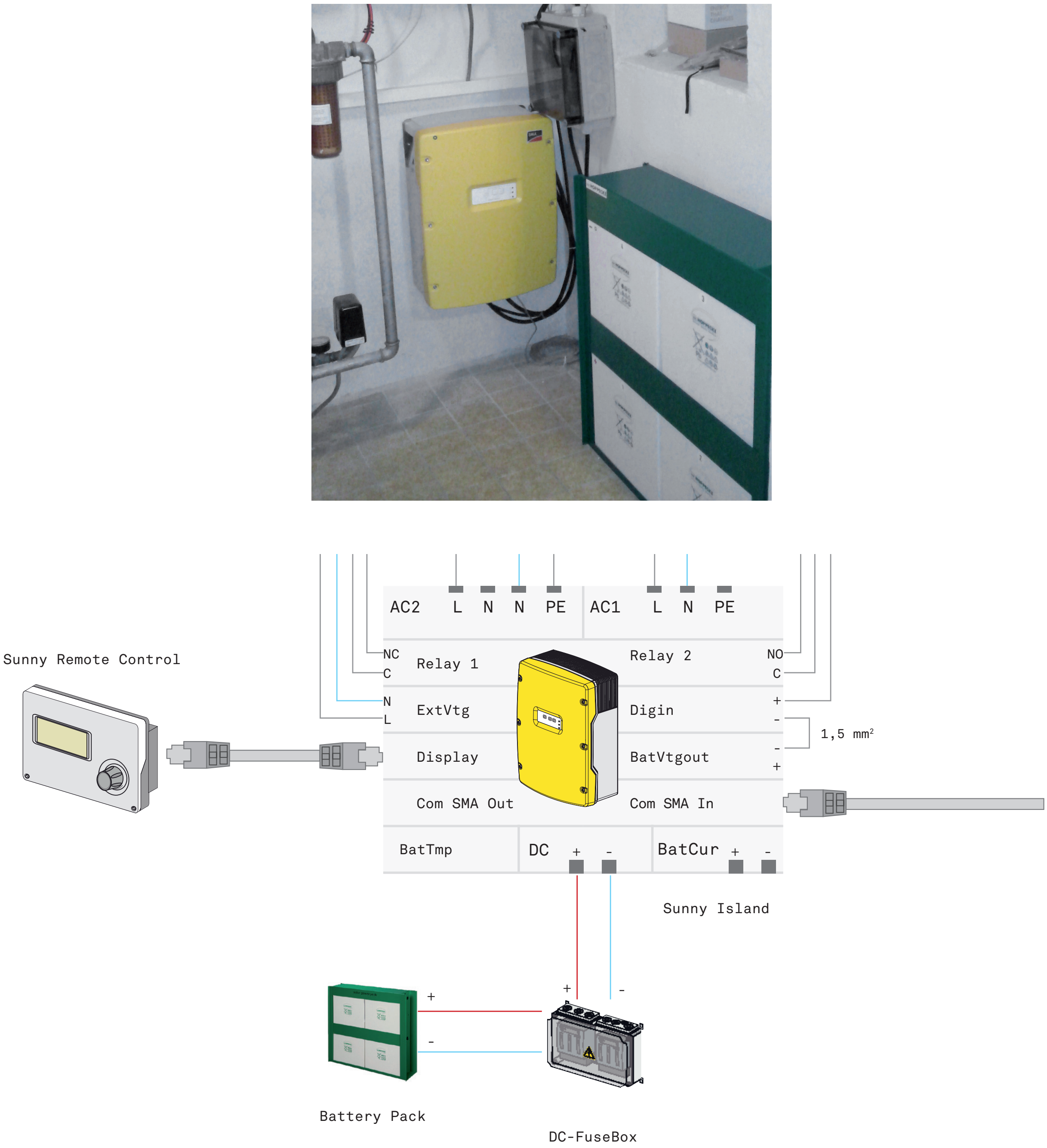


**FIGURE 4:** RESIDENTIAL-SCALE STORAGE SYSTEMS FEATURE A CONVERTER, A BATTERY AND A DISTRIBUTION PANEL (TOP: INSTALLED SYSTEM IN THE FIELD, BOTTOM: EXTRACT FROM THE WIRING DIAGRAM)

## COMMERCIAL-SCALE STORAGE SYSTEM

The commercial-scale storage system consists of two parallel 90 kVA converters with full access to the internal control software. The converters support four-quadrant operation and a three-phase plus neutral AC connection. They are connected to a Li-ion battery pack with a 58 kWh capacity and integrated battery management system. The system is connected directly to the MicroSCADA via the 3G telecommunications network.

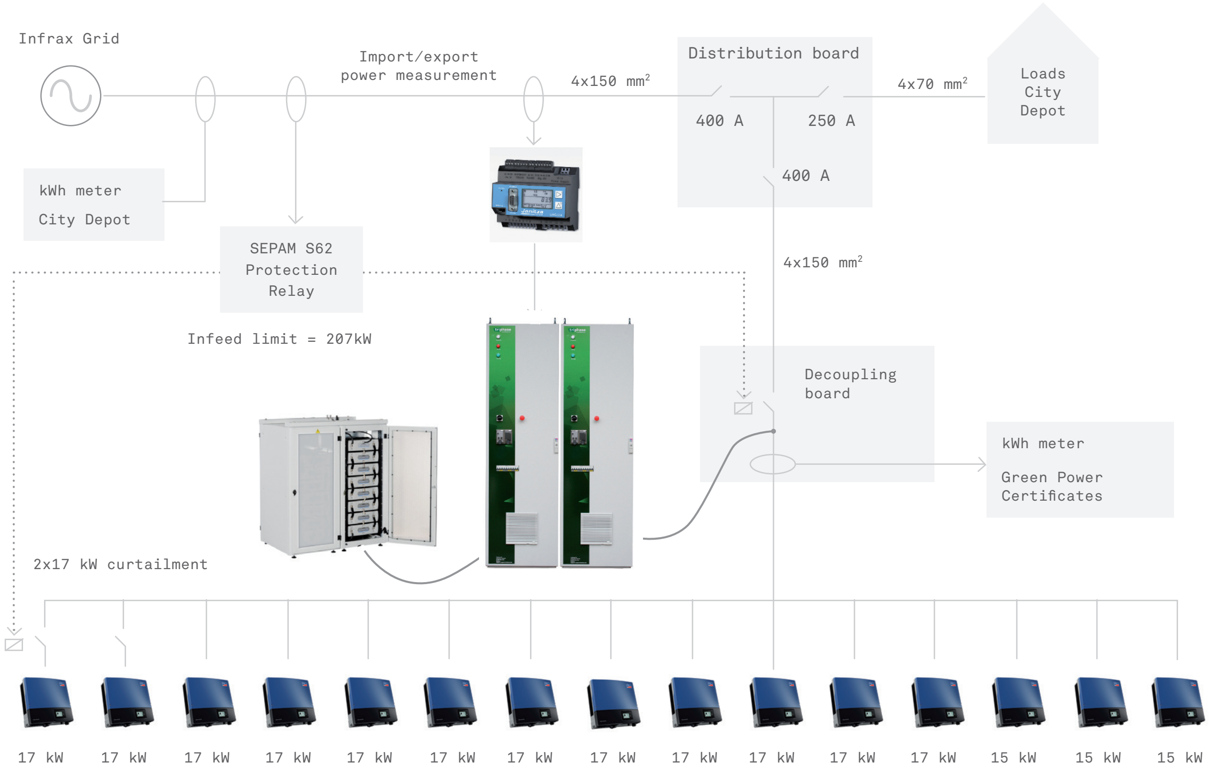


**FIGURE 5:** THE COMMERCIAL-SCALE STORAGE SYSTEM INTEGRATES WITH THE PV SYSTEM AT THE MUNICIPAL WORKSHOPS OF SINT-TRUIDEN; IT COUNTERACTS BOTH OVERVOLTAGE ON THE FEEDER AND TRANSFORMER OVERLOADING

## VOLTAGE CONTROL FUNCTIONS OF PV INVERTERS

The two PV inverter types generally contain the same functions for control and communication. These are first of all functions for *local control*: the inverter adapts its active and reactive power output as a function of a quantity measured at the point of connection. The available local voltage control functions are listed here.

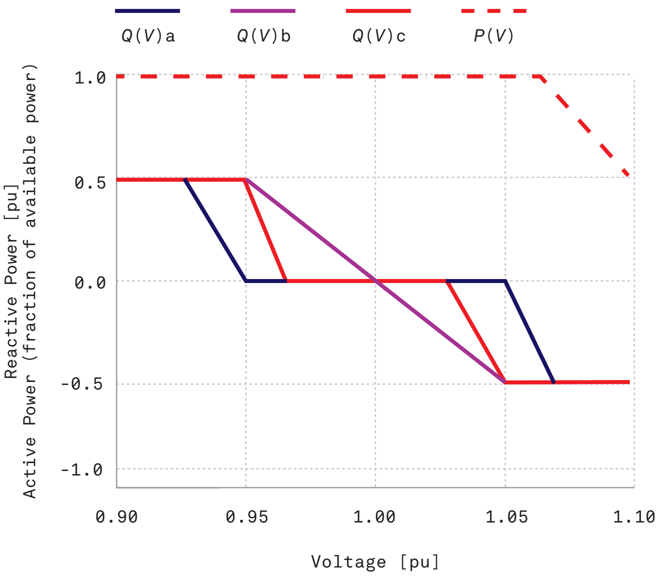
**Constant power factor $PF$ = const.** keeps the ratio of reactive power ($Q$) to active power ($P$) fixed. In particular, the project investigated $PF = 0.9$.

**Constant reactive power setting $Q$ = const.** keeps the reactive power output fixed. The project investigated $Q = -0.5$ pu extensively. This equals the maximum reactive power setting and, therefore, results in the maximum possible effect on the feeder voltage. Using this control is generally not advised but it allows to test the maximum effect of reactive power.

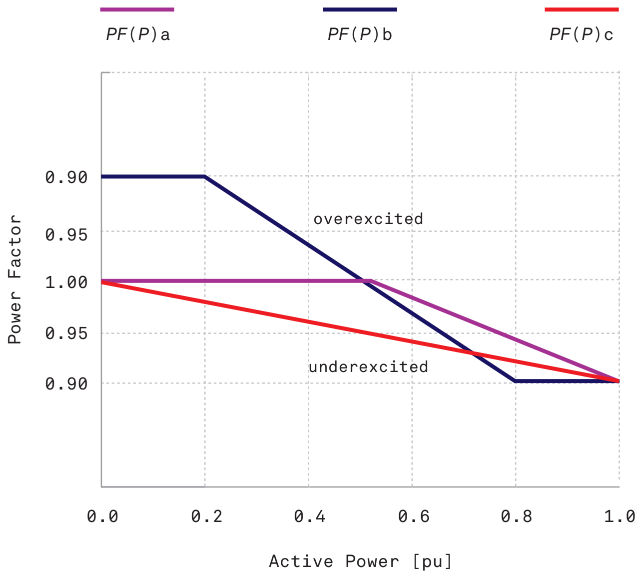
**Reactive power / voltage characteristic $Q(V)$** causes a higher reactive power consumption when higher voltage is measured locally. For voltages below the nominal voltage (e.g., 1 pu in Figure 6), the PV inverter consumes additional reactive power when the voltage increases. This control function is implemented with a linear relationship between $Q$ and $V$, with possibly a deadband around the nominal voltage avoiding reactive power exchange during moderate voltage variations. The $Q(V)$ control was tested with different settings as indicated by the labels $Q(V)$a, $Q(V)$b and $Q(V)$c in Figure 6a. The functions $Q(V)$a and $Q(V)$c include deadbands of different sizes, $Q(V)$b does not. $Q(V)_{LDB}$ denotes a location-based deadband.

**Power factor / active power characteristic $PF(P)$** moves the power factor towards underexcited values when the active power of the inverter increases. As high voltage and high inverter power are often correlated, this control function indirectly controls the voltage. The resulting voltage reduction is not fed back into the controller, making it very stable. The control is commonly parameterised with $PF(P=0) = 1$ but other setpoints are possible. The $PF(P)$ control was tested with different settings as indicated by the labels $PF(P)$a, $PF(P)$b and $PF(P)$c in Figure 6b.

**Active power / voltage characteristic $P(V,P_{available})$** provides a more powerful alternative to the $Q(V)$ control. Instead of reducing the voltage with additional reactive power, the voltage is directly forced downwards by reducing the power infeed. This active power control function is referred to as intelligent curtailment. It is obviously at the expense of slightly reduced PV energy yield. Instead of defining the resulting active power relatively to the inverter power rating, this control relates it to the actual available PV power, always ensuring a reduction of active power in case of high voltage. The $P(V)$ control was occasionally tested in combination with $Q(V)$c. The control function is indicated by the label $P(V)$ in Figure 6a.



(a) *Q*(*V*) and *P*(*V*) control functions



(b) *PF*(*P*) control functions

**FIGURE 6:** ILLUSTRATION OF CONTROL FUNCTIONS IMPLEMENTED IN THE INVERTERS FOR DE MONSTRATION; VOLTAGE NORMALISED TO NOMINAL GRID VOLTAGE; ACTIVE AND REACTIVE POWER NORMALISED THE INVERTER POWER RATING

A full description of these control functions can be found in [8].

Besides local control, any of the controllable PV inverters in the demonstrator can be addressed remotely in order to select one of the functions above and set the desired parameters for the chosen control function. Moreover, they can be controlled by a supervisory control system that sends them setpoints for active and reactive power output. Setpoints could be calculated centrally, based on broader network knowledge. We then talk about *coordinated* or *supervisory control*.

The inverters also feature frequency control according to an active power / frequency characteristic $P(f)$. This feature was operational at all times.

### CONTROL FEATURES OF STORAGE INVERTERS

In principle the storage inverters offer the same features for voltage control as described above for the PV inverters. This means, installed along a distribution feeder, they can contribute with reactive power as the PV inverters do. Moreover, they can be controlled to withdraw or inject active power from or to the grid using their battery packs as buffers. Consequently, they can control active power as a function of voltage ($P(V)$) or simply constant active power ($P$ = const.) according to a given setpoint, e.g., calculated from external measurements. Their ability to control active power is constrained by their power rating and by the storage capacity of the battery pack.

## 2.4 Communication and Remote Control

All these controllable PV and storage systems communicate with the DSO via a private GPRS network (Figure 7). With proper credentials, the project partners can access the systems from the internet through the firewall of the DSO. This way, the inverters are shielded from cyberattacks; however, at the cost of reduced bandwidth and signal strength in comparison to a regular internet connection.

The PV systems support standard web protocols. The monitoring data is transferred to a file server for the purpose of detailed scientific analysis and to the web portal of SMA Solar Technology both via File Transfer Protocol (FTP). The inverter control settings can be updated via Hypertext Transfer Protocol (HTTP). On the web portal, the plant owners can follow up on the data from their own plants.

The storage systems communicate directly with the MicroSCADA system installed at Infrax using the IEC 61850 protocol according to [7].

Notably, the MetaPV project did not in particular look for innovation in the field of communication technology. Consequently, this architecture is intentionally based on commonly available technology which should just be fit to do the job. Reliability, network security and scalability of the communication system were no priorities for the project.

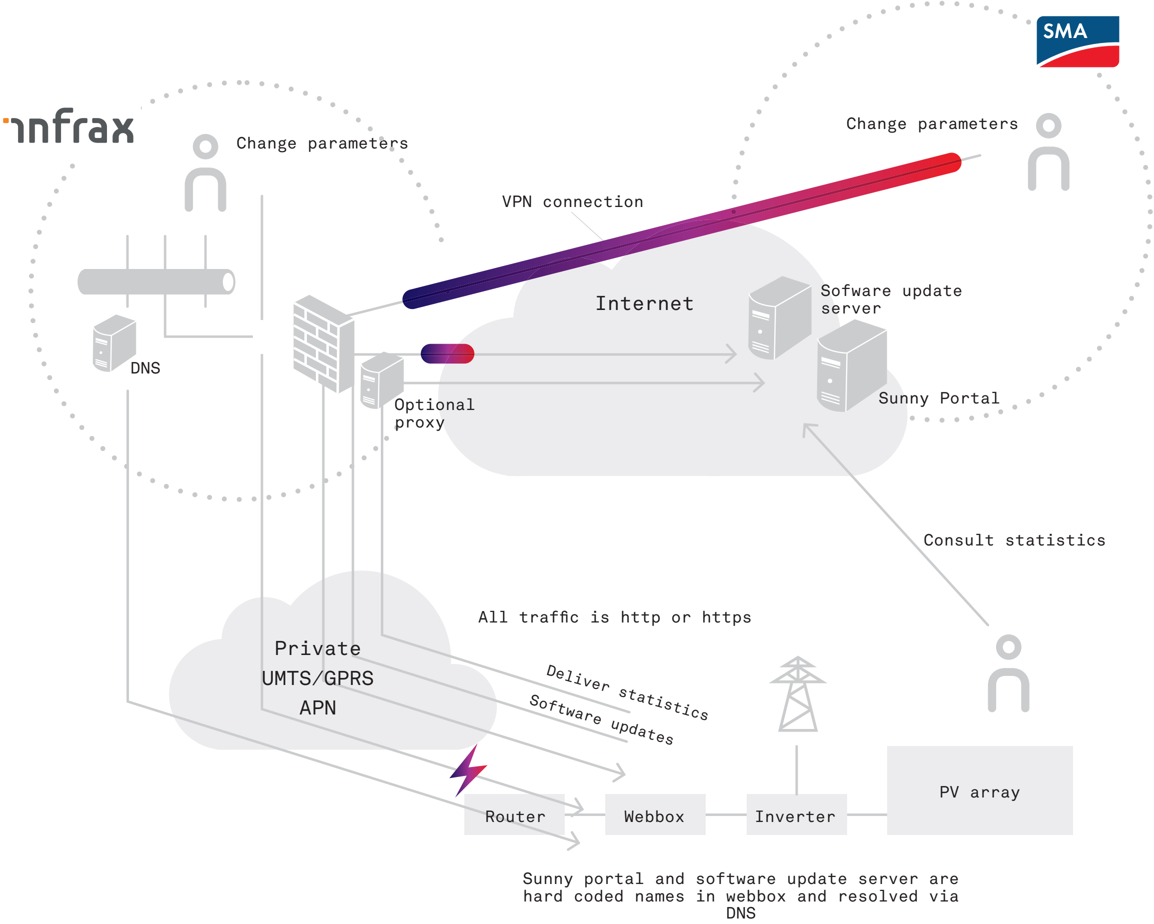


**FIGURE 7:** FOR MONITORING AND CONTROL, THE CONTROLLABLE INVERTERS ARE CONNECTED VIA A PRIVATE GPRS NETWORK AND SHIELDED FROM THE INTERNET THROUGH A FIREWALL; FOR THE PLANT OWNERS, MONITORING DATA IS FORWARDED TO THE SMA SUNNY PORTAL

## 2.5 Lessons Learned from the Field

In addition to the specific technical conclusions as they have been presented in Section 3, the MetaPV consortium has formulated a number of observations and lessons learned from the implementation of the project. Other stakeholders may review them and build on the experience of MetaPV for similar demonstration actions or when deploying similar technologies.

- The involvement of external participants offering access to their own property and sharing private PV system data makes a demonstration project very complex. In the case of MetaPV, the realisation of the envisioned controllable PV plants by households and local businesses required continuous and proactive communication with the participants and close follow up of the commercial and contractual aspects.

- Unexpected difficulties occurred with the communication between the operation and control system of Infrax and the low-voltage PV installations. They were mainly due to the wireless communication via GPRS and required several revisions of the installation. For replication, particular attention should be dedicated to the communication architecture and channels in view of reliability, security, bandwidth and simplicity.

- Outside Germany, storage systems are not yet common in a residential context. Installations need to comply with national safety regulations. These can differ a lot from country to country which makes it difficult to offer turn-key solutions. As a consequence, residential storage systems as demonstrated here require close follow-up of suppliers, installers, certification bodies and DSOs.

- Many of the household participants were collaborative and interested in the research results. Concerns were mainly related to reductions in energy yield from their PV installations as a consequence of the trials foreseen in MetaPV. In addressing these concerns, transparency and regular communication are key: participants were happy to accept small reductions in active power output when they understood that these result in a negligible loss of PV energy yield over the year.

- The different grids for implementing the MetaPV demonstrator were selected based on the likelihood that additional PV will cause regular events of overvoltage on feeders. These should then have been mitigated by means of the controllable inverters. After all, not all of these grids regularly suffer from overvoltage. Nevertheless, this broad approach allowed us to end up with a number of grids that were operated close to the upper voltage limit and where the effect of inverter control could effectively be demonstrated. A posteriori, this illustrates that for the ambition of demonstration in a real grid, the large scale of the MetaPV demonstrator was absolutely necessary.

# CONCLUSIONS & RECOMMENDATIONS

# 03

# 3 CONCLUSIONS & RECOMMENDATIONS

## 3.1 Hosting Capacity and Overvoltage

THE VOLTAGE HOSTING CAPACITY IS REACHED FIRST, OVERLOADING OF TRANSFORMERS OR FEEDERS OCCURS RARELY.

MetaPV observed that the voltage rise and risk of violating the upper voltage limit according to EN 50160 [9] can be considered as the most relevant limit to integrating PV into distribution networks. This confirms results from previous research projects [10]. Also imbalance of the line voltage over the three phases of a low-voltage grid can be a concern, caused or exacerbated by unbalanced PV injection. Reverse power flow observations were limited to the feeder and cabin level. They were hardly observed at the primary substation. Next to this, reverse current values never reached the load current values. Overloading hence was never observed in the demonstration area. These reverse power flows still cause, however, very low power factors. This is because all active power demand of network loads is then supplied locally by PV while the reactive power demand is commonly supplied from the grid.

Overvoltage is defined in the Belgian grid code [11] as an instantaneous voltage excursion above 1.15 pu or a ten-minute average voltage above 1.1 pu. Overvoltage according to this definition is hardly observed in the demonstrator due to three reasons: (i) for grid code compliance, inverters already disconnect from the network at voltages slightly below the limit, (ii) the DSO is obliged to reinforce the network to avoid overvoltage, and (iii) not all PV systems of the demonstrator are located at network locations that are regularly operating close to the upper voltage limit.

In the demonstrator, few inverters encountered a ten-minute mean voltage of 1.1 pu and above. Voltages near the instantaneous voltage limit of 1.15 pu were never observed. Therefore the analysis of demonstration data focussed on high voltage values (above 1.07 pu) rather than on events where the allowed voltage band according to EN 50160 [9] is exceeded. Voltages exceed 1.07 pu for the majority of the demonstration inverters. Some inverters even exceed this voltage for 30% of the time they are generating power.

To detect and counteract voltage violations due to distributed PV systems, DSOs are advised to increase the observability of their grids to improve tracking the evolution of voltages and reduce voltage levels proactively in a structured way.

### UNBALANCED LOADING OF LOW-VOLTAGE SYSTEMS REDUCES THE EFFECT OF REACTIVE POWER.

In situations with unbalanced voltages over the three phases, reactive power-based voltage control is less effective and some side effects appear. For example, consuming reactive power in one phase will reduce the voltage in this phase, further decrease it in a second phase and increase it in the third phase.

Grid operators should pursue balanced systems by, e.g., changing the phase distribution of loads and generators. Notably, this is not always possible in practice. When selecting measures for increasing the hosting capacity in practice, possible unbalanced network states must be taken into account. With the rollout of smart meters throughout Europe, additional possibilities such as area-wide phase identification are offered to DSOs. They can be used to identify heavily unbalanced feeders and thus concentrate the efforts on situations with a high benefit.

### THE HOSTING CAPACITY CAN GENERALLY BE INCREASED BY APPLYING THREE-PHASE INSTEAD OF SINGLE-PHASE INSTALLATIONS.

Single-phase PV installations are not necessarily a source of voltage imbalance. They may also reduce the existing imbalance caused by single-phase loads. However, in most low-voltage networks, unbalanced infeed increases the imbalance. The overall hosting capacity may be severely limited with PV power being unevenly distributed over the three phases [12]. Due to a lack of visibility, DSOs have to use conservative rules which limit the PV penetration accordingly. For this reason, most DSOs have been limiting the maximal power of single-phase installations, e.g., to 4.6 kW in Germany and Austria and 5 kW in Belgium.

Particularly for very long low-voltage feeders, if the additional inverter investment costs are acceptable, it is advised to promote or even demand three-phase installations.

## 3.2 Effectiveness of Voltage Control

### THE DIFFERENT CONTROL FUNCTIONS TESTED ARE EFFECTIVE AND THEIR EFFECTIVENESS IS COMPARABLE.

Different voltage control strategies using reactive power from PV inverters have been evaluated by simulations and tests in the demonstration areas. For situations with high active power from PV and high voltage on the feeder, all reactive power control strategies succeed in reducing the voltage, often to similar extents. Figure 8 shows that all considered control strategies increase the total hosting capacity between 30% and 40% compared to a situation without reactive power control.

Combined $Q(V) + P(V)$ control has been proven very effective in reducing the voltage at high PV power. The $P(V)$ control function gradually reduces the PV power output before the upper voltage limit is approached. Such kind of active power control functions are referred to as intelligent curtailment. Intelligent curtailment comes at the expense of slightly reduced energy yield.

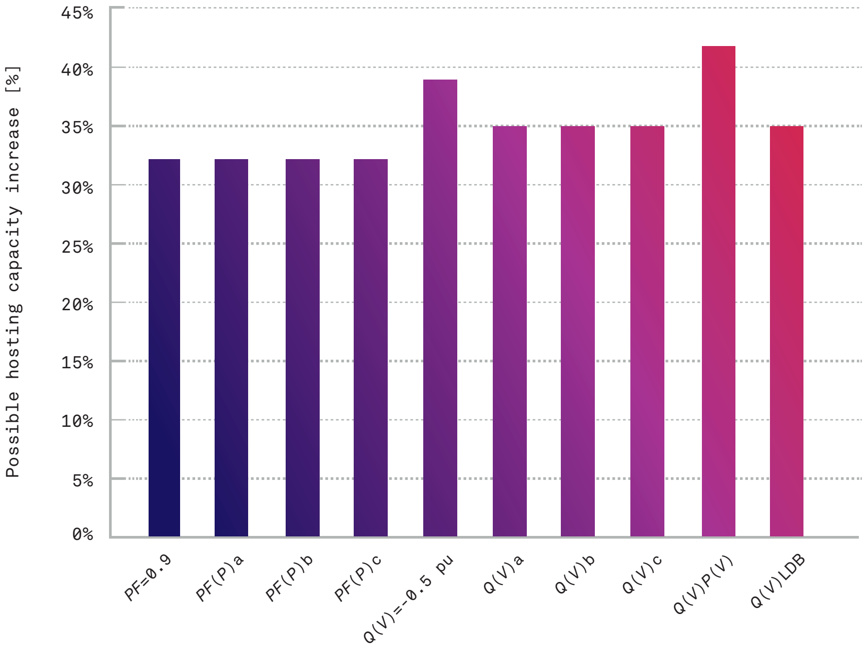


**FIGURE 8:** POTENTIAL FOR HOSTING CAPACITY INCREASE IN THE STUDIED LOW-VOLTAGE GRIDS FOR DIFFERENT CONTROL STRATEGIES COMPARED TO NO CONTROL, BASED ON SIMULATION RESULTS

It is worthwhile considering distributed voltage control with PV inverters for a hosting capacity increase of up to 40%. The specific choice of control function and parameter settings depends on other criteria than effectiveness (see Section 3.3).

### THE EFFECTIVENESS OF REACTIVE POWER CONTROL LARGELY DEPENDS ON THE R/X RATIO OF THE GRID.

The effectiveness of reactive power-based voltage control is roughly inverse-proportional to the $R/X$ ratio of the network. In addition, the contribution from the transformer reactance to the total reactance should be considered when evaluating the effectiveness of reactive power control.

For underground cables, the $R/X$ ratio is large, typically from 1.7 to 7 for common low-voltage cables. Consequently, the effect of consuming reactive power on voltage over the feeder is relatively small but nevertheless significant. For example, for an AL150 $mm^2$ cable, operating a PV inverter at $PF$=0.9 instead of 1 reduces the voltage increase due to PV by about 20%. This figure means that the hosting capacity is extended by about 25% at least. In practice, the total increase in hosting capacity will be larger due to the reactance of the MV/LV transformer.

For overhead lines, the $R/X$ ratio is smaller, commonly between 0.8 and 1.9. Consequently, the effect of consuming reactive power is larger than for cables. For example, for an AL70 $mm^2$ overhead line, operating a PV inverter at $PF$=0.9 instead of 1 reduces the voltage increase due to PV by more than 33%. This means that the hosting capacity for this example is extended by more than 50%.

Voltage control based on the reactive power consumption of PV inverters is effective in all kinds of distribution networks, including low-voltage cable networks. When evaluating this solution, DSOs should calculate the effect based on the R/X ratio of the particular network

### COUNTERACTING THE VOLTAGE RISE CAUSED BY PV BY MEANS OF REACTIVE POWER CONTROL DOES NOT COMPROMISE THE GRID STABILITY.

Simulations, lab tests and field tests confirmed that the $Q(V)$ control can operate stably under all network conditions. This control function is stable when the internal delays present in the control loop are not too large compared to the time response of the current controller. Unwanted delay comes, e.g., from data processing and communication between microprocessors. The stability criterion is rather weak and easy to comply with. Only for large PV installations requiring communication over a certain distance between the controller and the inverters, the stability criterion should be checked and re-confirmed since the resulting delays may reduce the stability margin.

## ON-LOAD TAP CHANGERS ON MV/LV TRANSFORMERS ARE MOST EFFECTIVE ON CABINS WITH HOMOGENOUS PV DISTRIBUTIONS OVER THE DIFFERENT FEEDERS.

Installing an MV/LV transformer with OLTC can also be an effective solution for controlling voltage levels, especially when the PV plants are distributed relatively homogenously over the different feeders. It was found that MV/LV transformers with OLTC can significantly reduce (or even avoid) the need for reactive power from PV to keep the voltage within the acceptable boundaries. The use of MV/LV OLTC transformers for increasing the hosting capacity with large amounts of distributed generation has been demonstrated for one of the MetaPV cabins as well as in other projects [13], [14].

Despite the additional investment, an MV/LV OLTC transformer can be a good solution to increase the hosting capacity when the voltage levels on all feeders are similar. It may then be deployed alone [15] or in combination with local reactive power control in order to exploit the advantages of both systems.

If applied together, DSOs should coordinate the interaction of both solutions by adapting the local controller setpoints to the OLTC setting.

## Q(V) CONTROL IN THREE-PHASE INVERTERS WORKS BEST WHEN CONTROLLING EACH PHASE INDEPENDENTLY.

When implementing a $Q(V)$ control function in three-phase inverters, the controller input voltage ($V$) can be determined in different ways, namely as:

a. Individual voltage, i.e., unbalanced $Q$-exchange with $Q_i = Q(V_{iN})$, $i$=1..3,
b. Highest voltage, i.e., balanced $Q$-exchange with $Q_1=Q_2=Q_3=Q(\max\{V_{iN}, i=1..3\}$,
c. Average voltage, i.e., balanced $Q$-exchange with $Q_1=Q_2=Q_3=Q(\mathrm{mean}\{V_{iN}, i=1..3\}$, or
d. Positive sequence, i.e., balanced $Q$-exchange with $Q_1=Q_2=Q_3=Q(V+)$,

where $i$ denotes the phase and $V_{iN}$ is the voltage between phase $i$ and neutral conductor. The voltage $V+$ refers to the voltage of the so-called positive sequence in symmetrical components while $V-$ is the voltage of the negative sequence.

For a balanced network, these implementations will yield the same result. For an unbalanced network, the maximal voltage rise is significantly reduced by applying the individual phase voltages (a). When using the average voltage (c), the effect is significantly smaller [12].

Also the spread between phase voltages is significantly reduced by applying the individual phase voltages (a). It is virtually not reduced for any other implementation (b, c or d).

The voltage unbalance factor $VUF=V-/V+$ is increased by applying the individual phase voltages (a), which may cause a violation of the normative limit of $VUF$=2% for heavily unbalanced conditions. The voltage unbalance factor is slightly decreased for any other implementation (b, c or d).

Normally, DSOs reduce voltage imbalance by redistributing loads and generators over the phases. In addition, large single-phase PV installations are prohibited in many interconnection guidelines.

If imbalance would persist despite these measures, the maximum voltage is reduced most effectively by controlling the phase voltages individually when the VUF is not a significant concern.

## CONTROLLING REACTIVE POWER ONLY AT THE LOCATION OF OVERVOLTAGES IS MOSTLY INSUFFICIENT.

To achieve effective voltage control with reactive power, as many PV plants on the feeder as possible should participate and not only the ones experiencing very high voltages. If only few PV inverters contribute to voltage control, this will often be insufficient.

As illustrated in Figure 9, sufficient inverters need to be involved for effective local voltage control. When more inverters contribute, overvoltage will be mitigated more effectively and the reactive power contribution will be distributed more fairly among the inverters.

In practice this implies that all new inverters should be capable to support voltage control even if applied in a grid where no overvoltage is expected on short term. For centrally coordinated control, instead of local control, this requirement is less stringent.

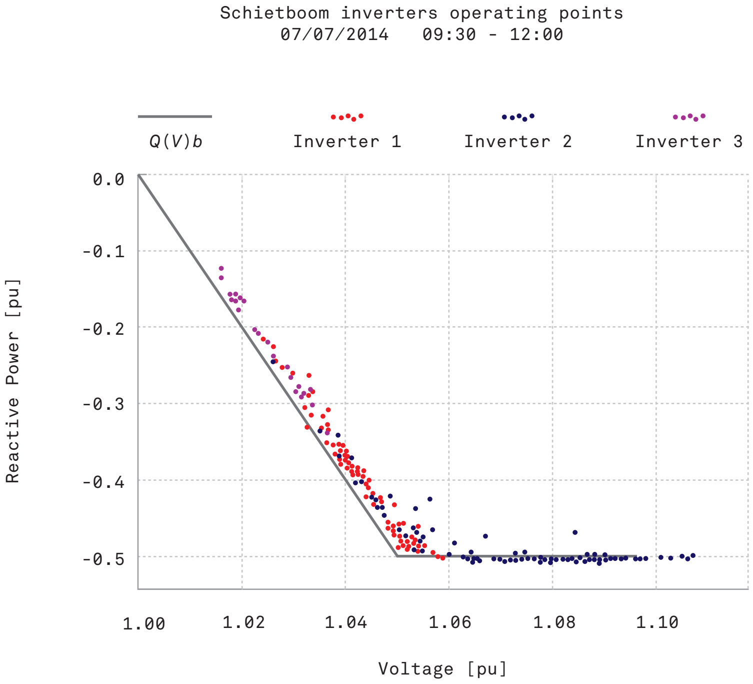


**FIGURE 9:** DIFFERENT INVERTERS ON THE SAME FEEDER OPERATING AT DIFFERENT OPERATING POINTS. THE (LIMITED) REACTIVE POWER CONSUMPTION OF INVERTERS 1 AND 3 COULD NOT PREVENT THE OVERVOLTAGE AT INVERTER 2.

STORAGE IS MOST EFFECTIVE FOR VOLTAGE CONTROL WHEN LOCATED AT THE MOST SENSITIVE GRID LOCATION.

The best location for storage was identified with an iterative method, based on voltage sensitivity analysis [16]. Assuming a DSO would have full control over storage devices in the grid, a central storage system at the end of the feeder was found to be the option with minimal power and capacity required for voltage control. This solution is hence preferred over, e.g., storage devices distributed over the entire feeder length. Furthermore, the storage capacity required for a certain increase of hosting capacity is much lower for a combination of storage with reactive power from the PV plants than for a storage-only approach [17].

## 3.3 Selection of a Voltage Control Function

THE SELECTION OF CONTROL CHARACTERISTICS IS DRIVEN BY EFFECTIVENESS, EFFICIENCY, FAIRNESS AND SIMPLICITY.

**Effectiveness** of a control measure in the context of MetaPV denotes how well the measure can contribute to increasing the network hosting capacity. Section 3.2 shows that the different functions studied are comparably effective. Therefore, additional selection criteria for the different voltage control functions become decisive.

**Efficiency**, in this context, relates the effectiveness of a measure to the expense required for achieving the desired effect. The efficiency mainly depends on the amount of reactive power flowing over the network with the different control systems. This reactive power may cause electrical losses and additional costs.

**Fairness** evaluates the distribution of reactive and active power control actions over different PV installations connected to a feeder. By intuition, a control function may be considered fair when it ensures that the burden of voltage control is shared by all PV plants on a feeder in proportion to their active power outputs.

**Simplicity** evaluates the effort required for implementing, operating and maintaining the voltage control approach on a large scale. Control schemes can be implemented simply if they do not require case-specific parameters to be adjusted before commissioning or if this can be fully automated. Schemes requiring a parameter update from time to time are more complex than those which do not. Schemes requiring communication are more complex than those which do not.

**TABLE 2:** QUALITATIVE COMPARISON OF REACTIVE POWER CONTROL SCHEMES (++ CRITERION FULFILLED, + CRITERION APPROACHED, - CRITERION NOT FULFILLED)

| | Effectiveness | Efficiency | Fairness | Simplicity |
|---|---|---|---|---|
| $Q(V)$ with small/no deadband | ++ | - | - | ++ |
| $Q(V)$ with medium deadband | + | + | - | ++ |
| $Q(V)$ with large deadband | - | ++ | - | ++ |
| $Q(V)$ with location-based deadband | + | ++ | + | + |
| $PF(P)$ without deadband | + | + | ++ | ++ |
| $PF(P)$ with deadband | + | ++ | ++ | ++ |
| Coordinated control with uniform $Q$ | ++ | + | + | - |
| Coordinated control with uniform $PF$ | ++ | + | ++ | - |
| Coordinated control (hierarchical) | ++ | ++ | - | - |
| Constant $Q$ / Constant $PF$ | ++ | - | ++ | ++ |

The results show that different local control functions offer a different trade-off between effectiveness, efficiency, fairness and simplicity (Table 2). The best solution depends on the particular network and the local voltage conditions. For a simple and efficient solution, $PF(P)$ and $Q(V)$ with an appropriate deadband are the first choices. For a fair solution, $PF(P)$ or coordinated controls can be used.

### AVOID HIGH LOSSES AND POWER FACTOR PENALTIES BY LIMITING REACTIVE POWER TO THE TIMES WHERE IT IS NEEDED.

A continuous, high consumption of reactive power may be the most effective solution. However, this generally comes with an unacceptable increase in network losses. Moreover, it may cause penalties for a low power factor at the primary substation. Therefore, it is not advised to use constant power factor or constant reactive power, such as $PF$=0.9 or $Q$=-0.5 pu. In the study cases of the MetaPV project, inverters with these control functions consumed approximately 97% of their total reactive energy consumption while the local voltage was below 1.05 pu, i.e., when no voltage control was needed. This is inefficient as the reactive power often comes from another grid section, causing electrical losses and possibly also penalties.

In contrast, with $Q(V)$ or $PF(P)$ control, inverters consume "only" 60% to 95% of their reactive power below 1.05 pu and in absolute terms they consume much less reactive energy overall. Here, the decisive parameter for trading off effectiveness against efficiency is the size of the deadband. Reactive power exchange (Figure 10) and additional network losses (Figure 11) are low with large or location-based deadbands ($PF(P)$a, $Q(V)$a, or ($Q(V)_{LDB}$). Reactive power control with location-based deadbands ($Q(V)_{LDB}$) can improve both effectiveness and efficiency, but require elaborate and recurring implementations.

The ideal function for local voltage control meets the required effectiveness. It is efficient, i.e., it consumes reactive power mainly when this is needed. And it fulfils the grid operator's expectations in terms of fairness and simplicity.

Therefore, it is not advised to use fixed power factor or fixed reactive power settings. Also $Q(V)$ and $PF(P)$ controls without deadband should be used with care.

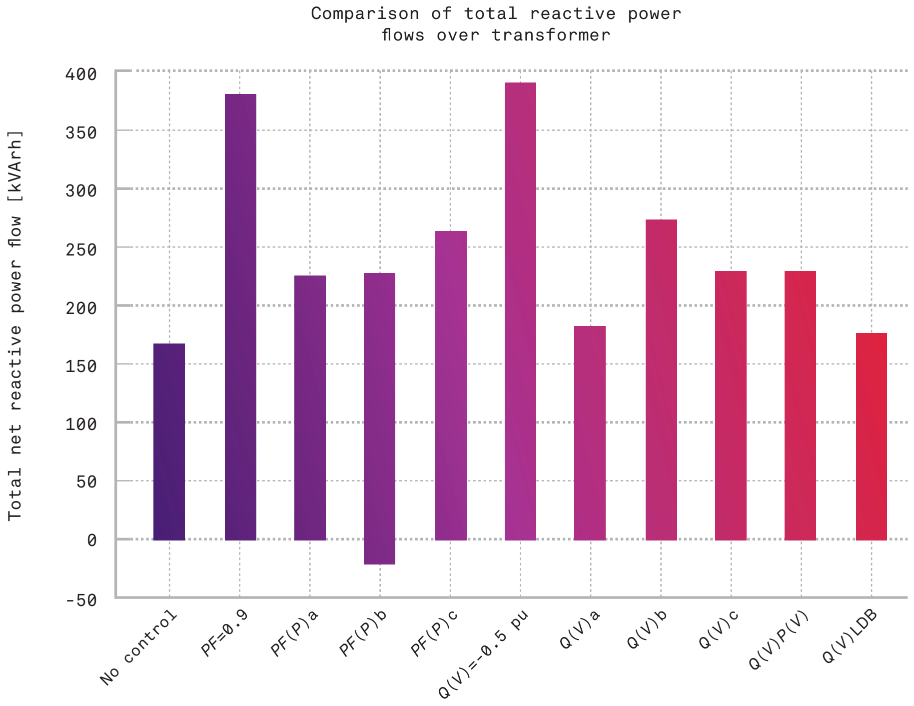


**FIGURE 10:** NET REACTIVE POWER EXCHANGE WITH THE GRID FOR DIFFERENT CONTROL STRATEGIES

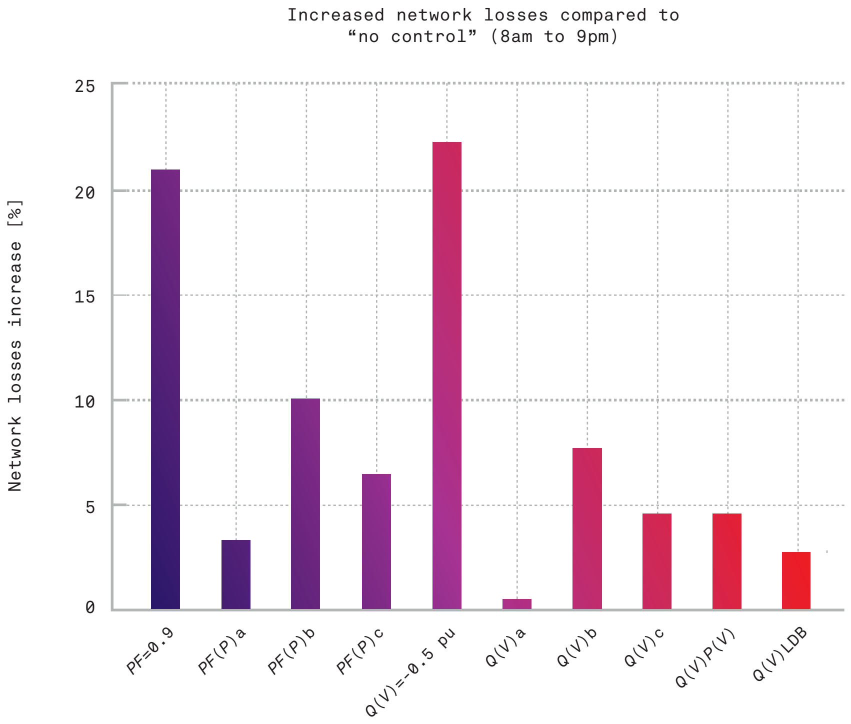


**FIGURE 11:** IMPACT OF THE REACTIVE POWER USE OF DIFFERENT CONTROL STRATEGIES ON THE LOSSES

## LOCAL REACTIVE POWER CONTROL IS LESS EFFICIENT THAN COORDINATED CONTROL BUT EASIER TO IMPLEMENT.

Coordinated control can effectively limit the feeder voltage while the inverters consume only one third of the reactive energy consumed with *Q*(*V*)c (medium deadband). For high increases in hosting capacity (>50%), both local and coordinated power control will require the inverters to operate close to their maximum reactive power limits more often. As a consequence, the efficiency of coordinated control decreases, approaching the one of the most efficient local control functions.

Coordinated control always relies on communication which makes it more difficult to implement, particularly in view of the reliability and large-scale deployment throughout an entire distribution area.

Consequently, coordinated control of PV inverters is mainly advisable for DSOs that have or plan to introduce a strong communication infrastructure. This way, the specific effort for introducing reliable, secure and scalable means of communication and data handling will be of relatively lower weight.

## 3.4 Implementation

NETWORK PLANNING STRONGLY
DEPENDS ON THE CURRENT
AND ANTICIPATED CAPACITIES OF PV.

MetaPV, as well as other projects and studies [7], [8], showed that distribution networks are heterogeneous and that only a fraction of the distribution networks pose a severe limit to PV integration while the majority of them is able to host a large amount of PV generation. This does not mean that the potential of smart grid solutions as alternative to network reinforcement is low but simply that a general roll-out is not necessary and that target networks have to be identified individually.

For small increases in PV hosting capacity, a simple change of feeder connections or transformer tap may be sufficient. These solutions are trivial and, throughout this text, the default hosting capacity assumes a network of which the static configuration and tap settings have been optimized already.

Besides the future uncertainty of local generation and demand, particularly the uncertain spatial distribution of PV within a given distribution network complicates the network planning. The saturation of a given section of the distribution network depends on the homogeneity of the PV distribution over the feeders and the location at the individual feeders. For single-phase inverters, the phase distribution also affects the hosting capacity.

For making grid integration economically more efficient, grid operators are recommended to expand their standard procedures for enhancing the hosting capacity by the steps 3 and 4 as listed:

1. Monitoring
2. Network optimisation: network topology, phase distribution & other settings
3. Network solution studies & planning: evaluation of grid reinforcement, complemented with reactive power control, MV/LV transformer OLTC, and possibly storage
4. Implementation of extended network solutions in case of an economic advantage
5. Network reinforcement

### THE DISTRIBUTED NATURE OF VOLTAGE CONTROL BY PV INVERTERS RENDERS ITS IMPLEMENTATION MORE COMPLEX THAN CONVENTIONAL SOLUTIONS.

For large-scale deployment of the voltage control solutions investigated in this MetaPV report, several non-technical issues must be considered. Particularly, local control functions require the following:

- dedicated commissioning procedure and/or type testing to verify that the controller is properly parameterised,
- documentation of the capabilities for voltage control and the selected control functions and parameter settings ,
- visibility to the DSO of possible adaptations to the PV systems that may affect the behaviour of the grid interface, e.g., firmware upgrades or inverter replacements.

These requirements are more extensive than the current requirements in most European grid codes but comparable in kind.

Where DSOs wish to introduce distributed voltage control by PV beyond the pilot scale, these requirements for inverters with voltage control features should be considered.

### COMMUNICATION WITH PV INVERTERS NEEDS TO BE RELIABLE AND SECURE.

Within MetaPV, GPRS communication was insufficiently reliable for wireless communication to both residential and industrial installations. For future deployment, more reliable alternatives such as existing broadband connections need to be explored. Inverter settings could then be dynamically updated via a direct connection to the DSO or, more statically, be downloaded automatically as is the case with firmware updates. If introduced on a large scale, these solutions need to be secured against faults or cyber-attacks.

Local voltage control by inverters does not strictly need a communication link if local control settings have been properly set upon installation of the inverter. However, when the initial settings become outdated due to structural changes in the network, they cannot easily be updated without a communication link.

## 3.5 Standardisation

### THE REQUIREMENTS FOR ACTIVE AND REACTIVE POWER CONTROL AS REQUIRED BY GRID CODES AND STANDARDS SHOULD BE FURTHER HARMONIZED.

Since the beginning of the MetaPV project, concepts have been developed to take advantage of the new functionalities offered by controllable inverters. These are mainly the control of active and reactive power for the purpose of congestion management, frequency control, and voltage control. These capabilities are in the meantime requested by many national grid codes or connection guidelines in Europe (e.g., DE, BE, FR, IT). Nevertheless, they are not widely used.

Harmonisation of the grid-code requirements for these capabilities is needed in order to ensure that the available functions can be applied broadly. This way, DSOs have access to the control of their choice and exchange their experiences. Standardisation is required in terms of hardware design, software design and communication as listed:

- Hardware design:
  - inverter capability as defined by the $P$-$Q$-diagram,
  - inverter interoperability between different brands,

- Software design:
  - supported control functions, e.g., $Q(V)$, $PF(P)$, or $P(V)$,
  - uniformity of the parameterisation, e.g.,
    - units and resolution for the settings, e.g., voltage setting in $V$ or %,
    - sign conventions, e.g., for inductive versus capacity reactive power,

- Communication:
  - standardisation of protocols, e.g., a wider use of IEC 61850 [7],
  - data security and integrity levels for communication.

Test procedures for type approval are still missing for the concepts demonstrated in MetaPV. They should include interoperability tests for installations with equipment from different vendors. Tests and procedures for commissioning are needed to ensure that the connection process becomes a standard procedure without case-specific requirements. Connection rules should be harmonised across DSOs in different countries. EN 50438 [18] and TS 50549 [19] are examples of existing and ongoing standardisation.

DSOs should align their requirements for generators with existing standards and technical specifications. Doing this, parameter settings for different control functions should remain adjustable per country or per grid.

## 3.6 Economics

FOR INCREASING THE VOLTAGE HOSTING CAPACITY OF EXISTING GRIDS, VOLTAGE CONTROL BY PV INVERTERS IS SHOWN TO BE AN ECONOMICALLY VIABLE ALTERNATIVE TO GRID REINFORCEMENT AT A FRACTION OF THE COST.

The economics of voltage control depend on different aspects, as shown in Figure 12. This figure was made for low-voltage grids. For medium-voltage grids, the quantitative results differ but point into the same direction. The results on the ordinate show the lifecycle costs in net present value as they incur for achieving the increase in hosting capacity denoted on the abscissa. The hosting capacity increase relates to a reference situation without further measures. The different cases, as indicated by the legend, differ in whether the reactive power is controlled centrally or locally, whether it is complemented by either storage or intelligent curtailment to remove excess generation peaks and, in addition, the communication equipment used. They are compared to grid reinforcement by means of an additional distribution cable. To correctly read the figure, one has to look (i) at the targeted capacity, (ii) at the colour representing the voltage control solution and (iii) for the final cost at the marker representing the type of communication. Notably, in practice, this evaluation is case-specific and sensitive to the future costs of the different communication solutions. Therefore, the figures are estimates only. Nevertheless, the principle conclusions as described below remain valid.

In low-voltage grids, voltage control by PV inverters is the preferred choice for increasing the hosting capacity up to 40% (or 90% when allowing for intelligent curtailment). In medium-voltage grids this goes even up to 60% (or 90% with intelligent curtailment). Larger increases result in too high costs for curtailment or storage, favouring grid reinforcement.

The cost of communication is crucial for the business case of inverter voltage control. Especially the communication equipment at the PV plant can be expensive. On low voltage, local control without communication is very competitive. The solution of low-cost communication modules integrated in the inverters along with communication via internet is still clearly competitive and can complement local control, e.g., for regular parameter updates. Coordinated control with a private SCADA connection is much more expensive and currently not clearly competitive on low voltage.

On medium voltage, due to the larger size of PV installations, both local and coordinated control functions are competitive for a hosting capacity increase of 50% and more, with local controls being the most economical solution for small increases in hosting capacity.

As the required increase in hosting capacity for the future is often unknown, voltage control with PV inverters can help postponing large investment decisions, e.g., until the further development of PV in a neighbourhood becomes clear. This helps avoiding stranded investments.

For small to medium increases in hosting capacity, reactive power control by inverters is recommended. Both in low voltage and medium voltage grids, local control solutions are the most economically attractive.

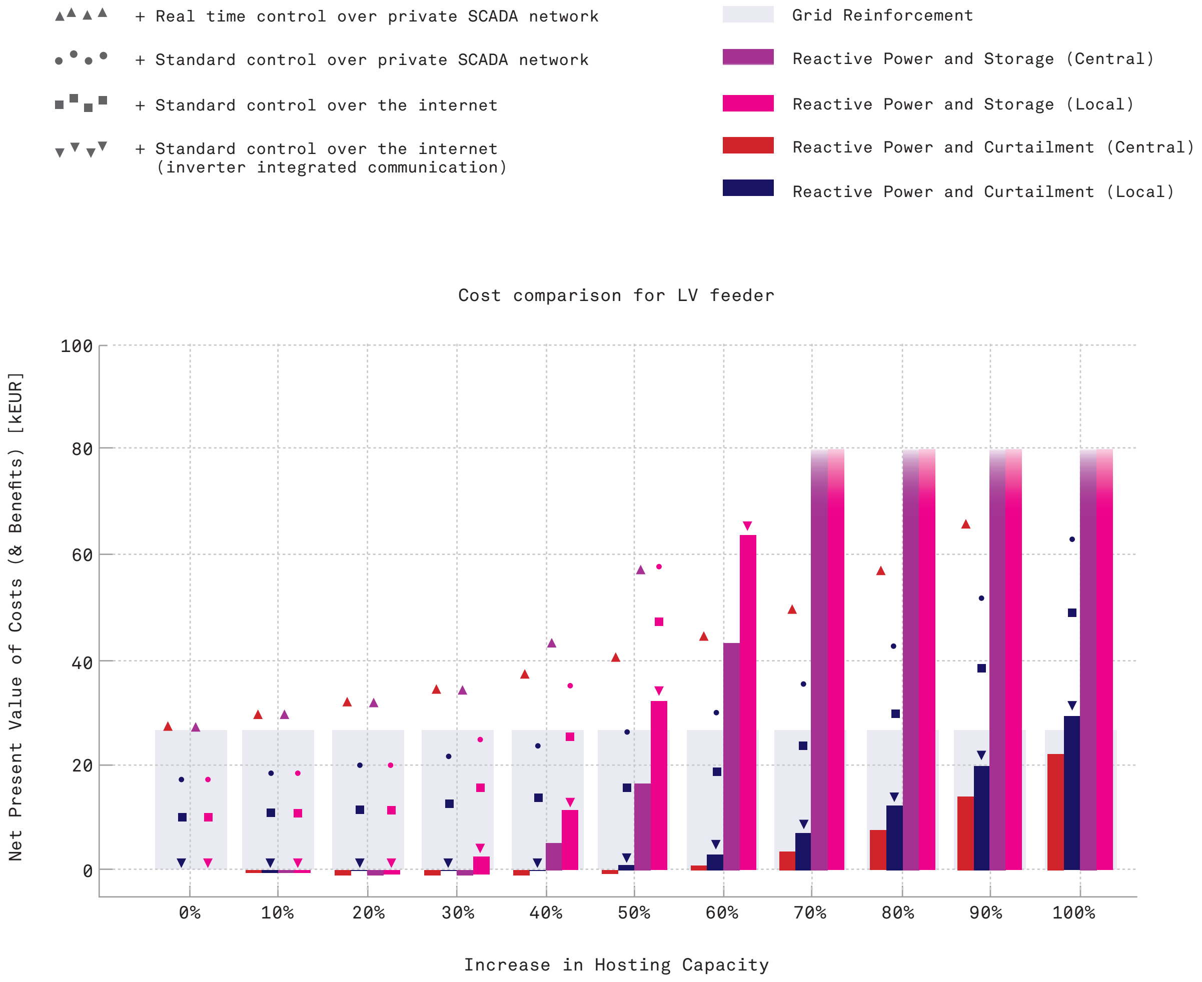


**FIGURE 12:** COST COMPARISON FOR LOCAL OR COORDINATED (CENTRAL) REACTIVE POWER CONTROL AND GRID REINFORCEMENT, COMPLEMENTED BY EITHER STORAGE OR CURTAILMENT FOR DIFFERENT WAYS OF COMMUNICATION

### ACTIVE POWER CONTROL IS A TECHNICALLY AND ECONOMICALLY SUITED COMPLEMENT FOR REACTIVE POWER CONTROL, BUT IT REQUIRES A CLEAR LEGAL AND REGULATORY FRAMEWORK.

Active power control can be used for reducing overload on feeders and transformers or controlling the voltage on distribution feeders. By accepting a very small decrease of the annual energy yield, active power control can contribute to significantly increasing the hosting capacity of a network.

Currently, in most parts of Europe, active power control is not foreseen as a means for increasing the hosting capacity of existing grids. If it should contribute to a certain extent in the future, the following questions need to be answered and translated into regulation.

- Should available power from renewable sources be wasted?
- If so, to what extent is this acceptable?
- Who can decide to control active power?
- Should this be financially compensated and, if so, how?

### STORAGE TODAY IS BARELY COMPETITIVE TO INTELLIGENT CURTAILMENT. IN FUTURE ITS DEPLOYMENT WILL DEPEND ON COSTS AND ITS ABILITY TO SERVE COMPLEMENTARY USE CASES.

With current storage prices, storage is more expensive than intelligent curtailment. Together with reactive power control, small storage can be an economic alternative to grid reinforcement for hosting capacity increases of up to 40 to 60%. Whether storage will become a common solution for increasing the hosting capacity of distribution networks for distributed generation mainly depends on the price development of batteries and the feasibility of combining complementary use cases for a single storage system. For example, increasing the hosting capacity locally may be complemented by increasing the local self-consumption of electricity from PV or providing ancillary services to the transmission system operator.

## 3.7 Overall Conclusion

The MetaPV project has shown and documented how PV can contribute to increase the hosting capacity in practice and thus increase the share of variable renewables that can be integrated into the distribution grid. The proposed solutions can veritably complement network reinforcement on distribution level. They can reduce investment costs by introducing a more agile and stepwise solution for increasing the hosting capacity of our grids. As such, they contribute to keeping grid fees affordable in the future.

Most of the detailed project results are publicly available in project reports and scientific papers. Distribution system operators, industry and regulators are encouraged to build further on these results for improving, replicating and upscale the solutions presented here.

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