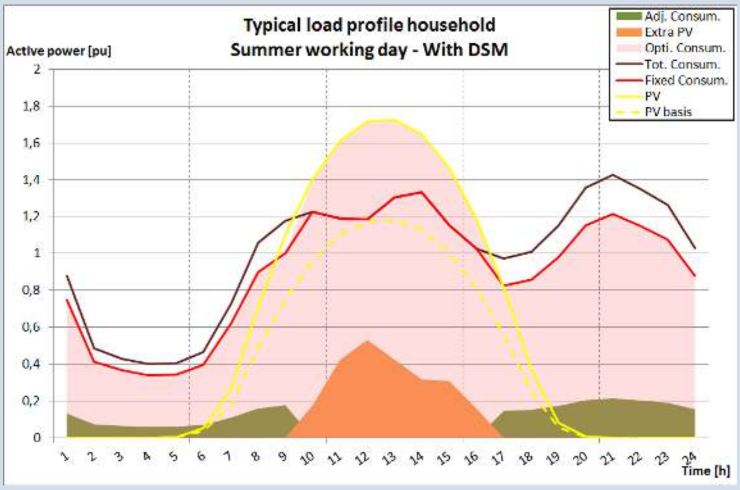
IEA INTERNATIONAL ENERGY AGENCY

Network driven demand side management

Final Report of activity 1.2 from Subtask 1



PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

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Report IEA-PVPS T14-07: 2016
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Foreword

The company Planair, as the main builder of this document would like to thank PVPS and Task 14 team for the good coordination around the construction of this document.

We would especially like to thank Kenn H.B. Frederiksen from Energimidt (Denmark), Jan Von Appen from IWES (Germany), SMA, Schneider Electric, Barry Mather from NREL (USA), Manoël Rekinger from EPIA (Belgium), Karel De Brabandere from 3E (Belgium) and Sara Ghaemi from AIT (Austria) for all their inputs during the edition of this document.

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Davy Marcel and Lionel Perret, Planair.

Preface

The International Energy Agency (IEA) founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) that carries out a comprehensive program of energy cooperation among its 23 member countries.

The IEA Photovoltaic Power Systems Programme (IEA-PVPS) is one of the collaborative research-and-development agreements established within the IEA, and since 1993 its participants have been conducting a variety of joint projects in the applications of photovoltaic (PV) conversion of solar energy into electricty.

The overall goal of the IEA-PVPS Task 14, “High Penetration of PV Systems in Electricity Grids”, is to promote the use of grid-connected PV as an important source of electric power systems at higher penetration levels at which additional efforts may be required to integrate dispersed generators. The aim of these efforts is to reduce the technical barriers to achieving high penetration levels of distributed renewable systems.

This report presents some investigations of the Demand Side Management concept and its relation with PV at household level.

Nomenclature or List of Acronyms

DC	Direct Current
DSM	Demand Side Management
DSO	Distribution System Operator
EEG	German Renewable Energy Sources Act
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Systems

Executive Summary

Photovoltaic energy deployment is paving the way for deep changes in the way electricity is produced and the grid is managed. While multi megawatts power plants and High Voltage power system remain the main drivers for balancing production and consumption, we see now the emergence of production of electricity and storage systems at Low Voltage level. This leads to new opportunities and challenges for active power balance and power system management. Demand Side Management is identified as a major opportunity and in this report the title "Network Driven Demand Side Management" has been chosen to emphasize a collaborative approach between decentral generation, loads, storage systems and the grid.

The report provides the following information:

- Definition of Demand Side Management (in terms of time, scale etc.) and overview of DSM opportunities in relation to PV and power system.
- Identification of different inherent potentials for PV energy production without reverse flow (fully self-consumed) due to different load profiles.
- Identification of DSM opportunities in relation to households with PV battery systems.

The main conclusions of the report are the following:

- Network driven DSM involves many actors, potentially impacts many existing mechanisms, and overtakes by far the sole development of household PV. Network driven DSM is indeed closely related to many other trends such as smart metering, demand response, energy efficiency, expansion of inter communication within the power system, storage, etc.
- The question is not "why" anymore but "how". The understanding of existing transmission and distribution controls is of foremost importance and any new controls shall adapt to power system integrity requirements.
- Taking a closer look at the study undertook for chapter 3 that considers PV without reverse flow, the following results can be highlighted: Depending on the country, the present study shows that 5% to 12% of the annual consumption can be covered by PV without reverse flow at the medium grid level. These amounts raise from 10 to 20% with DSM and up to 40% with DSM and a usual household storage (6 kWh)
- Demand Side Management is taking shape via various technologies appearing in the market and creating new directions of their own. Many different technical mechanisms already exist and the biggest foreseen challenge is the integration of all new mechanisms within the grid management in a holistic way.
- An efficient holistic mechanism raises big challenges. The organizational skills of the actors involved will be of foremost importance for techno-economic efficiency of Demand Response development (e.g.: avoiding to

result in a house with 5-6 close control schemes acting on various loads, avoiding private "control aggregators" to act independently from transmission grid priorities for Demand Response, synchronizing intelligences etc.).

Table of content

1 Introduction

1.1 Motivation

The electrical industry worldwide is experiencing enormous changes as a reflection of our current society's evolution: Human Lifestyle modifications, globalization and borderlines redefinition, energy independency needs and natural resources limitations are all examples of parameters that putt pressure on electrical power systems.

The electrotechnical industry, based on a centenary permanent evolution, has to cope with many new challenges rising at the same time. We can name among others the following:

- limitations in terms of transmission grid development (environmental acceptability...) especially in "old" industrial countries,
- rise of power electronics and multiplication of non-synchronous machines natural behaviour (e.g. in case of fault, or major power plant loss or transmission event..),
- necessary implementation of financial market mechanisms in order to boost green energy investments in a smooth, robust and fair-competitive way,
- deployment of High Voltage Direct Current technology over existing AC grid,
- rising issues in terms of power quality (e.g. frequency erosion, black outs risk,..),
- power variability and dispatched nature of new renewable energy power plants (e.g. wind, PV).

There are for instance real technical challenges to make room for PV generation in an integrated resources planning process and to allow solar electricity to be fully integrated into power system operations.

Within that dynamic and challenging situation, the whole electrotechnical world also witnesses the emergence of true opportunities arising with the communication revolution. Therefore in this chapter we would like to intent clarifying what we talk about when mentioning the terms "Network Driven Demand Side Management" in relation with small PV or very local low voltages loads.

"Network driven Demand Side Management" is a concept of collaboration between grid managers and private end consumers. According to (1), Demand Side Management was introduced by the Electric Power Research Institute (EPRI) in the 1980s. According to this whitepaper, DSM is a global term that includes a variety of activities such as load management energy efficiency, energy saving, etc.

Traditionally the permanent regime power flows in electrical distribution and transmission grid, have been managed by acting on main grid components via various grid mechanisms. "Network driven DSM" or "Demand Response" are suggesting that each end consumer household may participate in upper grids power flows management by enabling a possibility of reducing their loads (e.g. by switching off some non-priority loads) according to grid demand, by setting up systems that may be both beneficial for the end consumer and the grid manager.

The higher purpose of balancing energy used through energy management is to lead to positive impacts on:

- Minimizing peak loads in MV and HV grids,
- Increasing PV hosting capacity, penetration and in general PV deployment,
- reliability and the security of systems,
- price volatility,
- environment and climate,
- the cost of systems,
- industrial development.
- energy independency.

The prime motivation for this report has been the fundamental and yet innovative aspects of Demand Side Management today with a focus on an application to PV and household level. Demand Side Management is indeed generally considered as a tremendous opportunity for the PV sector, but we may also see it as a necessary solution to compensate its consequences on the existing grid.

The electrical industry has started only recently proposing products that generally only answer a little part of the whole challenge suggested by the concept. The market related to the holistic concept of "Demand Side Management" has not yet been created at a mass scale. Apart from islands and "off grid" contexts, only a few countries and regions have indirectly created the pre-conditions needed for a "DSM" market development. It can be observed that in those areas the price of the kWh consumed is high enough compared to the price of the PV kWh to be injected to the grid, taking into account the cost of self-consumption (or it could also simply be that no business model has been created yet!).

At this stage, the main potential opportunities that are identified in relation to "Demand Side Management", seen from the power system, are the following:

- **grid frequency stability in long term time span** (e.g. regional and continental under/overfrequencies)
- **grid voltage stability in long term time span** (e.g. transmission corridors lines saturation, congestion management, steady state overvoltages etc.)
- **electricity market prices regulation**

PV could be permanently de-rated for providing a power reserve, and, with the emergence of electrical energy storage in the LV grids we could use an aggregation of multiple small loads (e.g. households) synchronized together via communication network, to propose not only services to reduce active power when frequency is high but also injecting some "reserve power" from storage to the grid when frequency is low. Even though such "innovative" reserve control is relevant in theory, creating a robust and efficient mechanism involving numerous amount of low voltage loads represent an enormous challenge, especially for our human organization (e.g. practical setup, harmonization, robustness).

In parallel to more and more interconnected grids, the concept of "self-consumption" is starting to make sense from an economical point of view, at least from the electricity consumer side. In some situations and in some countries, the kWh price to be consumed in one household is indeed already overtaking the price of kWh produced by a PV installation, leading to new perspectives.

It is assumed that PV, as a distributed generation technology, will benefit from Demand Side Management (DSM) and storage. It has to be underlined however that a pre-condition for a long term techno-economical relevance will be an efficient collaborative work between grid operators and PV industry, both for understanding grid needs and utilizing "PV/DSM/storage" performances in the most optimized way.

To conclude with the motivation:

- it is generally accepted that DSM has the potential to improve several aspects of power system, and it could be especially beneficial for PV energy penetration. It is however believed that the main challenge will be to answer how such control should be implemented, in order to benefit all parties (e.g. at least avoiding to add more uncertainty to electrical power system management, crisis management etc.).
- whatever is the power system opportunity identified (grid frequency stability in the long term span or grid voltage stability in the long term span, electricity market regulation), the active power control from DSM will impose its intrinsic capabilities: Therefore, in this document (excl. the case study), it is mainly **slow active power control potential performances** that will be investigated, as a first step.
- DSM represents an opportunity for increasing **self-consumption.**

It has to be noted that:

- Local voltage control using reactive power of local PV, which is partly mentioned in the case study, will not be the focus of the whole document even though some links will be mentioned (especially in chapter 2.3)
- We will only talk about permanent and slow regimes in this document, namely (in electrotechnical industry) timescales of 10-30 seconds to minutes. All notion of dynamic performance, primary reserve, inertia, or grid transient stability etc. will therefore not be the focus of the present document (see remarks below about "fast inertial response").

1.2 Objective of the report

The present report has two main purposes:

- The purpose is to give an overview of the current solutions to **slow active power control**, and to present relevant case studies that may help the reader understand the potential of the main candidates for DSM and/or storage applicable to PV integration in distribution grids.
- The second purpose is first to estimate PV's coverage potential of household consumption in case of full **self-consumption** (no reverse flow). In a second step, the increase in the estimated PV's coverage that would result with DSM and storage applications is assessed.

1.3 Report structure

The report main structure is the following:

- Introduction
- Market overview
- Case studies
- Conclusions

The "Market overview" chapter aims at introducing the reader to the notion of Demand Side Management, and defines the limitations in scope (e.g. which industry concerned, which products and areas involved etc.). This chapter also aims at introducing the reader to the potential requirements and eventual benefits that the grid would get from such controls. We will also here develop an overview of the technologies that exist today, in the area of DSM and/or storage at a very local level (e.g. household), and we will give some remarks by referring to existing literature that was found particularly relevant.

The "Case studies" chapter constitutes the core of this report. It first evaluates the "pre-existing" situation in a few various countries (with relevant differences like different lifestyle, climate or position in the world) regarding PV's coverage potential of household consumption in the case of full self-consumption (no reverse flow from the PV installation). The second part of this chapter estimates to which extend DSM or storage applications may improve PV penetration in the case of full self-consumption. The overall objective of this chapter is to understand the "natural" pre conditions for improving self-consumption in various countries, by studying typical household load profiles, and comparing PV penetration performance with/without DSM/storage. The second case study integrates PV self-consumption approaches with voltage control. It directly links the current network state to the operation of the DSM system.

Further typical case studies may be:

- Analyses of self-consumption rates depending on various parameters (e.g. measurement conditions, technologies, pre-existing factors like type and level of shiftable loads, without DSM, with DSM, with or without storage, combinations of DSM and/or storage…)
- Measurements and practical case analyses (e.g. verification of self-consumed energy etc.)
- Study of potential DSM products and technologies applicable to household and/or very local residential level
- Study of potential storage products and technologies applicable to household and/or very local residential level
- Case studies bringing some relevant remarks and or allowing the reader in understanding various technical mechanisms

The “conclusions” aims at summarizing the result of the report, by highlighting main takeaways, and relevant remarks.

2 Market overview

2.1 Demand Side Management and decentralized photovoltaic

Behind concepts like «energy management », « micro grid », « demand response», « smart energy management system », or « demand side management » there is a similar trend toward more monitoring and more control of electrical loads at lower voltage grid layers than usually.

There may be today various motivations or potential independent reasons that could lead to a final electrical consumer acquiring a system that may directly help in controlling its electrical household loads.

Here is below a non-exhaustive list of technologies and industrial sectors that may all directly or indirectly participate in setting up or proposing some controls solutions that may improve « Demand Side Management »:

- Electrical vehicles : Today, electrical vehicles industry represent an opportunity for providing grid services such as slow or mid fast power reserve for mid-term stability issues. While the expansion of such vehicles at the large scale would bring enormous challenges to local grids (rising power needs both locally and regionally, higher power flows peaks and more variable flows of power), using batteries of such vehicles represent also an opportunity. Vendors are therefore adopting a proactive behaviour by encouraging the setup of a « household smart grid » that may help the consumer in controlling its loads and self-consumption level of its local PV generation. (e.g. (2))

- Smart metering: The expansion of smart metering is pushing for higher control of household loads. Such smart meters may be acquired by consumers or proposed by local grid managers (e.g. Siemens AMIS, Landys+Gyr portfolio..). The installation of smart meters in a house may rise from several motivations. It could come from a proactive behaviour from a local grid manager in setting up a better monitored low voltage grid (e.g. grid quality monitoring), helping consumer in monitoring and managing its energy better etc.

- Partial household loads control (via consumer products): Web connected electrical plugs switches (example of brands : Belkin, PlugWise .. (3)), connected lights and thermostats switches (e.g. Lutron, Smarthome), connected washing machines (e.g. Miele, Whirlpool..), connected air conditioners (e.g. Samsung smart wifi) etc. all represent potential improvement for Demand side management. It is expected that most of these specific monitoring and control systems shall not be integrated with each other, and they shall not give the possibility for interfacing one control with another, for obvious commercial reasons.

- Electrical energy storage: The improvements in efficiency combined with cost reduction of batteries is impacting a tremendous number of sectors. A massive deployment of electrical energy storage within households is expected and the nature of these devices will directly impact on Demand Side Management (e.g. Saft, Maxwell technologies etc.). Other storage technologies may also participate in DSM expansion. For updated information about cost, it is recommend to consult (4)

- PV industry: Photovoltaics being the first electrical production technology to be widely deployed at household level, it is expected that many inverter manufacturers shall propose some household loads systems, coupled with batteries or not. An example of solution, proposed by SMA, integrates its own radio controlled socket for controlling loads (Source: (5)).

- General electrical LV industry: Many companies are proposing central SCADA systems in order to monitor PV system(s), storages, loads etc. and setting up some priorities and other controls (e.g. Schneider, Revelio GmbH)

Household load management systems are expected to rise because of a combination of technologies cited above.

It has to be noted that also other factors will push for more interconnection and control of household, for instance household surveillance systems (cameras etc.) that may indirectly encourage the development of household control in general (e.g. This will push the need for common interface and control system).

Many various actors, from PV inverter manufacturers to electrical equipment providers, telecommunication companies, with various sizes or different nature of core activity, are therefore already proposing some solutions that may be categorized as demand side management with various automation mechanisms, integration level, user-friendliness, etc. We may name among others the following companies, as providers of hardware or software solution: GE, Schneider, ABB, Siemens, Belkin, SMA, Honda, Cisco, Apple.

We also may intend to categorize various **control types** linked to Demand Side Management:

1) <u>Decentralized human control, low automation and low integration:</u>

   Starting the washing machine at 12pm rather than randomly may be an example of action that imply a higher rate of self-consumption. The usage of manual decentralized time programmers, directly connected to various electrical plugs of the household. Another example may be for instance to shift the time when electric hot water boilers are switched on.
   The main advantage of such methods is the low cost and the enormous potential of improvement at a mass scale, while the main disadvantage is that « success » depends fully on human behavioral change.

2) <u>Centralized human control, middle level of automation, mid integration :</u>
   Various systems provide the possibility of controlling electrical plugs via a communication network with a permanently connected router located in the house.

Typically, control is possible via current smartphones, tablets, computer and/or directly at the device level. Communication protocols like Wi-Fi or ZigBee, may be used and interfacing possibilities with higher system control.

The main advantage of such systems will be the price and the efficiency, but it is expected that a disadvantage shall be the low level of integration and compatibility from one system to another.

3) Fully centralized human control, high level of automation, high integration :

The higher level of automation and simplicity will come from systems that will be thought as a whole. Typically, the most elegant, powerful and simple solutions shall come from new constructions market that will adapt to specific consumer requirement (e.g. level of delegated intelligence, human intervention frequency etc.). The number of loads that shall be integrated in the household power management system shall be high.

Such ultimate solutions shall require an important effort from the industry, in terms of standardization and harmonization.

Recently, new possibilities have also appeared, such as highly integrated and automated decentralized control.

2.2 Overview of the potential grid requirements

In order to think about the potential needs from the grid side, we propose to comment the picture below that illustrates the electrical grid in relation with potential household DSM:

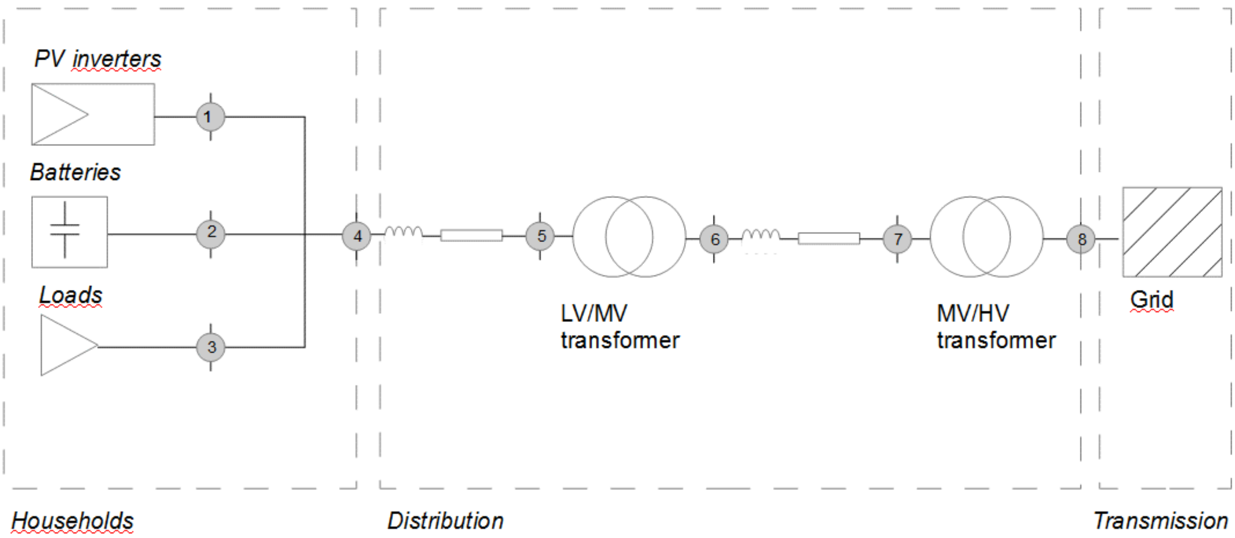


Figure 1 : schematic single line diagram of household PV+storage in the electrical grid (Author: Davy Marcel, Planair). Note: At point 8, the grid is mainly inductive.

Related to Figure 5, we have the comments below:

1) Household level: At one household level, there may be hundreds of ways for controlling various LV loads at (3), leading to partial loading control.

   We are now seeing the rise of new ways to control batteries loading at (2) and PV inverters production at (1) where the input signals are expected to be at (1) and (2).

   The solutions for controlling the load at point (4) with input signal at point (4) is the most elegant and efficient solution at a household level, by controlling all possible loads, storage, or production in a household. As a remark, only partial control is expected to be the most easily democratizing control at a mass scale.

   It is expected that several systems will control several groups of houses (e.g. definition of a geographical zone" of houses to be controlled may be good to be done by the grid manager).

2) Local distribution grid level: There is most of the time not much existing instrumentation from point (5) to (7) in most of distribution grids (e.g. at least in most European countries and/or installations created before 90's).

   LV/MV transformers are usually only equipped with fixed taps. Usually transformers HV/MV are equipped with On Load Tap Changers.

   It is assumed that local distribution grid managers may be interested in slow active power control from aggregated households for local voltage control (e.g. local areas) even though it has been traditionally the upper system (transformers HV/MV equipped with On Load Tap Changer) that were dealing with such local distribution voltage control.

   Such DSM controls may for instance use input signal at (5) or (6) to command household level controls with performances criteria to be defined.

   It will be of foremost importance to develop controls that shall be coordinated with the OLTC, in order not to disturb the voltage control mechanism at distribution level or leading to oscillations or poor performance result. First could be choosing settling time plus dead time far below the typical 30-60s settling time of most OLTC single tap change, and another could be finding systems that make sure that we do not reduce active power in houses while local voltage is already far too low (watchdogs).

   Besides, local voltage control requirements imposed to PV installations (e.g. local automated cos phi or U control type using reactive power capabilities of PV installations) will be necessary to fix existing inherent control issues between local OLTC transformer and PV installations. For instance, a coordination may be necessary in order to avoid that OLTC and PV lead to opposite objectives (e.g. one searching for increasing the voltage while the other one needs lower voltage), and PV voltage control time scales (deadtime, rise time, settling time etc.) shall be chosen according to OLTC time settings in order to avoid also oscillations or poor voltage control overall performance.

3) At transmission grid level:

The transmission grid safety and general quality level is of upmost importance. It is generally considered the following phenomena are the main transmission grid concerns to keep grid management safety level high (Source: (6))

- **Cascade overloading,**
- **Voltage collapse,**
- **Frequency collapse,**
- **Synchronization loss.**

These phenomena can come from very various reasons often interlinked with each other. Among these phenomena, we assume that **overloading cascades** mitigation measure may theoretically benefit from DSM, as long as it would be known, controlled, and integrated by the TSO in its own way of dealing with overloading cascades (again to avoid contradictions among controls).

Voltage collapse is usually dealt by reactive power control at the disposal of the TSO. It is assumed local reactive power control from decentralized power plants may participate in helping the system voltage going through such events (e.g. by, at least, avoiding disconnecting themselves from the system during the event because of voltage). In this report reactive power control from DSM shall not be considered.

As a remark (and as an example of mechanism that shows the foremost importance of TSO mechanisms understanding), in case of voltage collapse, the TSO will command immediately the freezing of OLTC operation (including Distribution Grid Manager HV/MV transformers), in order to participate in a controlled manner of re-establishing transmission grid voltage. This leads in thinking that local OLTC shall maybe use a sort of master control toward local PV voltage control, and that in any case some coordination is needed.

Frequency collapse may also obviously benefit theoretically from DSM controls, especially for steady state control or improvement of demand forecast. DSM is however not seen in this document as a candidate for fast load shedding (For more details see annex 5.1).

Synchronization loss will not be treated in this document for performance reasons.

Remark concerning Grid companies motivations:

Transmission grid managers have been traditionally using the performance of biggest national/regional synchronous generators (e.g. hydro, nuclear) in order to provide some ancillary services such as primary, secondary, and other controls. A trend (7), that has mainly started in the USA in decade 2000, shows that some groups of end consumer propose some services such as mid fast power reduction (e.g. 30s-minute(s)), geographically spread, to help TSO reducing slow power peaks and/or performing secondary control. Such mechanism, so called « Demand Response » may rise fast thanks to smart meters and communication possibilities, together with electricity market liberalization.

The development and expansion of such concepts will likely come from private companies or Distribution Grid Managers that will use their rights of proposing ancillary services to the Transmission Grid Manager, via end-consumer contracts. Despite the fact that the technology is ready, there may be a market for startups or private new comers in proposing some services in setting up the SCADA architecture (e.g. voltalis in France, stignery and ampard in Switzerland). This may likely lead to a situation where groups will merge and collaborate in an organic manner, and we have to expect a bloom of brand-owned control with low level of homogenity (e.g. private contracts multiplication, multiplication of « local » dispatch centers, rising need for collaboration between utilities and such private companies etc.).
Business case certainty, Data confidentiality, cybersecurity aspects and all general legal aspects are all examples of areas to be investigated and developed.

2.3 Performance and potential characteristics

In this chapter, we will define to the best of our knowledge the performance that may be relevant for slow frequency control and slow active power control based on the chapters above:

It is underlined that the performance parameters defined below are to be required and obtained at point 4 of the figure 5 defined above (individual household level).

Parameter	**Value**	**Unit**
Control mode	See figure 6 below. *It shall be possible to define a mode with flexibility in terms of thresholds. It shall be possible for the household installation to auto regulate P at point 4 for frequency control (see figure 5 defined above in the document), or receiving external setpoints to do it directly (the decentralized intelligence/costs would be then reduced). Very important : Priority of P control over Q control shall be settable (see remark below)*	[Text]
Input signal	Local frequency measurement with standard accuracy measured at point 4 of the figure 5 OR external P signal for both f control or local congestions (cheapest way possible)	[Text]
Pmax	corresponding to the maximum production/minimum consumption (threshold reachable under control corresponding to P1 in figure 6) of the household shall be defined contractually	[W]
Pmin	*corresponding to the minimum production/maximum consumption (threshold reachable under control corresponding to P4 in figure 6) of the household shall be defined contractually*	[W]
F thresholds	f1, f2, f3, f4 to be defined (see in figure 6)	[Hz]
Droop	0-10 *An adjustable droop shall be configurable*	[%]
Control speed (dP/dt)	0-0.01	[pu/s]
Deadtime	0-5	[s]
Rise Time	5-10	[s]
Settling Time	10-20	[s]
Steady state error	20 (pure guess)	[%]

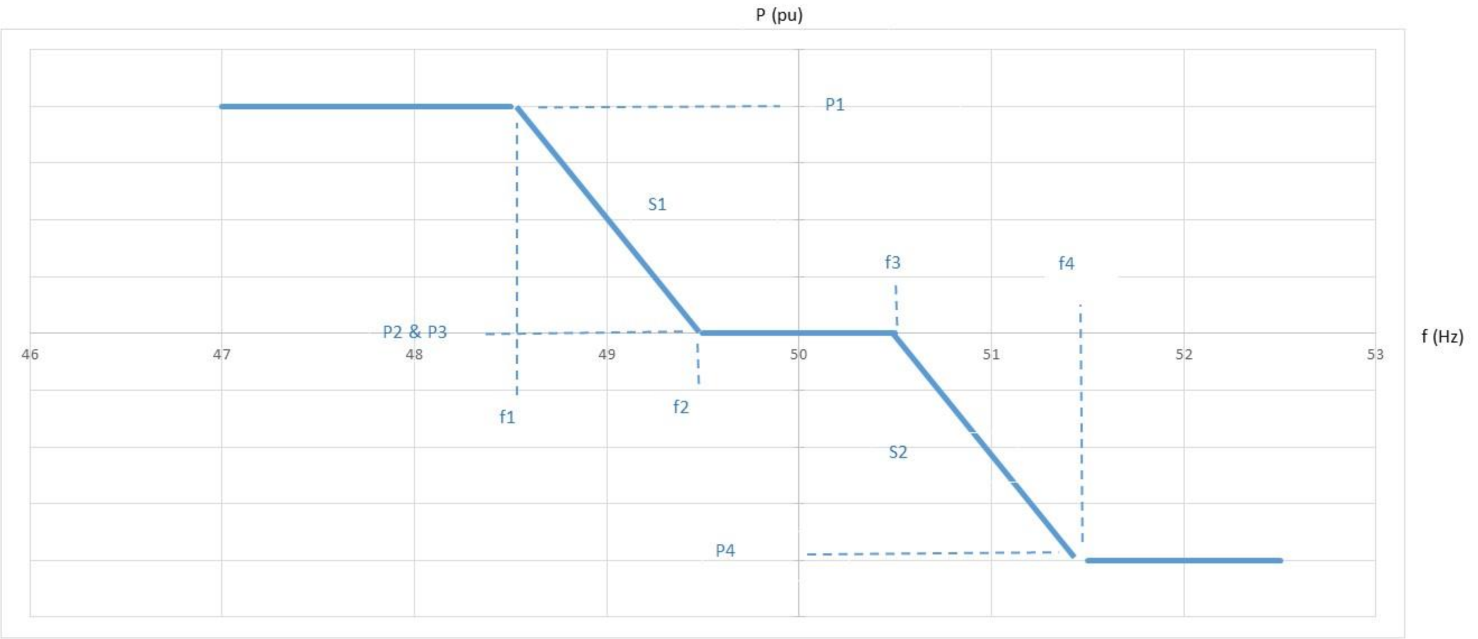


Figure 2 : illustration of generic frequency control requirement, with thresholds in terms of active power and frequency (Author: Davy Marcel, Planair)

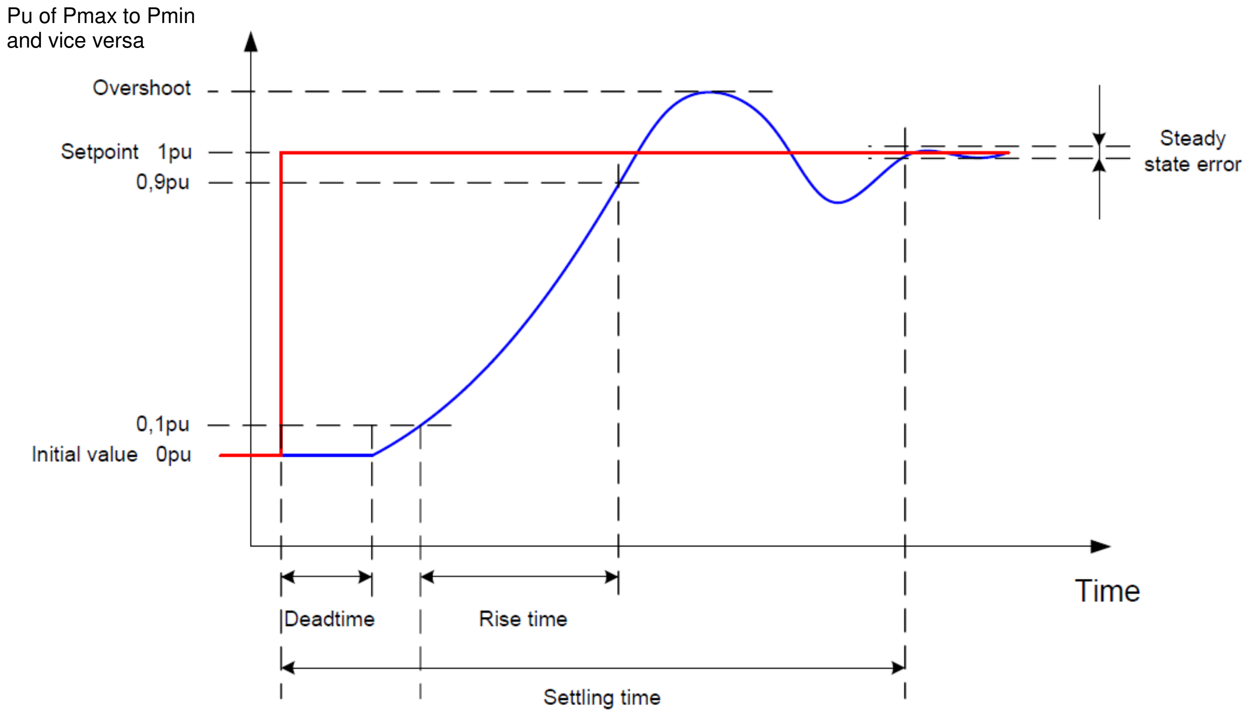


Figure 3 : illustration of step response performance parameters related to suggested frequency control (Author: Davy Marcel, Planair).

Beside these performance requirements, the following shall be mentioned:

- Performance testing and control at household level should focus on simplicity and cost minimization. Lack of accuracy of one single household performance shall contrast with global performance of the aggregated houses (control intelligence and monitoring accuracy shall be centralized for economic reasons).

- The **most important and final performance shall be defined and controlled at point 8** of the figure 5 (HV transmission grid). Any "aggregator" shall be subject to total performance requirement (e.g. Sum of households active power step response) according to TSO requirements. The performance required at point 8 shall be expected far more precise that the household level performance thanks to the aggregation effect (e.g. steady state error of few percent instead, longer dead time etc.) but the way to control and test will be also far more difficult (meshed grids).

- The robustness of such mechanism shall be softly tested gradually via tests, meaning that number of houses connected shall be extended softly to check first the coordination of various grid layers and efficiency (distribution grid layers and transmission).

- Behind the words "external signal setpoint", we assume there may be a necessary coordination between TSO and DSO. Typically a global frequency control requirement shall not lead to a local voltage disturbance. This also implies a good coordination between TSO and DSO.

  Regarding the decision process, it is proposed the following configuration below:

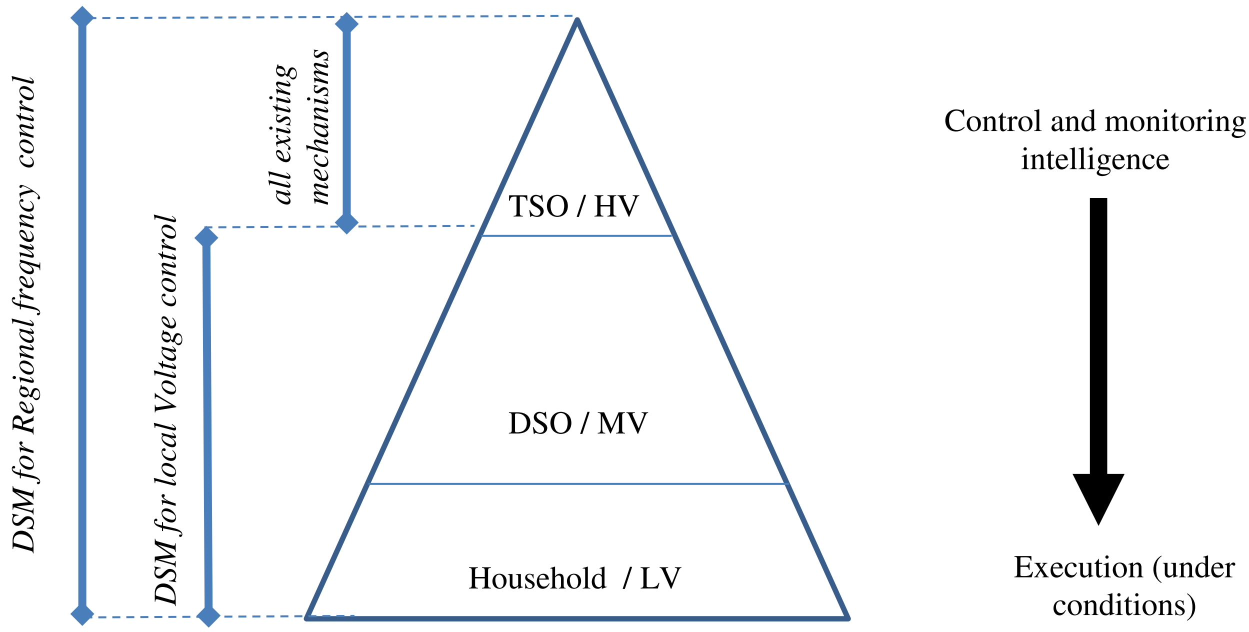


Figure 4 : illustration of the decision process for household active power control (Author: Davy Marcel, Planair).

The control process we may for instance elaborate could be based on the following (to be developed):

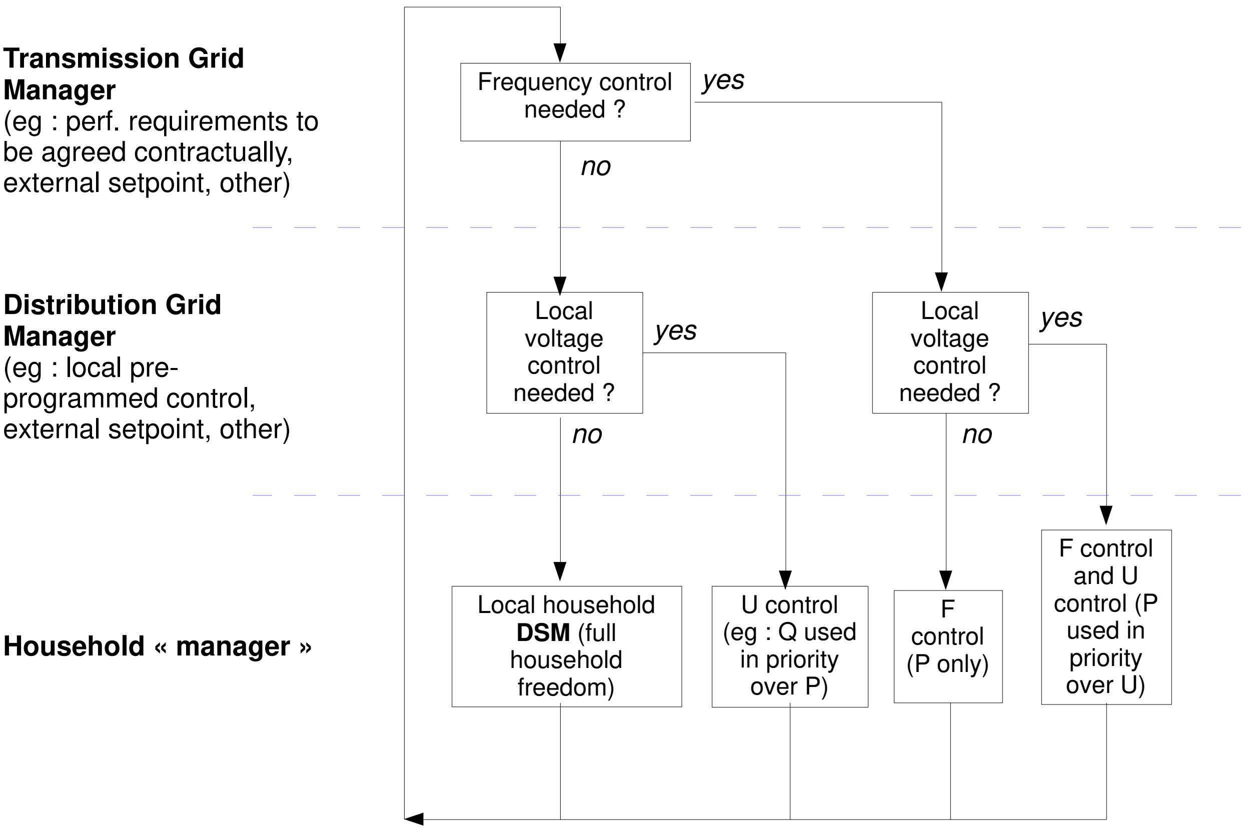


Figure 5 : Proposal of control process defining priorities between DSM, U, and f control (Author: Davy Marcel, Planair).

We have the following comments:

- The tough questions to be answered will be: How much does it cost? Which value does it bring?
- In terms of existing performance, we may notice that pre-programmed “auto” control for frequency control (with tunable setpoints) is available for most of PV grid inverters known. All controls that may be pre agreed (via grid codes, or bilateral grid contracts) shall be cheaper than ones using external setpoints etc. Some other cost will be verification, tests etc.

Remark concerning Reactive power control:
During major system troubles (e.g. loss of major power plant or major flux disturbance, cascade overloading, upper voltage line saturation etc.), the power grid will mostly need to count on a predictable active power behavior of the system (e.g. avoiding disconnections or active power undesired performance, making sure the protection system is behaving as expected etc.).

In any case, it is therefore strongly recommended that reactive power control of household PV production shall always be of secondary importance and secondary priority during such situation, and any steady state reactive power control should not endanger or lessen the predictability of system active power behavior during and after fault/event. Local reactive power control may however help in maintaining connection and production of local power plants.

For this purpose, it is suggested that PV and electrical industry in general should considerably improve and harmonize the technical requirements and performances information related to the behavior of PV during major events.

Preliminary basic information, especially about protection thresholds, P steady state behavior of PV during combination of voltage and frequency variations, ROCOF etc. are all examples of information that are typically not that clear, not from the requirements side nor from the products information side.

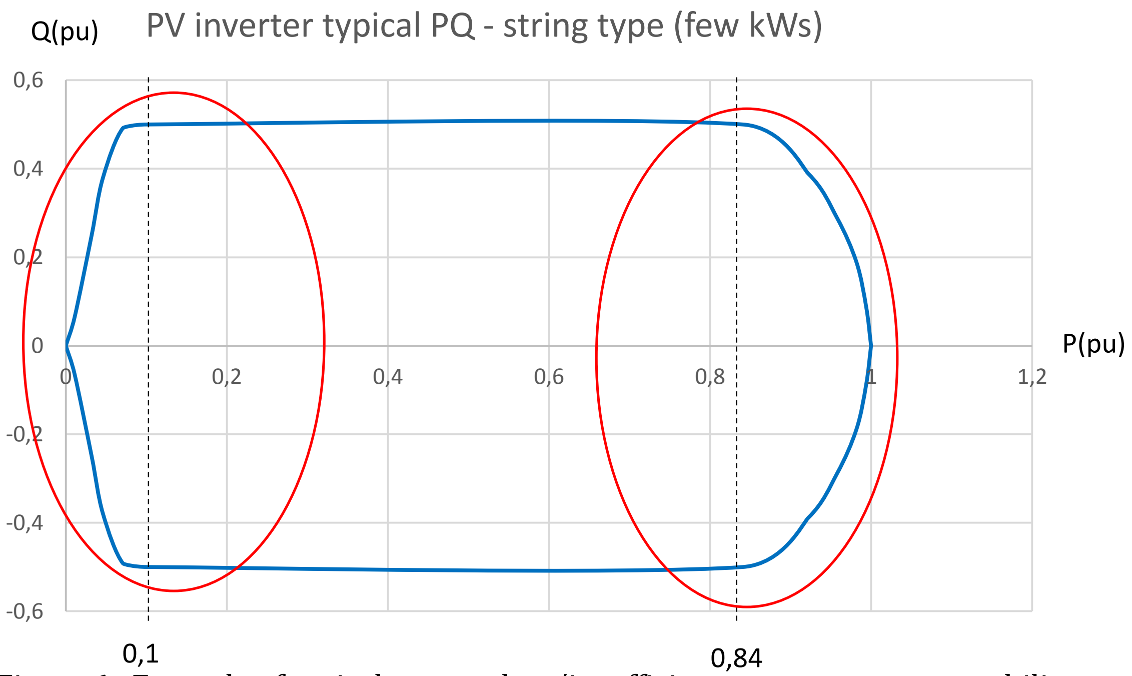


Figure 6 : Example of typical uncomplete/insufficient reactive power capability information from PV inverter, here a theoretical PQ chart with red circles showing particularly interesting areas with poor details (Author: Davy Marcel, Planair).

2.4 Remarks

In this chapter, we will propose to synthesize one position paper that was identified as particularly relevant in relation with the present document: "**Effect of the fluctuations of PV production and electricity demand on the PV electricity self-consumption** (8)**".**

This document reminds that both PV production and typical electrical consumption of a household is full of peaks and variability of different scales and various timelines, coming from various origins (e.g.: from the 30s-1min hot water boiler operation concerning load variability, to the 30s-minute(s) effect of cloud(s) passing above a PV system in the sky,..).

Some practical measurements were realized in several households in Switzerland in order to evaluate the deviation of "self-consumption rate" depending on various temporal resolutions of both the load curve and the PV generation curve, and the study is finally suggesting some "reasonable temporal resolutions" when talking about "self-consumption rate". The measured load profile was measured with a resolution of 6s and the PV generation curves were measured with a resolution of 1 minute.

Short term fluctuations of a household load have to be taken into account to evaluate the level of self-consumption of a household. The paper gives some figures and indications:

- Self-consumption rate deviates of approx. **0-1%** depending PV generation temporal resolution from **0 to 60s** and approx. **0-3%** depending on load profile temporal resolution from **0 to 60s.** Both errors will combine each other in reality.

- For accurate evaluation, temporal resolution of at least **30s for the load profile** and at least **10min for the PV production** are suggested.

- Battery storage system, in case of high self-consumption rate level, makes temporal resolution impact almost vanishing.

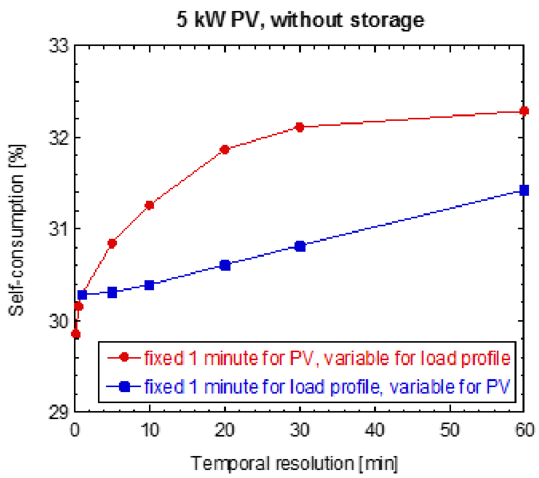


Figure 7 : Effect of the measurement temporal resolution on the self-consumption level for a 5kW PV system for a household with a 4.9MWh yearly consumption.

3 Case studies

The present report has two main purposes. The first is to give an overview of the current solutions and to present relevant case studies that may help the reader understand the potential of the main candidates for DSM and/or storage applicable to PV integration in distribution grids. The second purpose is first to estimate PV's coverage potential of household consumption in case of full self-consumption (no reverse flow). In a second step, the increase in the estimated PV's coverage that would result with DSM and storage applications is assessed.

This chapter constitutes the core of this report. It first evaluates the "pre-existing" situation in a few various countries (with relevant differences like different lifestyle, climate or position in the world) regarding PV's coverage potential of household consumption in the case of full self-consumption (no reverse flow from the PV installation). The first case study estimates to which extend DSM or storage applications may improve PV penetration in the case of full self-consumption. The overall objective of the first case study is to understand the "natural" pre conditions for improving self-consumption in various countries, by studying typical household load profiles, and comparing PV penetration performance with/without DSM/storage.

The second case study focuses on a potential application of a real network driven application in the context of PV self-consumption. Here, a voltage dependent charging of a storage system and active power curtailment depending on the network state are implemented for a German case study.

3.1 Case study 1: Theoretical study of inherent context

3.1.1 Objective, assumptions and method

Objectives

This chapter first evaluates the "pre-existing" situation in five countries with relevant differences in lifestyle, climate or position in the world regarding PV's coverage potential of household consumption in the case of full self-consumption. Full self-consumption is interesting since the absence of feed-in injections in the electrical grid allows for more PV penetration with less impact on the grid's functioning mechanisms. The second part of this chapter estimates to which extend DSM or storage applications may improve PV penetration in the case of full self-consumption.

The following countries have been studied: Denmark, Portugal, USA, Switzerland, and Germany.

Typical load profile for a medium-consumption of 4'000 kWh/year									
	Winter (01.11-20.03)			Summer (15.05-14.09)			Spring and fall		
	Saturday	Sunday	Working day	Saturday	Sunday	Working day	Saturday	Sunday	Working day
00:15	278	343.6	265.6	352.8	393.2	338.8	314.8	366.8	305.6
00:30	268	318.4	238.8	333.2	363.2	302	294.8	340.8	273.2
00:45	258.8	294.4	215.6	316.8	337.2	270	277.6	318.8	245.2
01:00	248.4	271.2	196	300.8	313.6	245.2	261.6	297.2	222.4
01:15	233.6	248.8	181.6	281.6	290.8	227.6	244.8	275.2	206
01:30	216	228.4	171.2	261.6	269.6	217.2	227.6	253.2	195.2
01:45	198.4	210.4	164.4	242	250.8	210.4	212.4	232.8	188
02:00	182.8	196	160.4	225.2	235.2	205.6	199.6	215.6	182.8
02:15	172.4	185.6	157.6	214	224	201.6	190	203.2	178.8
02:30	166	178.8	155.6	206.4	216	197.6	183.6	194	174.8
...	...	...	...	...	...	...	...	...	...
23:00	464	408.4	415.2	524	510.4	532.8	539.2	457.6	410.8
23:15	445.2	377.6	384.8	502.8	488.4	499.6	514.8	422.4	385.2
23:30	421.6	347.2	354	484.4	446.8	461.2	478.8	386.4	358.8
23:45	396	316.8	324	469.2	402.4	420.4	438	350.4	342
24:00	369.6	287.6	294	428	359.6	378.8	398.4	316.8	328.4

Figure 8 : Extract of load profile example used in the study.

Assumptions

- From the analysis of the breakdown of a Swiss private household consumption, it could be considered that 30% of the consumption can be moved at another time on the day. To be conservative it has been here calculated with 15% of adjustable consumption, considering only the part of the solar curve peak where PV generation is below or equal to consumption.
- The worst case for electric grid is represented by a summer working day: PV generation is greater and consumption lower.
- The typical theoretical solar curve used in this study results from a Polysun® simulation
    - Switzerland, Neuchâtel,
    - May, 12 (maximal power and generation in the year),

- South orientation (0°), inclination 30°,
- Sovello standard solar panels (power 10 kWp, output ~13.5%).

- According to an article in (9) about a study by a German research institute: *"Depending on the size of a PV system, the ecologically optimum scale for an onsite storage system currently ranges from 4kWh to a maximum of 8kWh of useful capacity"*.
  A 6 kWh storage system is chosen, moreover with a "smart management", which means that PV generation is stored only if it exceeds the local consumption.

The distribution of consumption in a typical Swiss private household is described in the following figure.

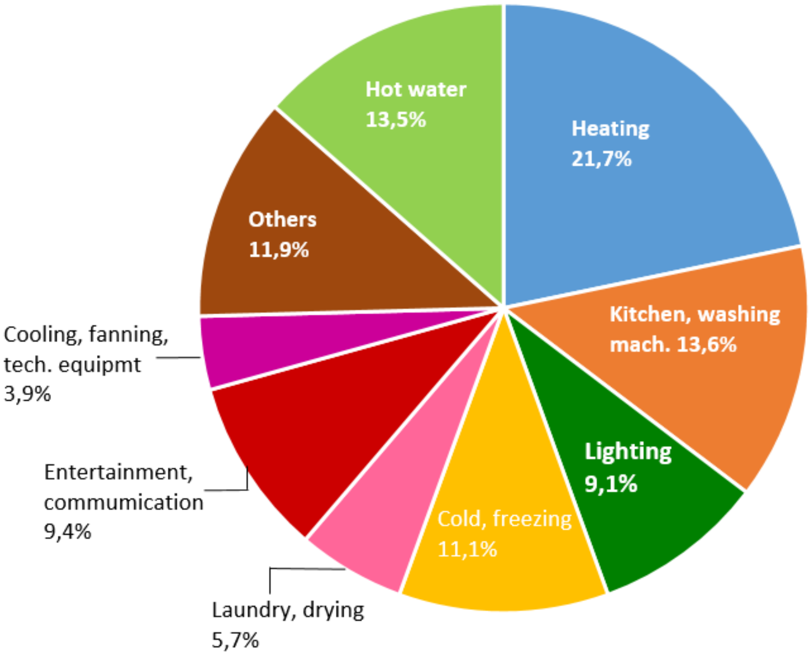


Figure 9 : Private Swiss household consumption (sources: (10) (11))

Methodology

The load profiles from various countries have been collected with following common features:

- typical household (e.g. group average etc..),
- for one complete year or at least the sunniest period,
- with quarter-hour data (or at least hourly data).

The data have been normalized for a year-long household consumption of 4'500 kWh. The average power load is therefore 115 W in the following figures.

Data nature and source:

- Switzerland: Average of 47 household load profiles from a village (12).
- Denmark: Consumption data of three typical household in central Jutland, Denmark ((13)).
- Germany: Statistical load profile (VDEW – Dynamisierungsfaktoren) of household in Bucholt, Germany (2007) (14).
- Portugal: Average of load profiles in a village (15)

- USA: Three different residential (domestic) load profiles:
    - **USA 1 (AP)**: typical residential load profile (2012) from Appalachian Power which serves about 1M customers in West Virginia, Virginia and Tennessee. (16)
    - **USA 2 (CSP)**: typical household load profile (2013) from Columbus Southern Power (CSP) that serves the bulk of Columbus Ohio. (17)
    - **USA 3 (SCE)**: typical household load profile (2013) from Southern California Edison (SCE), a very large utility that serves the majority of Southern California. This profile will definitely contain considerable energy use by air conditioning systems. (18)

For each country, 4 scenarios are generated:

Basis case
This is the case in which no PV is integrated to the electric grid. All PV generation is used on site by the household. PV is sized to avoid losses, which means that PV generation is always lower or equal to consumption.

Integration with Demand Side Management (DSM)
In this case 15% of the household consumption is shifted to hours where PV generation is at his higher level (between about 9.30am and 5pm). PV generation used on site can also be increased in comparison of basis case without integration into electric grid.

Integration with storage
In this case batteries with 6kWh capacity are used to store additional production, avoiding this electricity to be injected into electric grid. Energy is also kept on site and can be used at another time. PV generation can also be increased in comparison of the basis case.
It is reminded that annual consumption have been normalized to 4'500kWh (Typical battery size in Germany is for instance 6kWh, for typical household annual consumption of 4500kWh).

Integration with Demand Side Management (DSM) and storage
In this case both solutions above are combined to make an optimum case: more energy produced can be directly used on site due to DSM (15% of consumption shifted) and additional production can be stored in batteries (6kWh).

Legend of graphics

Storage	Part of generation that can be stored
Opti. Consum.	Household optimized consumption for maximal PV generation
Adj. Consum.	Household adjustable consumption (can be moved)
Extra PV	Extra PV : PV that can be consumed by the shifted load or stored
Tot. Consum.	Household total consumption
Fixed Consum.	Household fixed consumption (can't be moved)
PV	PV generation
PV basis	PV basis without DSM and/or storage

3.1.2 Typical load profiles of various countries

The figures below illustrate how typical household load profiles may have different shapes in each country:

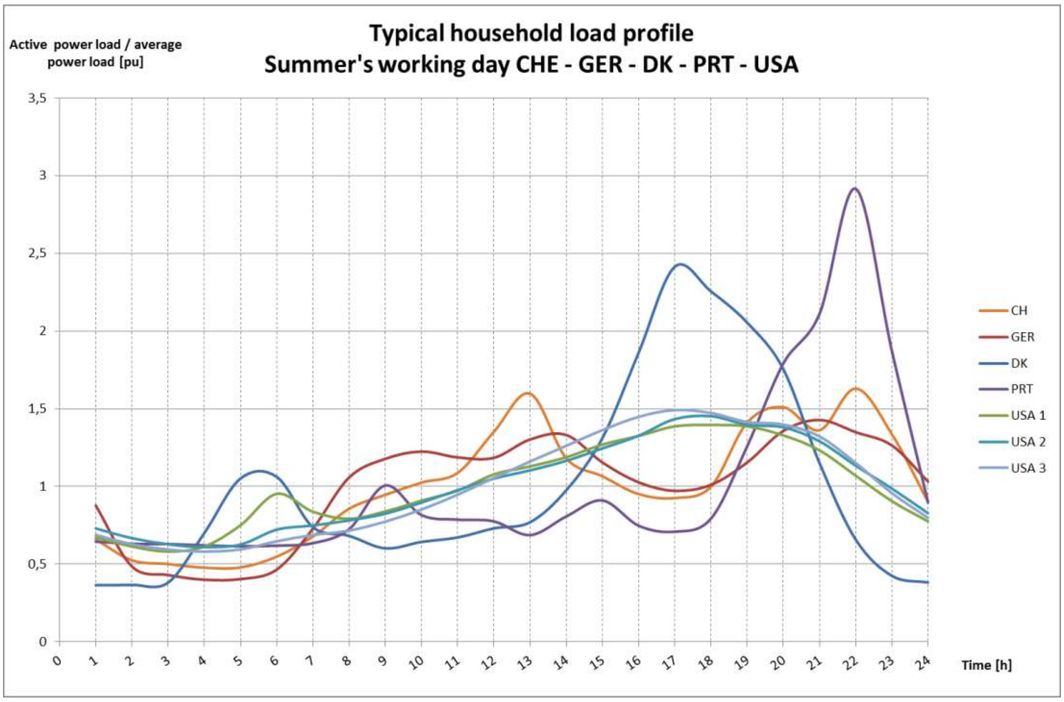


Figure 10 : Typical load profiles on summer's working day, normalized.

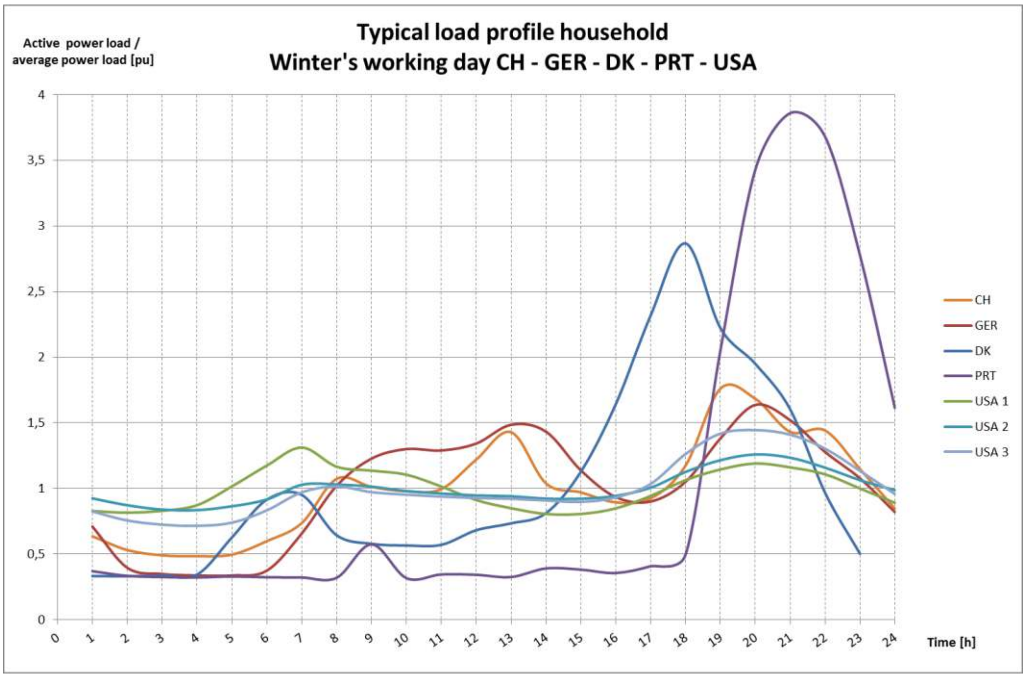
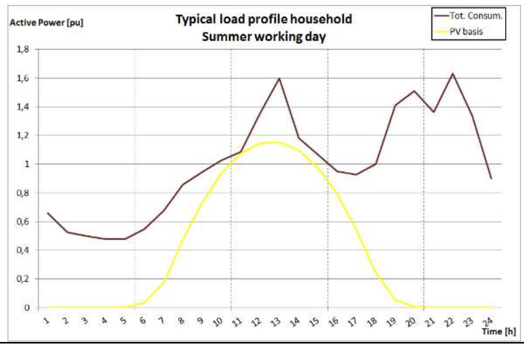


Figure 11 : Typical load profiles on winter's working day, normalized

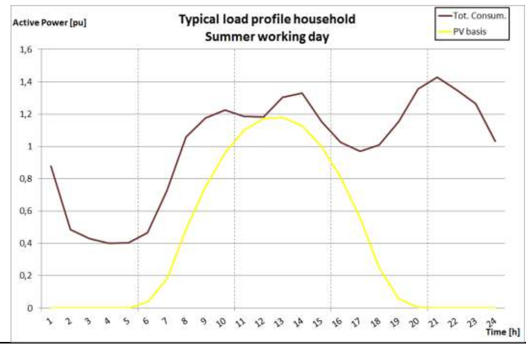
3.1.3 Basis integration

The graphics below illustrate the inherent potential for self-consumption depending on various countries typical household load profile. It may be seen from these curves that some load profile are "naturally" more adapted to PV typical production curve shape, compared to others. The power of the PV plant has been chosen to avoid grid injection with the given load profile.

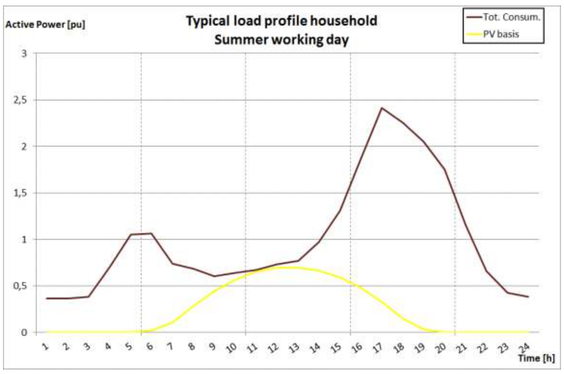
CHE



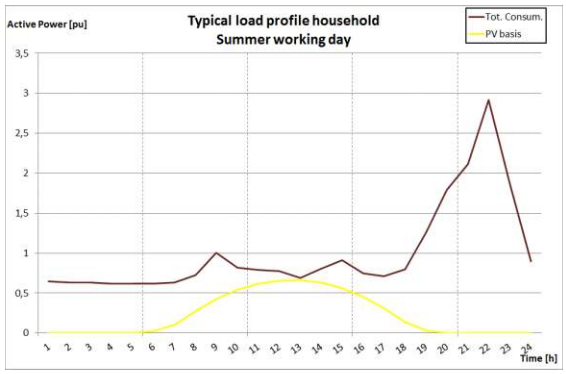
GER



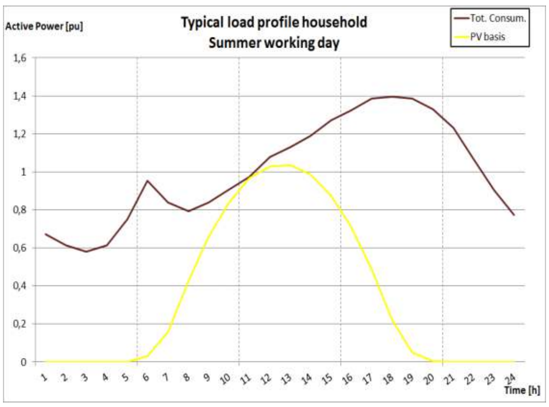
DK



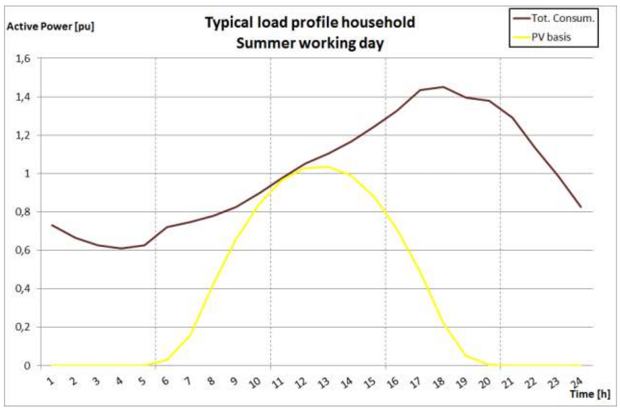
PRT



USA1



USA2



USA3

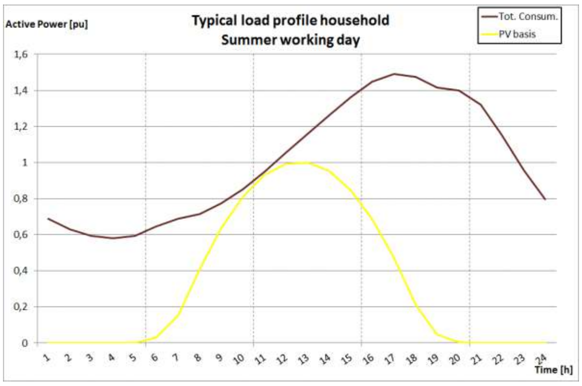
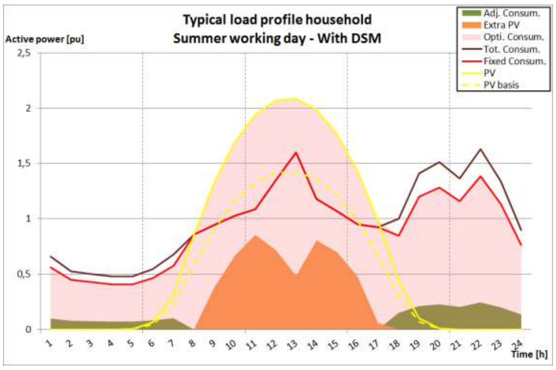


Figure 12 : Results overview per country, without DSM nor storage, normalized.

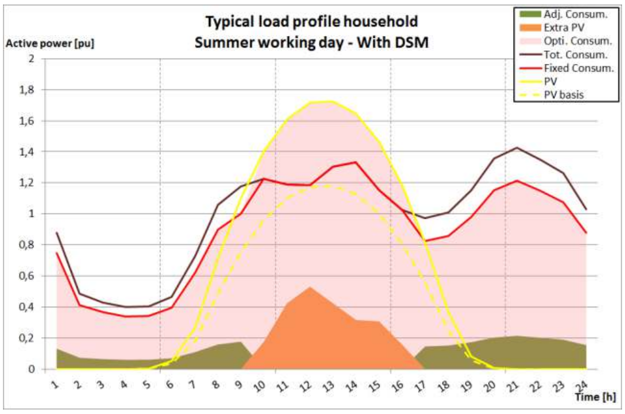
3.1.4 Integration with DSM

The graphics below show how much “PV” power may be installed and PV energy may be self-consumed, with the same ratio of DSM. It shows for instance that Portugal typical household load profile will imply more efforts needed to increase self-consumption level compared to Switzerland by using same ratio of DSM.

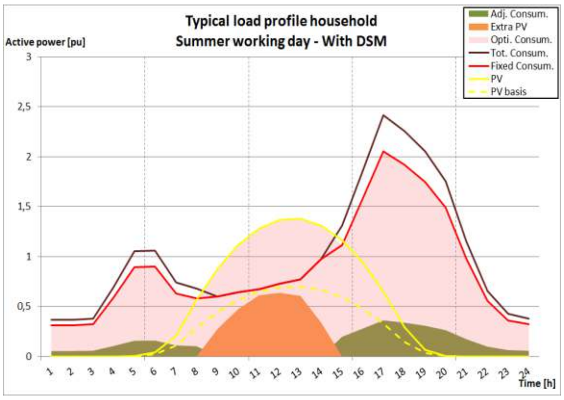
CHE



GER



DK



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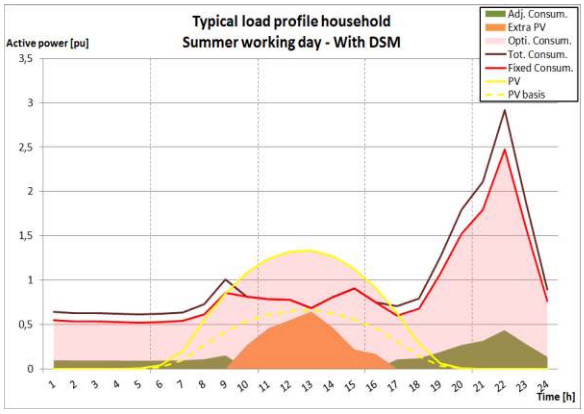
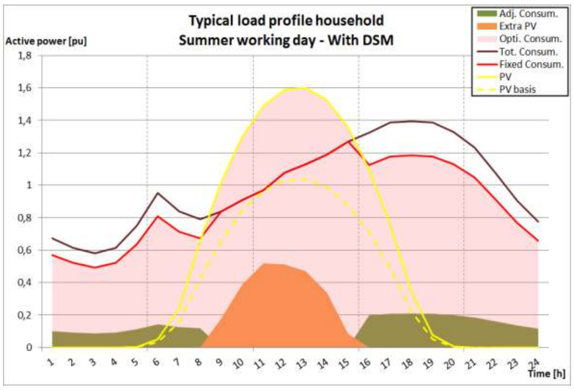
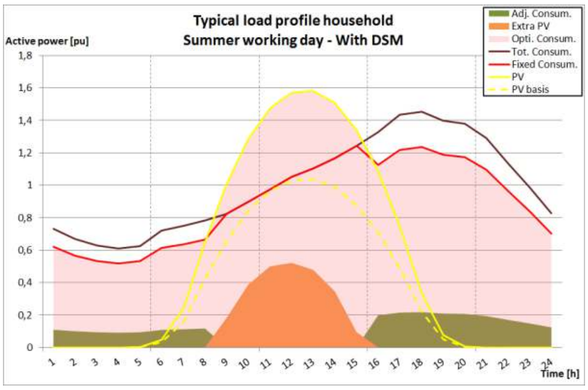


USA1



USA2



USA3

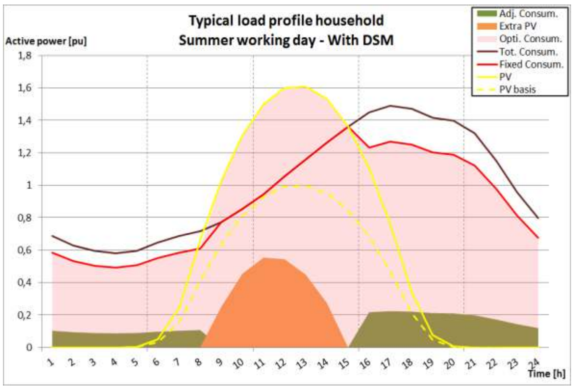
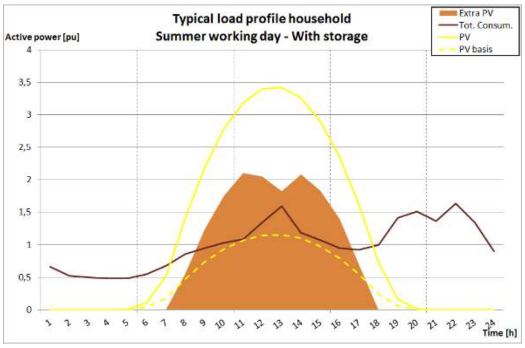


Figure 13 : Results overview per country, with 15% energy DSM, normalized.

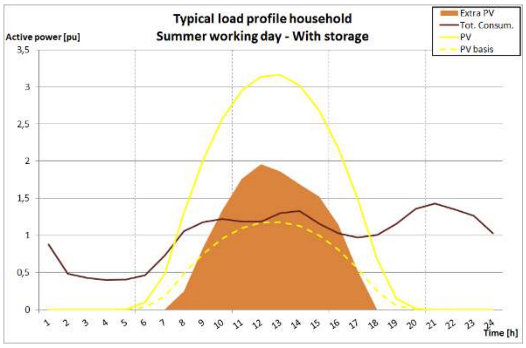
3.1.5 Integration with storage

The graphics below show how much "PV" power may be installed, and how much PV energy may be self-consumed with same capacity of storage. It shows for instance that Denmark typical household load profile will require higher efforts to increase self-consumption level compared to Germany by using same capacity of storage.

CHE



GER



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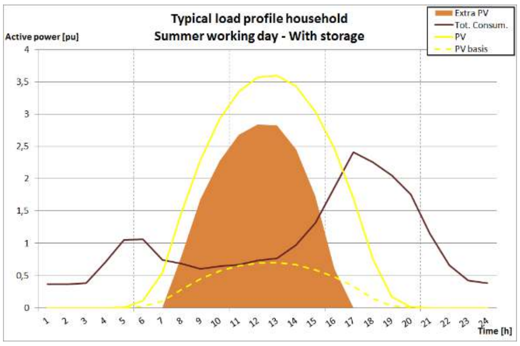

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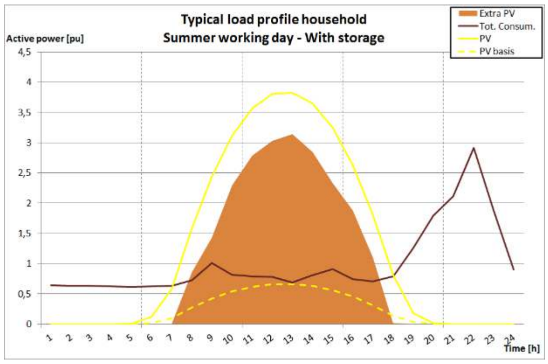
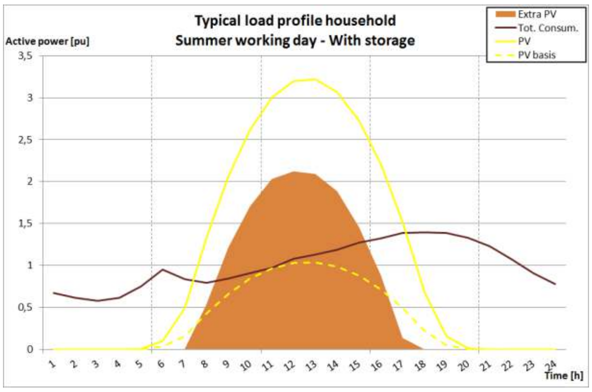
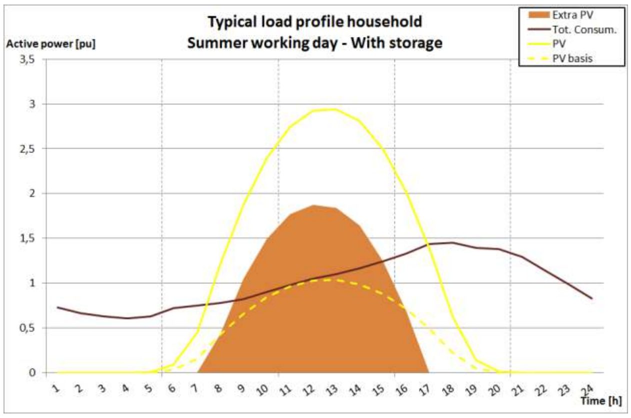


USA1



USA2



USA3

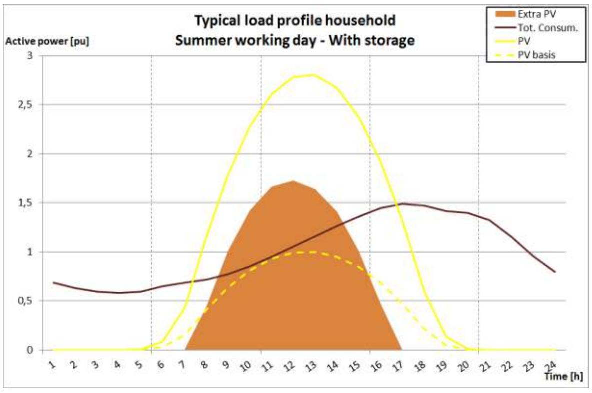
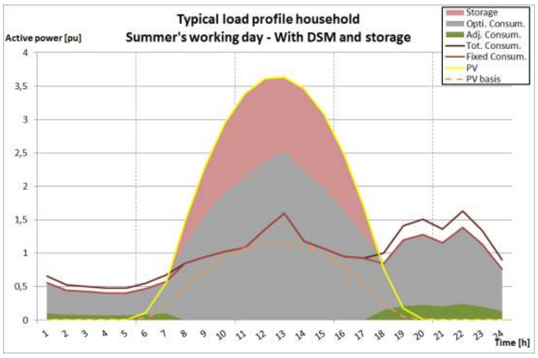


Figure 14 : Results overview per country, with storage, normalized.

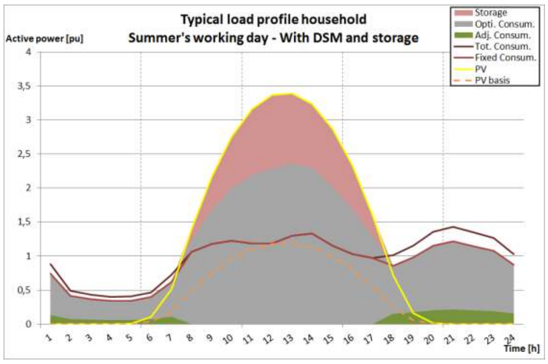
3.1.6 Integration with DSM and storage

The figures below show how much "PV" power may be installed, and how much PV energy may be self-consumed with same ration of storage. It shows for instance that Denmark typical household load profile will imply more efforts needed to rise self-consumption level, when compared to USA 3, by using same ratio of DSM and storage.

CHE



GER



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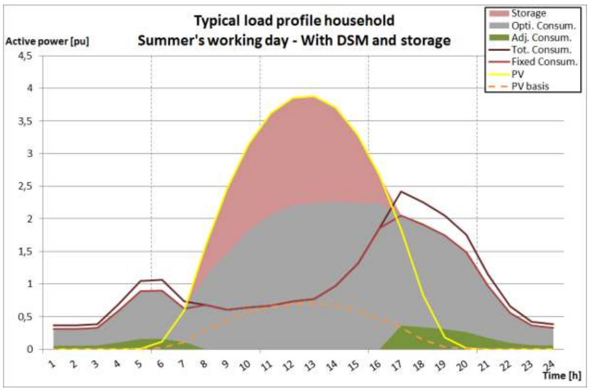

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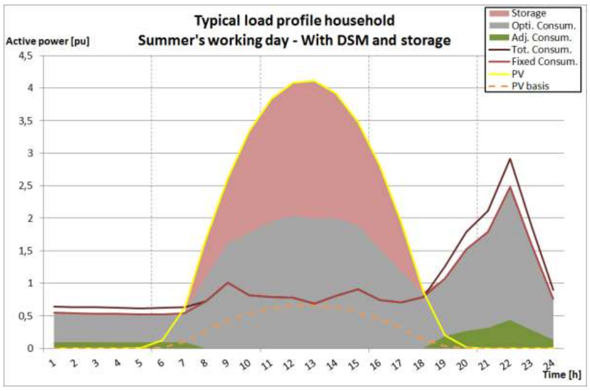
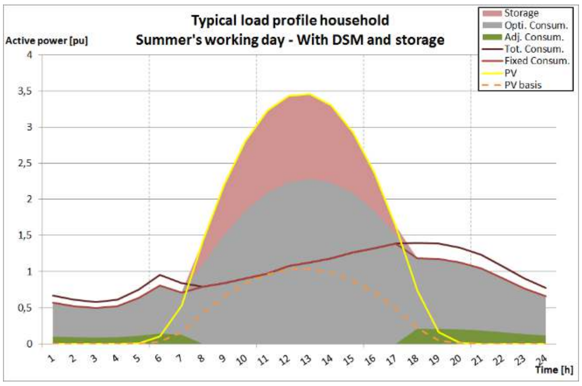
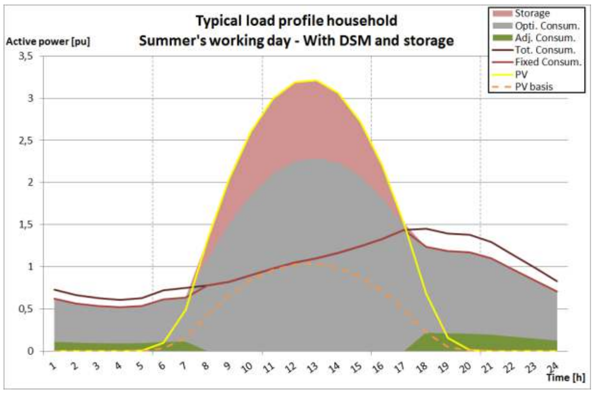


USA1



USA2



USA3

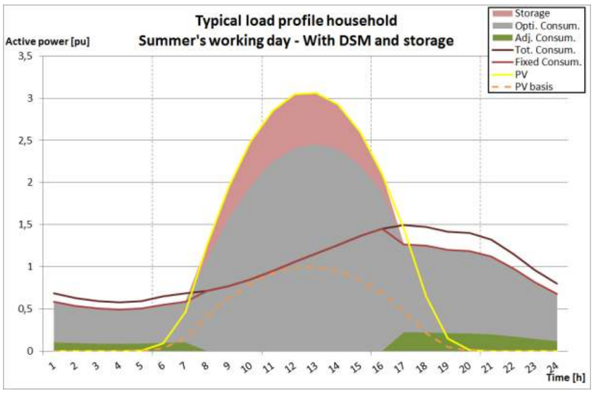


Figure 15 : Results overview per country, with 15% energy DSM and storage, normalized.

3.1.7 Results

The table below shows the different self-consumption rates obtained per each country and the self-consumption rate rise of the different scenarios (with DSM, with storage, with DSM and storage).

		Power (W)	Generation (kWh)	of 4'500kWh yearly consumption
CH	**Basis**	495	445-550	10-12 %
	DSM	797	717-797 (+44%)	16-18 %
	Storage	1473	1326-1473 (+166%)	29-33 %
	DSM+storage	1564	1408-1564 kWh (+95%)	31-35 %
DEU	**Basis**	550	495-550	12-14 %
	DSM	800	720-800 (+45%)	18-20 %
	Storage	1470	1323-1470 (+167%)	33-37 %
	DSM+storage	1580	1422-1580 (+187%)	36-40 %
DK	**Basis**	230	207-230	5-6 %
	DSM	460	414-460 (+100%)	10-12 %
	Storage	1210	1089-1210 (+426%)	27-30 %
	DSM+storage	1300	1170-1300 (+465%)	29-33 %
PRT	**Basis**	230	207-230	5-6 %
	DSM	460	414-460 (+100%)	10-12 %
	Storage	1320	1188-1320 (+474%)	30-33 %
	DSM+storage	1410	1269-141 (+513%)	32-35 %
USA1	**Basis**	440	396-440	10-11 %
	DSM	680	612-680 (+55%)	15-17 %
	Storage	1370	1233-1370 (+211%)	31-34 %
	DSM+storage	1480	1332-1480 (+236%)	33-37 %
USA2	**Basis**	480	432-480	10-11 %
	DSM	740	666-740 (+54%)	17-19 %
	Storage	1370	1233-1370 (+185%)	31-34 %
	DSM+storage	1500	1350-1500 (+213%)	34-38 %
USA3	**Basis**	550	495-550	12-14 %
	DSM	890	801-890 (+62%)	20-22 %
	Storage	1560	1404-1560 (+184%)	35-39 %
	DSM+storage	1700	1530-1700 (+209%)	38-43 %

By comparing various results obtained, it can be concluded that:

- Some households may have some natural predispositions for the self-consumption of PV production. The load curves of typical German, Swiss, and Southern Californian households seem for instance well adapted to PV generation curve.
- The predisposition of a country for self-consumption has nothing to do with radiation potential. For instance, Portuguese household will not reach easily high self-consumption rates since, according to the data used in this study, the typical Portuguese load curve shape is mainly flat with a high peak in the late evening.
- ”Simple“ DSM will in some cases constitute a great participation to self-consumption rise. For instance Danish and Portuguese typical household self-

consumption rate is rising 100% with DSM while other countries rate is rising 50-60% only.

Main limitations of this studies and results are the following:

- Each household may have very different load profile in the same country
- Each household will have different production profile
- The size of the roof, the efficiency of the PV system, the nature of the shiftable load etc… are parameters that shall, at the end, influence the self-consumption of local PV production
- No economical criteria have been taken into account.

3.2 Case study 2: network driven demand side management using PV battery systems for voltage control (Source: IWES)

While the previous case studies assumed that there is no interaction with the network, this section presents a control strategy which allows for active network integration of PV storage systems by charging the storage system based on the network state. In Germany, the difference between the end customer's electricity price, approx. 28 ct/kWh, and the current PV feed-in tariff for systems under 10 kWp, approx. 13 ct/kWh, has set an incentive to install PV battery systems to increase the local consumption of the locally produced PV power (19), (20).

Usually, their network supporting functionality is realized by fixed power curtailment to 60 % of the installed PV power. This means the battery is operated under a two-fold approach:

- increasing self-consumption by charging the battery with PV power that exceeds the local demand and would otherwise be fed into the network
- a peak shaving approach. Yet, the peak shaving approach is sometimes only realized by curtailing PV power, when the battery is fully charged.

The upper limit of PV power feed-in provides an advantage for the overall PV hosting capacity, yet, it does not necessarily support an active voltage control during network operation and thus does not realize network driven DSM (21).

In this section, we analyze how an additional voltage controlling component can facilitate PV network integration.

The standard state-of-the art PV battery control strategy increases PV self-consumption is adapting the following logic:

If the residual load P_{res}, defined as the difference of P_{PV} and the absolute load demand P_{Load} is positive, the battery $P_{Bat,ch}$ is charged with P_{res} until the SOC reaches its upper limit. Vice versa, the battery $P_{Bat,disch}$ is discharged with P_{res}, if P_{res} is negative and the SOC is above its lower limit. In this example, the SOC varies from 0-100%, where 100% is defined by the useable battery capacity (21).

To realize a voltage controlling ability, the droop based voltage control strategy is proposed. Here, local voltage rises are addressed by consuming inductive reactive power or reducing the active power output of the system. Two voltage droops for reactive power consumption and afterwards active power reduction, as shown in Figure 20 below, are introduced (22).

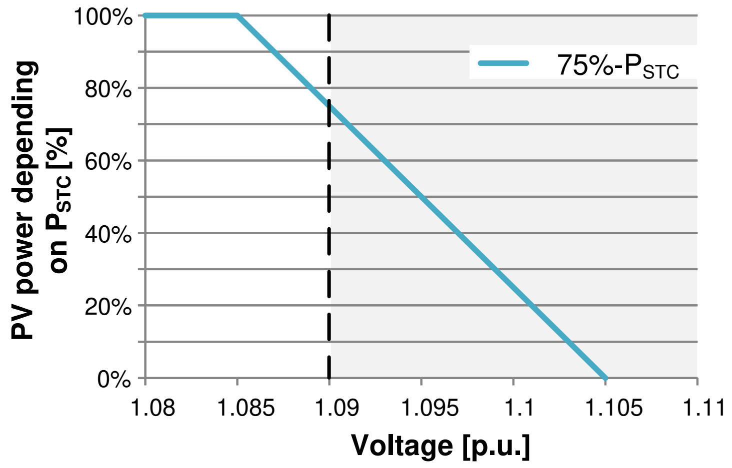


Figure 16 : Droop control for PV systems

The battery system provides an additional degree of freedom to support voltage control (23). Therefore, a voltage based charging is introduced on top of the residual power charging for self-consumption. Whenever the voltage surpasses a certain level, the battery not anymore charged only with P_{res}, but with P_{PV} at the maximum. In consequence, the PV battery system lowers the voltage as no PV power is fed into the grid and the load adds a voltage lowering component as well.

To benchmark such a strategy against the fixed curtailment, a highly PV penetrated low voltage grid is simulated, as described in (24). In an extreme scenario, all households are equipped with PV Systems, of which 50 % are controllable and depending on the scenario also have a battery system installed. The newly introduced strategy is compared to the strategies shown in Figure 21 which are fixed power curtailment (PV1, PV-Bat1), automatic voltage limitation (PV2, PV-Bat2) and the droop based voltage control (PV3, PV-Bat3).

System	Control strategy	Abbreviation
PV system	X%-P_{STC}+ cosφ(P)	PV1
	Automatic voltage limitation (AVL)	PV2
	Q_{PV}(V)-P_{PV}(V) characteristic	PV3
PV storage system	X%-P_{STC}+ cosφ(P) + Standard operation	PV-Bat 1
	P_{Bat}-Q_{PV}-P_{PV} (AVL)	PV-Bat 2
	P_{Bat}(V)-Q_{PV}(V)-P_{PV}(V) characteristic	PV-Bat 3

Figure 17 : Different control strategies for PV and PV storage systems [(22)].

The automatic voltage limitation dynamic adjusts the PV output in case a certain voltage threshold is surpassed, while the droop based control strategy is following a predefined characteristic curve when reducing the active power output in case of overvoltages.

The strategies are evaluated according to their ability to increase self-consumption, reduce PV curtailment and mitigate overvoltages.

All control strategies are able to reduce overvoltages. Yet, as the fixed power curtailment strategies are only able to reduce higher voltages up to a certain level of PV penetration of the grid as they do not address overvoltages directly.

Two factors are important to evaluate the economic impact of the different strategies on the system owner: PV energy losses due to power curtailment and self-consumption rates. The reduced PV energy is a measure of the power that is not fed into the grid due to grid integration reasons. Figure 22 below shows the PV energy losses over all additional PV systems over one year for the given example.

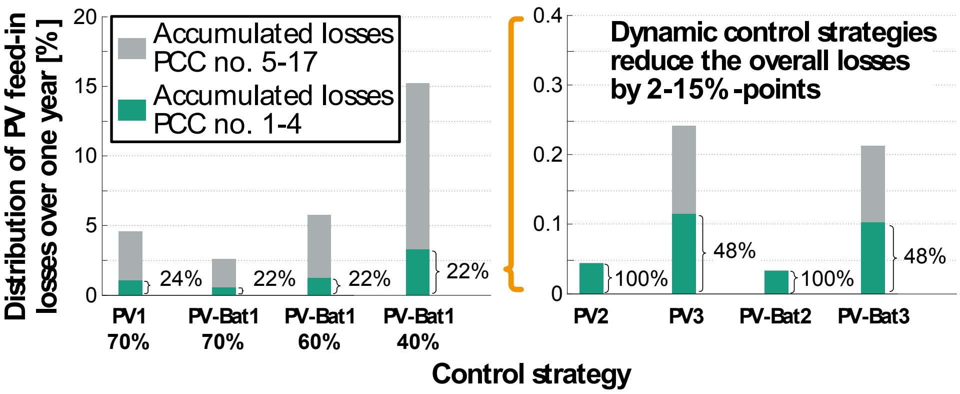


Figure 18 : Distribution of PV energy losses over different PV systems and PV storage systems depending on the control strategy **(22)**.

The analysis is divided into two parts: the overall losses and the contribution of the losses of the four systems that see the highest voltages in the grid to the overall losses of all additional systems. It becomes clearly visible that the overall losses decrease tremendously when switching from fixed power curtailment to dynamic voltage control (strategies PV2-3, PV-Bat2-3). In this example the losses are reduced by almost 2.5-15 %. The AVL strategies reduce the losses even more compared to the droop based strategy. Nevertheless, with these strategies voltage control is entirely performed by only a few systems. They lead to a more uneven distribution of the PV energy losses, while the droop based strategies reduce the asymmetry by half.

In terms of self-consumption, all strategies achieve the same increase when using a battery.

Figure 23 shows the change in net present value (NPV) (See definition (25 p. 15)) of the PV or PV battery system connected to the point of common coupling (PCC) at most critical grid node, with highest voltages conditions. This figure leads to the following conclusions:

In general, higher self-consumption rates increase the value of the system as less electricity has to be purchased from the grid. Higher PV energy reduction resulting from power curtailment for grid integration reasons decreases the NPV of the system as the system owner receives less revenue from the feed-in tariff paid for PV grid injection.

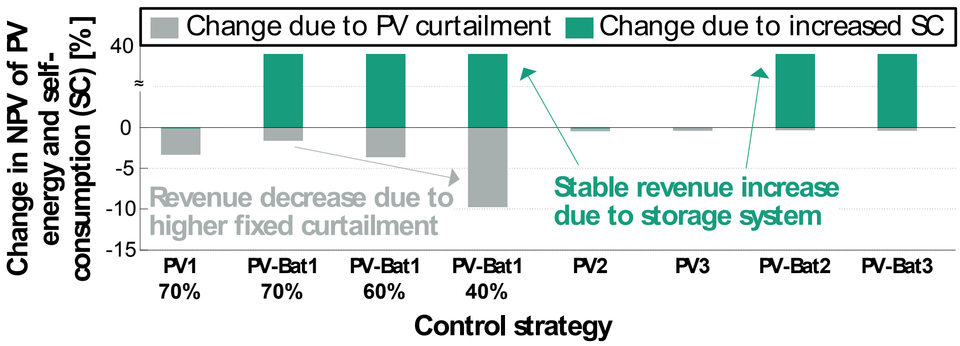


Figure 19 **:** Change of PV or PV storage system's net present value (NPV) for static and dynamic control strategies for system at most critical grid node **(22)**.

Using batteries increases the potential revenue and therefore the NPV for the system owner of a PV battery system compared to just a PV system, as one can see from the green bar charts. Furthermore, for the fixed power curtailment strategies (PV1, PV-Bat1) the potential revenue decreases with a lower curtailment threshold. The dynamic voltage control strategies lead to no significant decrease in NPV compared to fixed power curtailment strategies.

In summary, one can state that dynamic voltage control strategies for PV storage systems offer a high potential to handle the trade-off between curtailing energy and supporting grid integration of such systems. These strategies allow for an increase self-consumption and a minimization of PV power reduction and therefore PV energy losses. At the same time, they increase the PV grid integration potential as they address voltage rises dynamically (21). Furthermore, droop based strategies ensure that the contribution to voltage support is shared among more systems and potential PV energy losses are as well as. Yet, the distribution of these losses is more asymmetrical for this strategy compared to fixed power curtailment, but the overall losses are tremendously reduced in the given example.

4 Conclusions

4.1 Obstacles and limits

After a **general** overview of the subjects treated in the present report, we may list the following obstacles and limits for higher penetration rates of PV systems using grid driven demand side management:

- First of all, the main difficulty that we are facing is a need for understanding the complexity of existing grid management before defining future "smart" solutions. PV indeed needs to rely on power grids and its development will benefit from a robust grid in a long term perspective.

- The second obvious obstacle identified is of organizational nature:
  - The first organizational challenge is lack of requirements harmonization. The pre-existing power system requirements environment is indeed extremely decentralized (standards, academic spheres, Grid Operators etc.).
  - The second organizational challenge we see is the number and variety of products and mechanisms involved in "network driven demand side management" applied in household. Patents, market competitiveness, and lonely paths will not help in developing robust controls.

More **specifically**, the following obstacles and limits were found:

- The definition of Demand Side Management may be very large, and we willingly decided to focus on active power control mainly, even though reactive power control has also an influence on upstream losses and upstream kVAs.

- There may be many various control concepts and particular performances depending on countries, regions, towns etc.

4.2 Main take-aways

Household PV represents an opportunity for:

- Developing DSM as described in chapters 2.1 and 2.2.
- Participating to global frequency control and local voltage control. Frequency control set of parameter and performance figures were proposed in chapter 2.3 and local voltage control strategies using reactive power were identified in chapter 3.2
- Integrating large amount of PV without reverse flow as the medium grid transformer (results of chapter 3). Depending on the country, 5% to 12% of the annual consumption can be covered by PV without reverse flow on the medium grid. These amounts raise 10 to 20% with DSM and up to 40% with DSM and a usual household storage (6 kWh).

Historically, the Low Voltage grid levels were not the areas where the control intelligence was. However, it is the opinion of the authors that:

- traditional transmission grid control mechanisms should be reinforced for most important aspects of grid security (e.g. frequency control, system stability reinforcements, new global phenomena risk like damping and frequency oscillations etc.)

- monitoring of lower voltages layers of the grid shall be intensified (data exchange etc.)

- available opportunities such as active power control of PV and household loads and reactive power control of PV should be seized. According to the simulations of chapter 3, DSM can double the hosting capacity of a local grid.

4.3 Recommendations

The following recommendations may be given:

- A structural approach equivalent to what has been described in chapter 2.2 and 2.3 is recommended for studying DSM. Trying to define technical requirements as precisely as possible is the necessary first step towards defining what the grid requires (e.g. capabilities, control loop parameters etc.). We shall then analyze what performance we may obtain today from PV and DSM depending on typical conditions at household level.

- DSM controls shall be designed and embedded within existing grid management mechanisms (see example of control process proposed in figure 9), via collaborative work with Grid Managers.

- From an active power and grid perspective, DSM and batteries should be concentrated on reducing the midday PV pic to improve potential PV penetration.

- In a context of cost optimization and economic relevance of DSM, we shall focus on obtaining the cheaper cost and effort per household (P control accuracy will not matter at a single household level) and invest on control intelligence, monitoring quality and robustness of the aggregated load.

4.4 Outlook

In the perspective of further activities, the following tasks may help to develop our thinking in relation with DSM:

- Collecting and analyzing the feedback of Transmission Operator(s) or group of Transmission Operators to better understand the current frequency variations within the power grid.
- Collecting and analyzing more information about the current mechanisms of coordination between Transmission Operators and Distribution operators.
- Targeting and addressing some technical questions to "state of the art" DSM groups, regarding performance, implementation issues, relations with Grid Operators etc. (e.g. In USA, it seems DSM democratized in largest scale).
- Collecting and analyzing more data regarding the performance of the existing systems that combine PV, batteries and loads.

The following actions are thus necessary:

- development of a "performance specification" by collaborating with industries and grid operators focusing on the research of an economic optimum by trying to fulfill to relevant requirements.
- general development of all remaining issues: business model development (first step could be valuing the kwh of tertiary control based on current market conditions), cybersecurity and privacy matters, development of the robustness of such controls (how reliable would be such control?) etc.

Additionally, it would be particularly relevant to study load management mechanisms and DSM applied to industrial PV installations (e.g. P>100kW).

5 Annex

5.1 Annex 1 - A grid requirement: participation to long term and short term grid frequency stability

"Deviations of 100mHz happen every day now without anybody worrying about it while 30-40 mHz deviations were making everybody nervous before"

Source: interview with Walter Sattinger, 7.05.2013, Swiss grid web site.

Frequency stability deteriorates in many locations around the world. Reasons behind this development may be electricity markets development (increase in market participants), and the fact that systems are operating closer to their limits nowadays. Taking into account such a trend, we may reasonably guess that Demand Side Management may theoretically constitute a potential improvement. The figure below shows the evolution of the average ENTSOE (formerly UCTE) frequency variations from 2002 to 2008 in Europe, and illustrates a potential need.

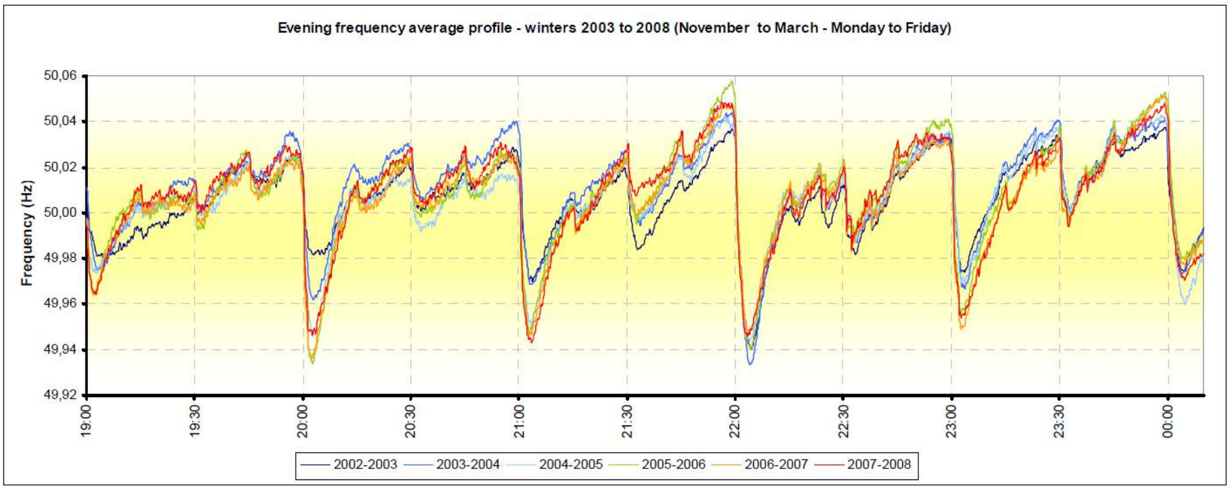


Figure 20 : Average UCTE frequency recordings from 2003 to 2008, Source Frequency Quality investigation, (26) (remark: biggest variation peaks are reached within minutes only in this picture)

On the **4th of November 2006**, European transmission network faced an extremely severe event originating from the North German transmission grid, that led to power supply disruptions for more than 15 million European households and a splitting of the UCTE synchronously interconnected network in three areas. The investigations about the origins of the issues, sequence of the event, etc. are available on the web and, just like most of other power system crisis investigations, constitute a rich source of information.

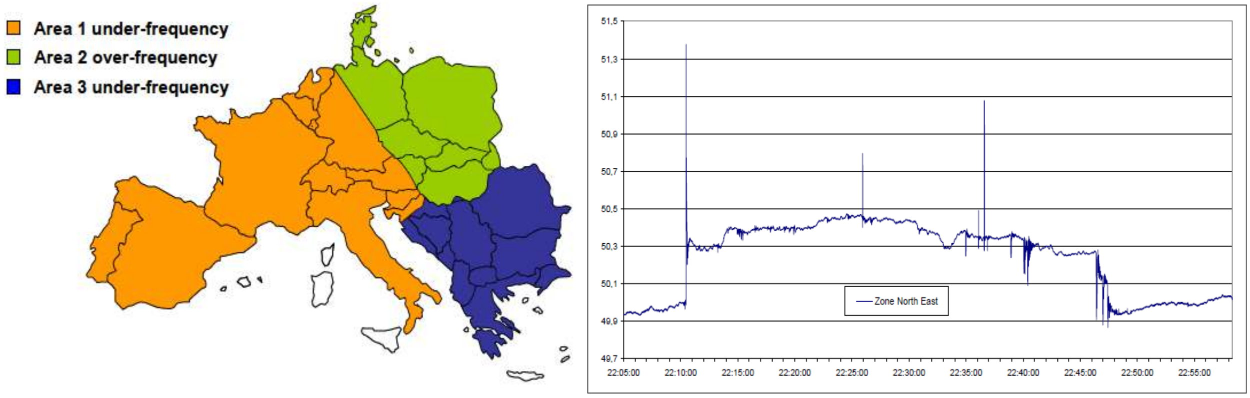


Figure 21 : Schematic map of UCTE area split into three areas, and recording of the area 2's frequency between 22:00 and 23:00 on 4th of November (Source: (26))

We can see that in the north east area, a situation of overfrequency (frequency around 50.3Hz) has been experienced for more than half an hour. It has to be mentioned that, according to the investigation, overfrequency was partially fed by an uncontrolled increase of wind power in the region following the split.

Looking at the frequency recordings of area 2 (frequency around 50.3Hz for nearly 35 minutes), we may reasonably assume **that a massive Demand Side Management could have participated in a situation improvement**, if properly tuned, controlled and geographically spread.

Even though the most important "players" dealing with major grid events are synchronous machines, other potential candidates could also participate in frequency restoration (several seconds after the disturbance) as long as the system would work in a controlled and robust manner as a whole.

5.2 Annex 2 - Remarks about fast inertial response

What would happen if a major power plant (e.g.: 1-2GW nuclear power plant), or a major loaded electrical transmission line, is disconnected from the electrical grid?

In the best case, the situation will be handled by the TSO(s) using the meshed nature of the grid and the various mechanisms at their disposal to rebalance the active power flows, without impacting end consumers. And in the worst case, we will experience a regional and continental collapse that will affect millions of people and economies (effect also known as a "black out").
The first impact of such an event will be stability margin reduction. The figure below illustrates the generic "power-angle curve" that is well known to Grid Operators. To sum up, the TSO is keeping stability margin by adjusting the power to be transferred within a grid line. During a normal operation, a safety margin is kept positive (e.g. 30% margin) but when a sudden loss of power occurs, the "sending end source S" will experience an immediate shift in angle. If the angle difference between the two extremities of the line is overtaking 90°, the whole system will become unstable.

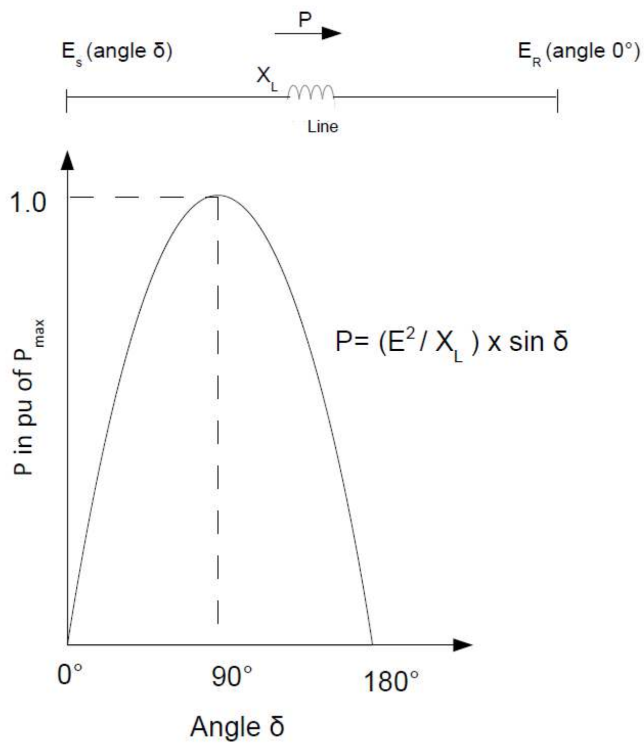


Figure 22 : Power-angle relationship in a transmission line (system model and power angle curve with E line to line system voltage) (Source: (27))

The fastest and most powerful help that the TSO will get from the power system will be a natural reaction from all synchronous generators that will immediately (in terms of ms) inject active power following the shift in angle (effect known as inertial response). This "inertial response" has no need for communication line, nor any human or computer mechanism! This means that thanks to the inherent nature of the predominant existing power plants, there is a firm, immediate, and needed interaction within the global AC grid, regardless of border lines, communication systems, or human organizations.

But then, even without entering into angle instability, the system may likely experience voltage undesired behavior and frequency drop as a consequence of the sudden power flow shift. Following inertial response, primary reserve will bring the energy needed for rebalancing the frequency (several hundred MWs synchronous generators, nuclear power, hydro power etc.). The frequency will fall (see figure below). A second threat that the whole Transmission system will have to take care of will be preventing that the peak of minimum frequency will not overtake existing relays and protections limits (49.7Hz in the figure below). During such an event, it is of higher importance not to lose even more power in order to minimize the frequency drop. It is easy to understand that any additional unexpected active power production loss shall be undesirable within the system. For instance we should make sure there is no mass scale renewable energy disconnecting from the grid because of voltage variations or frequency drop (e.g. just like what happened in November 2006 European UCTE event according to the investigation report).

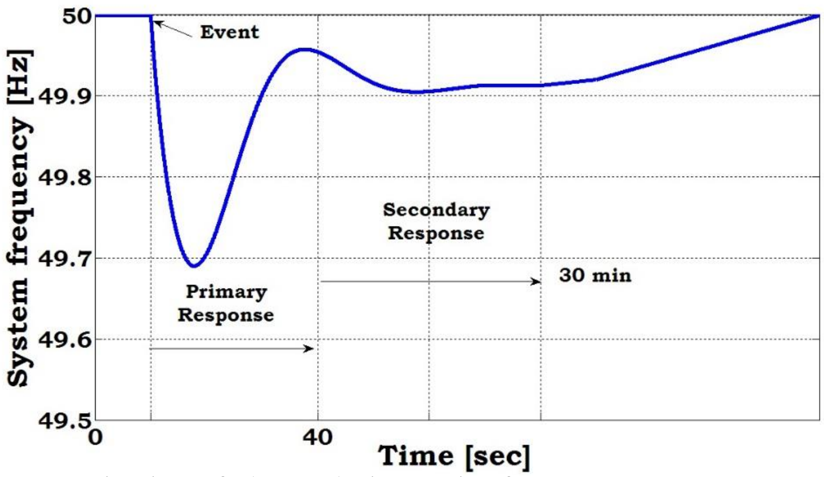


Figure 23 : categorization of phases during major frequency event (Source: (28))

We could therefore say that because of the emergence of non-synchronous power plants within the production mix (e.g. asynchronous machines, IGBT and power electronics emergence, wind, PV, etc.), green energy needs to be subject to precise requirements and their behavior shall be fully controlled and understood in advance. It is the opinion of the authors that these new technologies represent powerful opportunities (e.g. "artificial" primary control and power reserve, local voltage control, etc.) as long as they will be subject to clear, harmonized, and relevant grid requirements, that fit with their techno-economical capabilities and performances (e.g few % constant derating for power reserve).

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