
Cover picture:
Modelling of the Swiss power grid (Prof. Olaf Schenk (USI))

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and industrial partners including strategic partners that contribute to more than one WP such as

Introduction

Swiss Energy Strategy 2050

In 2011, the Swiss Federal Council and Parliament decided to phase-out Swiss nuclear power plants. In view of this decision, the Federal Council developed a long-term energy policy known as "Energy Strategy 2050" that provides the basis of revised energy perspectives for the decades to come.

For the implementation of this strategy, there are two major challenges that should be overpassed, (a) the enabling of the vast connection of distributed renewable energy resources in to the energy grid; and (b) the improvement of the energy efficiency at the final-consumer side. This requires the entire Swiss energy system to undergo through radical changes.

About Swiss Competence Centers for Energy Research (SCCERs)

In 2014 the National Commission for Technology and Innovation (CTI) established the Swiss Competence Centers for Energy Research (SCCERs), in order to address these challenges. The SCCERs are looking for solutions to the technical, social and political associated challenges. Eight SCCERs were created, covering the full spectrum of the current energy innovation chain.

About SCCER-FURIES: the SCCER that shapes the Future Swiss Energy Infrastructure

The SCCER-FURIES is the power grid member of the SCCER’s “family”. It bring together all the key actors of the power grid in Switzerland, including 32 institutes and 14 leading companies, in order to transfer knowledge among them and develop innovative solutions, both products and services. Furthermore, being a member of the SCCERs family, provide FURIES partners access to an extended pool of capacities of 165 groups around Switzerland. This holistic and multidisciplinary approach, which is required for the proper implementation of the “Energy Strategy 2050”, is taken for the first time at this extend in Switzerland.

Vision: The SCCER-FURIES envisions “the enabling of seamless and sustainable powering of Swiss citizens’ houses, businesses and communities, by developing and demonstrating with the Distribution and Transmission network operators the essential knowledge and technologies for a sustainable and stable electrical infrastructure of the future which integrates cleaner and reliable power supplies and storage facilities.”

Objectives: Accordingly, the SCCER-FURIES’s objectives include the:

- Enabling of the development of massive distributed generation
- Guarantee of reduced grid costs associated to the massive connection of distributed generation;
- Improvement of the reliability and security of the entire electrical system.
### 2014-2016 Phase I

**Planning**

- Decision-support and forecasting tools for the planning of regional energy systems based on the Swiss 2050 scenario  
  *(Related projects in page: 22, 30, 31, 32, 33, 34, 35)*

- Techno-economic evaluation of the future Swiss energy system with increasing share of RES and geolocalisation tools for identification of optimal grid extensions, incorporating RES and hydro storage and improving grid stability  
  *(Related projects in page: 41, 42, 43)*

**Operation**

- Real-time monitoring infrastructure (using synchrophasor measurements – PMUs) and secure communication standards for Active Distribution Networks  
  *(Related projects in page: 14, 15, 63)*

- Optimal centralized/decentralized control approaches for distributed generation and storage and demand-side management processes  
  *(Related projects in page: 23, 25, 26, 29)*

- Ancillary services by DER  
  *(Related projects in page: 24, 27, 28, 49, 50, 51)*

**Components**

- Optimal multi-terminal AC/DC interactions assessment  
  *(Related projects in page: 20, 21, 52, 53, 54, 55)*

- Flexible and modular AC/DC converter concepts and materials for mixed frequency voltage stress  
  *(Related projects in page: 57)*

- Test facilities for high-power DC applications including circuit breakers  
  *(Related projects in page: 56)*

- Models for reliable battery and inverter for PV production optimization  
  *(Related projects in page: 16, 17, 18, 19, 64, 65, 66, 67)*

- Guidelines for the design of stable pumped-storage hydropower plants

- Modeling, simulation, and measurement of transients and partial discharge monitoring in grid components  
  *(Related projects in page: 20)*

- Test procedure for novel SiC MOSFET modules  
  *(Related projects in page: 68)*
## Introduction

### 2017-2020 Phase II

| Advanced forecasting tools for local energy systems |
| Algorithms to enable optimized multi-criteria geolocalised placement of storage solutions |
| Planning Strategies for Distribution Grids and Multi-Energy Systems |
| Experimental validation of monitoring infrastructure for real-time situation awareness in selected demonstration sites. |
| Computation frameworks for reliable and efficient operation of ADNs. |
| Experimental validation of the identified control strategies in demonstrators. |
| Development of detection and management faults devices; DC-test source and AC/DC integration tools; supergrid technologies such as hybrid DCCB; and novel power electronic converter technologies |
| Multi-tracker and battery inverter test series and test norms; and fire and snow coverage prevention for PV systems. |
| Multiphysics simulations of a coupled hydro turbine-shaft-generator system |
| Novel mitigation methods for power system transients; Modelling and simulation of dry-band surface discharges on insulation |
| Experimental assessment of SiC module reliability |

### Strategic Goal

- Provide Distribution and Transmission network operators tools for better integrated control of the two layers

- Provide Distribution network operators with planning and operate tools to integrate:
  - 4.4 TWh of RES by 2020
  - 14.5 TWh of RES by 2035
Topics: Therefore, the center addressed key topics such as (1) grid monitoring and dynamic control; (2) multi-terminal AC-DC transmission and distribution; (3) power electronics and switching; (4) control of massive DG and distributed storage; (5) multi-energy grids; (6) power systems planning and architecture; (7) demand side response; (8) standardization and grid control; and (9) technologies for power systems components.

These topics have been clustered in four main Work Packages, consisting of subtasks. The subtask teams are working on the achievement of specific milestones and development of deliverables. Also, they collaborate with other teams inside and outside SCCER-FURIES, particularly those of all the other SCCERs.

Summary of 2014-2016 achievements: Phase I was fruitful for the SCCER-FURIES and its partners had numerous achievement. This concerns:

a) the establishment of collaboration including
- 52 collaborations with different industrial partners across the entire value chain of the power grid were established
- 90 new projects were initiated
- 30M were raised for project development

b) the building of capacities
- 181 experts developed their capacities
- 2100 young scientists and 1800 practitioners participated in course and workshop given by FURIES’ partners

c) the development of innovative solutions
- 11 applications for new patents were submitted
- 2 licenses were granted
- 1 spin-off was established
- 44 new prototypes and demonstrators were put in operation across Switzerland (on energy storage; grid control; DSM; transformers; and integration of power production and consumption technologies)
- 39 innovative products, processes and services were developed, in close collaboration with the industry
- 30 models and 36 data collections were developed. Included in the FURIES power grid database

d) the dissemination of the findings
- 9 book chapters and technical reports; 34 journal peer-reviewed papers; 86 conference peer reviewed papers
- 153 presentations in national and international conferences

Phase II (2017-2020)

For the 2017-2020 Phase, SCCER-FURIES is further evolving, moving from the development to the demonstration of innovative solutions. Therefore, it has grown from a CHF30M to a CHF 50M program, for the building of the capacities of higher number of experts; strengthening the collaborations with existing partners; and establishing new ones with new innovation-oriented industrial partners.

Purpose of the 2014-2016 Activity report

SCCER-FURIES, alike the other SCCERs, is closing its Phase I (2014-2016) on development and moves to the Phase II (2017-2020) on demonstration. The purpose of this report is:

a) to enlist the competences that make SCCER-FURIES a competence center, by including a directory with the capacities of each of the Participating labs. This enables the acknowledgement of FURIES-partners’ Phase I contribution and facilitates the establishment of new collaboration for Phase II.

b) to provide anyone interested in the future of the Swiss power infrastructure with an overview on innovation solutions developed during the Phase I of the SCCER-FURIES and insights on upcoming activities. Therefore it includes success stories from each of the SCCER-FURIES’ Work Packages; and a list of publications with links for one-click accessibility.

For further information please visit the SCCER-FURIES website: http://sccer-furies.epfl.ch
WP1
Regional Multi-energy Grids

Innovation Challenges
The increased penetration of distributed renewables poses a number of fundamental problems. First, the volatility and non-dispatchability of wind and solar energy requires an increased amount of generation reserves that, paradoxically, may produce an increased level of CO2 emissions. Second, power imbalances and the compensation of voltage-level fluctuations require expensive capital investments and engineering works associated to the upgrade and reinforcement of distribution/transmission grids. Third, the existing control methods were developed for traditional, centralized power systems with a relatively small number of large resources; they are not applicable to systems with a large penetration of dispersed and non-dispatchable generation. Such problems require a complete re-engineering of the electrical infrastructure with particular reference to the distribution systems since the direct control of every resource is clearly too complex when the number of systems gets large.

Objectives
The objectives of the WP1 were:
✓ to provide reliable, deterministic and real-time data for the assessment of the distribution grids real-time state through new smart metering infrastructures for both medium and low voltage. The knowledge of the network state has then served optimal control algorithms (see below).
✓ to assess the potential topologies of two different control architectures (i.e., centralized vs decentralized) and evaluate the elements to be controlled (i.e., storage systems, demand side management). Concerning the optimal control algorithms, research has been done in the four main item that refers to the interaction of the electrical grid with other energy network (in particular, in the urban context).
✓ to develop accurate forecasting tools of renewable energy production systems with the granularity of regional grids (i.e., urban/rural contexts). These forecasting tools were used to evaluate the contribution of these resources to the ancillary services of electrical distribution grids. This part of the project included photovoltaic and wind generation systems and small hydro-power units.
✓ to define a new grid codes with particular reference to the grid accessibility of distributed generation/active customers/storage systems.
Competences of WP1

WP1 is the largest work package of SCCER-FURIES Phase I, in terms of number of experts and activities. 98 experts from 13 academic laboratories and groups are contributing to this work package and further develop their capacities. These experts are coming from a variety of fields including, electrical, mechanical and environmental engineering and computer science, and focus on grid monitoring, control and security; and its interaction with power generation, storage and consumptions.

These internal competences are complemented through intra- and inter-SCCER collaborations. Within FURIES, WP1 partners collaborate with all the other WPs such as on grid layer’s interaction with WP2, on ancillary services with WP3 and the impact of PV system’s design on the grid with WP4. Furthermore, WP1 partners collaborate with all the other SCCERs, notably with those working on storage technologies (SCCER-HaE); hydropower generation (SCCER-SoE); socio-economic aspects of grids (SCCER-CREST); e-mobility (SCCER-Mobility); buildings’ and industrial efficiency (SCCER-FEEB&D; -EIP); and multi-energy grids (SCCER-BIOSWEET).

Through the collaborations with industrial partners, WP1 partners have acquired knowledge on market needs and transfer knowledge and technologies on technical capabilities. 49 companies collaborate with WP1 partners, including 22 DSO powering the 80% of the Swiss population; the national TSO Swissgrid and railway CFF; 20 Power technology companies; and 5 service providers and associations.

These capacities are continuously enriched through:

a) new collaborations with other SCCERs and the industry

b) Training activities provided by FURIES’ academic partners including

i. Specialization, e.g., a Smart grid specialization in a new cursus named “Environment & Energy Technologies”

ii. PhD school, e.g., the Eurotech on integrated approaches to energy systems (in collaboration with SCCER-HaE (storage))

iii. Master and Bachelor courses in ETHZ, UAS and UNI

iv. Certificates of Advanced Studies, e.g., CAS on PV System Design, CAS in grid management, CAS Smart Grid module

v. Professionals’ training, e.g., Workshop on Energy Storage
Head of SCCER-FURIES; Leader of WP1 and Leader of S1.1 Smart metering infrastructure

**EPFL, Distributed Electrical Systems Laboratory**

Main competences:
- Active distribution networks
- Distributed generation
- Distributed energy storage
- Monitoring and advanced metering
- Real-time operation and control
- Advanced protection techniques
- ICT integration into smart grids

Web: [http://desl-pwrs.epfl.ch](http://desl-pwrs.epfl.ch)

**Leader of S1.1 Smart metering infrastructure**

Prof. Dr. Mario Paolone

---

Leader of S1.2 Demand side response/management

**HES-SO Valais**

Main competences:
- Design, implementation and testing of control strategies
- Demand Response for grid control and energy markets.
- Power Quality and ElectroMagnetic Compatibility (EMC) for future grids
- ICT for smart grid and metering

Web: [http://www.hevs.ch/fr/technik/imvs/](http://www.hevs.ch/fr/technik/imvs/)

**Leader of S1.2 Demand side response/management**

Prof. Dr. Dominique Gabioud

---

Leader of S1.3 Ancillary services

**EPFL, Automatic Control Laboratory**

Main competences:
- Transient control in electrical grids;
- Robust distributed control of Microgrids;
- Control of networks with communication delay
- Data-driven control

Web: [http://la.epfl.ch](http://la.epfl.ch)

**Leader of S1.3 Ancillary services**

Dr. Alireza Karimi

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Leader of S1.4 Forecasting tools of RE production

**EPFL, Laboratory of Wind Engineering and Renewable Energy (WIRE)**

Main competences:
- Wind energy assess. and forecast.
- Wind farm design, control and optimization
- Theoretical & numerical modelling of wind over complex terrain
- Field and wind tunnel experiments

Web: [http://wire.epfl.ch](http://wire.epfl.ch)

**Leader of S1.4 Forecasting tools of RE production**

Prof. Dr. Fernando Porté-Agel

---

Leader of S1.5 Planning of regional energy systems

**EPFL, Industrial Process and Energy Systems Engineering**

Main competences:
- Integration of multi-energy systems
- Design and operation of district heating and cooling systems
- Predictive control of thermal systems, heat pumps, cogeneration
- Seasonal storage with thermal and thermo-chemical systems (power2gas)

Web: [http://ipese.epfl.ch](http://ipese.epfl.ch)

**Leader of S1.5 Planning of regional energy systems**

Prof. Dr. François. Marechal

---

Leader of S1.6 Development of standards/grid codes

**FHNW, Institute for Mobile and Distributed Systems**

Main competences:
- IT Security in Smart Grids, including:
  - Security for embedded systems for control
  - Security in operation e.g. updating mechanisms

Web: [http://www.fhnw.ch/technik/imvs](http://www.fhnw.ch/technik/imvs)

**Leader of S1.6 Development of standards/grid codes**

Prof. Dr. Peter Gysel

---

SUPSI, Institute for Applied Sustain. to the Built Environment (ISAAC)

Main competences:
- Design of adaptive algorithms DSM, using innovative forecasting techniques.
- Design and evaluation of techno-economic KPIs for energy solutions.
- Multiphysics simulations of thermal and electrical components
- Design, modeling, simulation, testing and monitoring of PV systems.

Web: [http://www.supsi.ch/isaac](http://www.supsi.ch/isaac)

**Leader of S1.6 Development of standards/grid codes**

Prof. Dr. Roman Rudel

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<th>Main Competences</th>
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| **EPFL, Laboratory of Hydraulic Machines (LMH)** | • Cavitation Detection and Monitoring  
• Flow Analysis in Turbines and Pumps  
• Rotor-Stator Interaction  
• Flow Investigation in Draft Tube  
• Stability in Francis Turbines  
• Active Control for Turbomachines Stability  
• Free Surface Flows in Pelton Turbines  
• Design Tools and Model Manufactur.         | [http://lmh.epfl.ch](http://lmh.epfl.ch) |
| **EPFL, Photovoltaics and Thin-Film Electronics Laboratory (PV Lab)** | • World leading research lab for PV cell technologies (c-Si-, perovskites- and thin-film silicon-based solar cells; transparent conductive oxides  
• PV modules for building integration with long term degradation/reliability  
• PV integration in the grid using optimum PV deployment, demand – side management and local storage | [http://pvlab.epfl.ch](http://pvlab.epfl.ch) |
| **HES-SO Valais, group Hydroelectricity**     | Flow simulations and experimental measurements of large and small hydropower plants’ hydraulic systems:  
• Flow analysis using numerical simulation  
• Development of new technologies for small hydro applications  
• Design of electrical drive systems  
• Performance measurements  
| **BFH, ESReC Grids lab**                      | • Static&dynamic grids modelling incl. oscillation phenomena by computer-based and hardware modelling  
• Power Quality field measurements, incl. frequency dependent grid impedance and analyze e.g. aggregation of long-term data.  
• Recommend. for network disturbances limitation and target grid planning. | [https://www.ti.bfh.ch/.../netze](https://www.ti.bfh.ch/.../netze) |
| **BFH, PV-Lab**                                | • Test PV systems with field campaigns/IR-drones/U-I equip./flasher& e-lumin.  
• Simulate and plan PV production profiles and their grid impact  
• Predict load profiles and simulating complex systems in the “prosumer-LAB”  
• Test of components <1 MV in HV test facility and surge current test chamber | [http://www.pvtest.ch](http://www.pvtest.ch) |
Key Activities of WP1

WP1 consists of **6 subtasks** that cover all the key aspects of the regional energy systems and includes:

- S1.1 Smart metering infrastructure
- S1.2 Demand side response/management
- S1.3 Ancillary services for distribution grids
- S1.4 Forecasting tools of renewable energy production
- S1.5 Planning procedures of regional energy systems
- S1.6 Development of standards/grid codes for distribution networks

During the 2014-2016 period, **78 projects** have been initiated in the frame of the abovementioned subtasks of FURIES, mainly focused on grid control, demand side management, grid flexibility and prediction of power generation.

These projects have already brought **tangible results**. For instances only in 2016, the following outcomes have resulted of WP1 projects’ activities:

- 1 License on Dispatchable Feeder (Software) granted to EATON
- 1 Patent on “Method for determining mutual voltage sensitivity coefficients between a plurality of measuring nodes of an electric power network”
- 3 Demonstrators on energy storage; DSM; and agents-based real-time explicit grid control
- 4 Pilot plants on pool of CHPs; flexible full scale distribution grid feeders; DR/DSM on 100 households in Valais; and MV/LV transformer stations and Smart meters
- 1 Prototype of motor/generator group of 3kW in the Gridlab
- 6 Innovative solutions such as a novel mechanic-electrical characterization method for power semiconductors for grid application; a new version of SIMSEN software for hydropower plants planning and operation; a secure tunneling client for remote operation of a load manager; an online spectral grid impedance meter; a demand side management smart-energy solution; and a dynamic Power System Fault Injector (DyPSyFI)
- 10 Models and data
- 64 Publications in peer-reviewed journals and conference proceedings

The following pages provide further details on representative projects of WP1.
REAL-TIME STATE ESTIMATION OF THE LAUSANNE 125 KV SUB-TRANSMISSION NETWORK USING PMUs

A single platform for the real-time monitoring, protection and control of the grid

Currently, distribution grids are characterized by a poor level of automation and need to undergo an extensive transformation in the upcoming years. State Estimation (SE) is a power-system situation-awareness functionality that computes the most likely state of an electrical grid (i.e., all the grid quantities: voltages, currents, powers) through the statistical processing of the measurements. With only the use of measurements provided by Phasor Measurement Units (PMUs), a very accurate, fast and frequent execution of SE, called Real-Time State Estimation (RTSE) can be achieved. In addition to the performance’ improvement of applications that are already using the SE solution (e.g., security analysis), RTSE can support real-time applications, such as protections and fault location.

Goal
This project aims at validating RTSE based on PMUs in a real-scale electrical grid and at demonstrating the capability of RTSE to support hard real-time applications, such as power-system protections.

Results
PMUs and a Phasor Data Concentrator were used, that are developed at EPFL and characterized by high accuracy and low latencies. RTSE has been successfully implemented and its performance assessed in the Lausanne 125 kV sub-transmission network. The proposed PMU-based monitoring infrastructure considerably improves the grid-operator visibility of its critical assets. A fault location method that is based on the RTSE solution was successfully experimentally validated. The performance of the developed fault location technique is not influenced by the fault type, the network topology (radial or meshed), the neutral treatment and the presence of distributed generation. The developed solution allows the grid operator to concentrate in a single platform the monitoring protection and control functionalities. This avoids the proliferation of heterogeneous monitoring infrastructures that are dedicated to the solution of a single problem. The developed fault location technique can be integrated within a Fault Location Isolation and Service Restoration (FLISR) logic that reduces the grid downtime and improves the related performance indices.

Next step
As a next step, this technology will be deployed and tested in a medium voltage distribution grid Energie.

Figure 2: Map of the 125 kV sub-transmission network of Lausanne highlighting the PMU and PDC locations
Remote control of load management devices with limited security without the need of VPN, which would require inbound connections.

Secure communication is more and more crucial for the operation of the distribution energy networks. The decentralization of the assets of the power systems increases the need of communication among them. Also, maintenance and operation of load management devices becomes more efficient when using remote control. However, this increases also the vulnerability of the network to external cyber attacks and the investment cost for the DSOs. Therefore, secure communication solutions are required that built upon existing management software of the network devices.

**Goal**
The project’s goal is to enable end-users to remotely configure and control ALPIQ’s load management devices in a secure way while using the original device’s management software.

**Results**
This project resulted to a secure tunneling approach that allows existing devices to be remotely controlled using the original management software, without the need of a direct connection or VPN access. Using ALPIQ’s secure communication infrastructure, remote access becomes possible even when network access is restricted to outbound connections. This secure tunneling client acts as a bridge between the software and the communication infrastructure. Also, the device management software was adapted to integrate the secure tunneling client, resulting in better usability. The remote management capability is an additional use case for ALPIQ’s secure communication infrastructure and a new service for its more than 1000 customers.

**Next step**
The software that was developed will be further improved in the frame other research projects and eventually be integrated in Alpiq’s products.

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**Figure 3 – Secure Tunneling Communication Schema**

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**Further reading**
HIGH PERFORMANCE PV SYSTEMS WITH LOCAL STORAGE FOR MASS INTEGRATION INTO ELECTRICITY NETWORKS

A combination of PV production curtailment with a small storage capacity is expected to ease drastically the problem given by the mass integration of PV in the grid.

Photovoltaics (PV) are considered as “low density” source of electricity with fluctuating output power. Indeed, mass integration of PV into electrical grids could become an issue as soon as peak power exceeds local demand. Peak shaving and self-consumption of solar electricity with the use of local battery storage system is an option more and more viable, since the cost of stationary battery systems goes down.

**Goal**

This project aimed to improve the grid integration of PV systems of single and family houses by optimizing the system sizing and developing local energy storage strategies for load shifting and peak shavings. The project also aimed at optimizing the overall energy yield and development and operating costs of these systems.

**Results**

The project mainly focused on cases with PV electricity feed-in limits. Optimal storage and peak shaving efficient strategies were developed that do not require forecasts of the consumption or PV production and maximize self- or local- consumption. Low PV feed-in limit (with potentially large power curtailment) resulted in low energy production loss. Furthermore, when there are limited PV production feed-in restrictions, forecasts are not required for the development of efficient storage strategies.

**Next step**

As a next step, this method on system optimization and sizing is analyzed in several different configurations. Case of industrial and commercial sites is studied with Romande Energie.

**Figure 4:** PV with storage system architectures studied: (left) storage system with own inverter and (right) “DC-bus” architecture

Funding

- EOS Holding
- EPFL (PV-Lab) (nicolas.wyrsch@epfl.ch)
- Romande Energie (for continuation activities)

**Project Duration**

- 2015-2018 (3.5 years)

**Project Scope**

- Domestic PVs

**Work Packages**

- WP1

Further reading

- Riesen Y, Ballif C, Wyrsch N Control algorithm for a residential Photovoltaic system with storage, to be submitted.
**Control framework to dispatch, peak shaving, congestion management, economic optimization of the consumption by using a battery energy storage system**

Dispatching the operation of inherently stochastic resources, such as distributed renewable generation and demand, allows for reducing the amount of regulating power required to operate the grid. This is a key issue for large-scale integration of renewable energy.

**Goal**

This project aims at demonstrating how utility scale storage can be integrated to achieve dispatched-by-design operation of stochastic resources without the need of complex communication and coordination mechanisms.

**Results**

For the achievement of this goal, a control framework has been developed for dispatching, peak shaving, congestion management, and economic optimization of the consumption by using a battery energy storage system (BESS). It consists of a day-ahead planning and real-time phase for the actuation of the battery active power set-point.

The concept was validated at the 750-kW/520-kWh Lithium Titanate BESS at DESL, EPFL in the so-called dispatchable feeder setup. The innovation of this solution lies on the applicability of the dispatchability concept to a set of heterogenous resources; the decrease of the need for regulating power during intra-day grid operation; the fully decentralized control with minimal coordination requirements; and the model predictive control by including electrochemical models of the battery.

**Next step**

As an next step, the control framework will embed multiple controllable elements, such as other batteries or shiftable demand.

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**Funding**

**Academic partners**

- EPFL (DESL) ([fabrizio.sossan@epfl.ch](mailto:fabrizio.sossan@epfl.ch))
- Leclanche

**Project Duration**

2014-2016 (2 years)

**Project Scope**

BESS

**Work Packages**

WP1

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**Further reading**

- Web: [http://smartgrid.epfl.ch/?s=node/20](http://smartgrid.epfl.ch/?s=node/20)

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**Figure 5a:** The dispatchable feeder setup (dashed line).

**Figure 5b:** Day-ahead operation. Forecasted prosumption of 5 EPFL buildings equipped with rooftop-PV panels in terms of expected value, prediction intervals and dispatch plan (dashed and shaded area; and thick line).

**Figure 5c:** Prosumption realization (full line) and the power flow at the grid connection point (dashed line), corrected by controlling the battery power injection.
Due to the increasing amount of photovoltaics’ integration in the power grid, battery systems are becoming more and more interesting solutions for grid stability. These battery systems can be use for the achievement of various objectives such as the increasing the self-consumption, grid shaving, and energy shifting. “Genossenschaft Elektra Jegenstorf” is a medium-size Swiss utility company near Bern, has a high and unique percentage of PV electricity in the grid (nearly 10% in end of 2016) and plans to achieve the national 2050-target of the Swiss Energy Strategy 2050 (20%) already in 2020.

However, Genossenschaft Elektra Jegenstorf” has already encountered over-productions of PV-derived power in their grid and had to transfer this excess electricity to the upper grid. In order to avoid this, “Genossenschaft Elektra Jegenstorf” plans to buy a big industrial battery storage system.

Goal
The goal of this project is to provide quantitative decision criteria for the purchase of such a system and to elaborate business cases based on the data gathered from the application of this system by, and joint with ”Genossenschaft Elektra Jegenstorf”.

Results
For the achievement of this goal, simulation cost-benefit analysis of different battery solutions was undertaken. The optimal battery capacity was determined, and a first market study was carried out for the tender. The potential suppliers were ranked and the decisions on a battery system to be purchased was made. The battery system is expected to be delivered in the last quarter of 2016. This collaboration with “Genossenschaft Elektra Jegenstorf” enabled the tackling in the real-grid of upcoming challenges. Specific information on the practical use and application of batteries in the grid were gathered. This knowledge is transferable to other utilities around Switzerland.

Next step
As a next step, the battery system will be tested by the Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf and the battery system will be installed at the headquarter building of “Genossenschaft Elektra Jegenstorf”. The outcomes of this project will be used in order SCCER-FURIES activities, such as the “Mont Soleil” demonstrator.

![Figure 6: Unit for the tests in the BFH PV LAB and at Mont Soleil (2015/2016)](image-url)
PERFORMANCE PLUS

Tools for Enhanced Photovoltaic System Performance

For a continued decrease of levelised costs of Photovoltaics (PV) derived power, the prices of PV system components have to be further decreased while performance, functionality, reliability and lifetime on the component- and system- level need to be increased. In an integrated view, PV system performance emerges from, but is not limited to, the performance of the components.

Goal

The aim of this project is to develop and validate (with empirical data) a collection of tools for modelling, monitoring and control of PV systems. This collection consists of tools for robust system design modelling for diligent design and bankability; robust operational modelling for optimising the system output; integrated energy management and storage control; and real-time monitoring and control through sensors communication and feedback. These tools will serve to optimize and enhance the performance, reliability and lifetime of commercial PV systems beyond the state of the art. Means for a better integration of PV-generated electricity into the power system shall be provided by methods for short-term forecasting, integrated energy management and storage control, PV system monitoring and control.

Results

As an outcome of this project, a new model for PV performance was developed and validated with CFD simulation and wind tunnel measurement; a new model for battery lifetime behavior was developed and used for MPC optimization in buildings in Belgium; and a new tools was developed for fault detection in PV systems.

The innovation of this solution lies on the integration in a collection of tools of simulation of testing method for the optimization of the design and operation of photovoltaic systems. Also, the modelling behind the simulation covers all aspects of the PV system, from cell level to large PV plant and storage solution integrated in industrial test cases. This results to the reducing the uncertainties in renewables project development and enhancing their integration into the grid.

Next step

The next step of this project includes further implementation of the collection of tools in order to increase the level of technology readiness and eventually lead to commercialization of the proposed solution.

Further reading

- Website: http://www.perfplus.eu/project-overview

Figure 7 – The integrated tools
Decentralized generation, electrical storage and controllable loads make great demands on the distribution grids. Some effects can already be measured today but the limits for the grids are less transparent. The optimal use of the grids needs a good knowledge base of the dependencies.

**Goal**

This project aimed to provide the distribution system operators with recommendation for the for the assessment of connection requests related to control circuits in order to fulfill the power quality standards considering the future changes. These would be achieved through the:

- Identification of critical oscillations in distribution grids
- Analyze measured instable situation with modelling and Simulation

**Results**

For this purpose, the project team worked on critical grids where existing effects were measured and the limits of charging were shown by adequate models.

As a result of this research, it was demonstrated that the stability of inverters in the distribution grid is dominated by the frequency-dependent grid impedance and the current control circuit/parameters of the inverter itself. Also, a higher number of parallel connected solar inverters affects the frequency dependent grid impedance dramatically. Together they build impedance resonances that could lead to a higher harmonic distortion by the inverter itself. The standard grid simulation tools are not able to predict the harmonics of a grid connected inverter.

**Next step**

As a next step, the resulted recommendations will be documented and results will be also published in the VSE-Bulletin.
Reduction of electromagnetic interferences in smart grid applications

For the integration of PV systems in the power grid, the electromagnetic (EM) interferences between PV converters and Power Line Communication (PLC) dedicated to Smart Meters should be considered. Currently, there is a lack of affordable and appropriate measuring and simulating tools in the frequency range 2 to 150 kHz and traditional EMC method are based on emissions and immunity limits defined for single equipment without considering the complexity of the complete system.

Goal
The project aims at developing measurement tools and models of grid components and equipment in the frequency domain up to 150 kHz. The tools will help DSOs and equipment supplier to assess and reduce EMI.

Results
In the frame of this project, EM Interferences between PV converters and PLC dedicated to Smart Meters were studied on real pilot site in Geneva. State of the art measurement techniques helped analysing the quality of PLC transmission and harmonics generated by the inverters. The Geneva site is partly reproduced at the GridLab HES-SO Valais-Wallis where different scenarios were evaluated and compared. Simulations based on inverters, lines and filters models in the frequency domain were used to predict and alleviate EMI at the smart meters deployment phase. As a result, G1-PLC signals, spectral grid impedance and supra-harmonics with different scenarios were measured on-line and analyzed at the pilot site. Also, a first version of the laboratory set-up is available at the GridLab and a new hi-resolution data acquisition and signal treatment board is ready to be integrated in the spectral grid impedance meter (HiRADDA).

These components and equipment models in the frequency domain will help to analyze EMI in a systemic and realistic approach and more efficiently than the traditional EMC method.

Next step
As a next step, the development of a Hi-Resolution grid impedance meter will be completed; a model for the Avusy pilot site and for the GridLab site will be finalized allowing accurate simulations in the frequency domain; and the complete model will be validated with measurement results.

Figure 9 – Avusy pilot site with PV production and smart meters (SIG)
SMMC - STUDY ON MESOSCALE-MICROSCALE COUPLING STRATEGIES FOR WIND ENERGY PREDICTION IMPROVEMENT

Models for wind energy prediction for researchers, planners and operators in the Wind Energy field

Wind energy prediction over complex terrain can be significantly improved if both large scale weather conditions and microscale topography effects can be captured in numerical models.

Goal
This project focuses on the investigation of strategies of coupling a mesoscale weather model with a microscale computational fluid dynamics model, and performance of case studies to verify and validate the proposed coupling approaches. This will allow the improvement of wind energy prediction over complex terrain and their impact on the grid.

Results
A simple strategy was developed to couple the mesoscale Weather Research and Forecasting (WRF) model with the Large-Eddy Simulation (LES) code developed by the SCCER-FURIES partner. Preliminary test of the coupled WRF-LES framework was performed in the Juvent wind farm at the Jura mountains. This tool predicts efficiently and accurately the wind and power output over complex terrain. These make it a powerful tool for assessing wind energy potential, and also for optimizing the design, operation and integration to the grid of wind farms.

Next step
The coupled mesoscale/microscale model is currently under further development and its applications to more case studies are on-going.

Figure 10 – Visualization of the terrain model and wind turbines for the Juvent wind farm at the Jura mountains, where the coupled WRF-LES framework has been tested.

Further reading
MODELLING A DOMESTIC HEAT PUMP IN APPLICATION TO DEMAND SIDE MANAGEMENT AND EXPLICIT SET-POINT CONTROL

A control-oriented model of the conversion system to benefit from low tariff periods and environmental heat gains (i.e. improved COP).

Heat pumps represent a highly attractive solution to reduce both the energy consumption and the greenhouse gas emissions released for the provision of low temperature service requirements. However, for the impact assessment of the heat source/sink quality on the unit performance and thus on the required power demand, optimal control methods are required to fully exploit the potential of the latter conversion system.

**Goal**

This project hence aims at developing novel multi-dynamic models for prediction of inputs and outputs, and control of domestic heat pumping systems. These models reflect the needs and interests of both the user and the grid operator.

**Results**

A control-oriented dynamic model of the standard heat pump was developed which can be implemented in both a predictive control framework for demand side management and an explicit set-point control method for active grid operation. The model parameters are fitting from actual measurements of a 9.3 kW (A2/W35) air-water heat pump installed at the DESL lab.

The proposed approach provides building service users and potential microgrid operator with non-intrusive (i.e. without requiring any additional monitoring instruments) model formulations which can be easily adapted to each heat pumping system to provide both fast power set-point predictions and dynamic thermal responses to the interested parties.

**Next step**

As a next step of this project, the defined models are implemented through model predictive control and explicit set-point control to validate the models for real-time applications.

**Further reading**

- A. Ashouri, P. Stadler and F. Maréchal. "Day-ahead promised load as alternative to real-time pricing." 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, 2015, pp. 551-556.
- Website: [http://smartgrid.epfl.ch/?q=prn70Commelec](http://smartgrid.epfl.ch/?q=prn70Commelec)
FLEXI - DETERMINING THE FLEXIBILIZATION POTENTIAL OF THE ELECTRICITY DEMAND

Detailed analysis of the household consumption can be obtained without additional hardware. Pricing of electricity can be used to trigger load shifting.

Solar power generation takes place when demand for electricity is not necessarily high. Households’ electricity consumption indeed peaks in the evening, when solar power generation is low. This mismatch might be reduced in several ways, including power transportation and consumption elsewhere, storage for later consumption and adaptation of households consumption with solar power generation. While the first two solutions imply high installation costs, the latter can be proved relatively inexpensive and easy to implement.

Goal
This technical study aimed at evaluating the potential of flexibilization of households’ electricity consumption to maximize the local consumption of electricity generated by photovoltaics (PV). For the analysis, fixed “PV production hours” were considered and households were asked to shift as much as possible their consumption to that period of time. The PV production hours were defined in the period 11 am to 3 pm which corresponding to the time window with the peak PV production. The goal was to evaluate theoretically and practically the share of the consumption that could be shifted and observe the time evolution and factors influencing this change of behavior.

Results
From this analysis, the share of consumption already in the PV production period was accounted as follows: heating of households or domestic water excluded (17-19%), flexible (6-8%), hardly flexible (6-8%). Households receiving financial incentives such as financial rewards for the best performing households were able to shift, in average, an additional 2.9% of their total consumption toward “PV production hours”. Biggest potential for load shifting (for households) should come from domestic hot water heating.

A new methodology based on a time use budget was used to infer the household consumption from ¼ of hour load curves. A small but sizeable share of the household electricity consumption can be shifted given the right (financial) incentive.

Next step
A second phase of the project is ongoing (2015-2018) to validate the results obtained during the first phase, analyze the effect of variable electricity pricing to trigger shift of consumptions and study the (change of) consumption behavior of PV system owners. The continuation study is conducted on the Swiss Energy Park with La Goule.

Figure 12: Share of electricity consumption of a group of households distributed among the following categories: Within the “PV production hours 11am-3pm” (blue), easy shiftable (red), hardly shiftable (green) and non-shiftable (purple).

Further reading
- Project report: http://www.bfe.admin.ch/dokumentation/energieforschung/index.html?
  lane=fr&project=500853
- Phase II website: http://www.flexi-goule.ch/

SFOE F&E
EPFL (PV-Lab) (nicolas.wyrsch@epfl.ch)
Plainer, UnInE, Groupe E (1st project phase), La Goule (2nd project phase) 2013-2014 (2 years)
Domestic PVs
WP1
CYBER-PHYSICAL SMART GRID

Framework for assessment of Demand Response scenarios thanks to cyber-physical systems

Flexibility of buildings will play a major role for the large scale deployment of intermittent distributed generation. However, the testing of the flexibility that Energy Management Systems of buildings can provide is challenging given that it requires interaction with the final energy consumers.

Goal
This project aims at developing an environment where the effect on the distribution grid of control strategies applied to buildings can be tested and assessed on a full scale lab environment.

Results
This builds upon the GridLab District facility at HES-SO. GridLab is made up of four low voltage test feeders linked with a force feeder via twelve 15 kW fully programmable electronic power converters. Each power converter is controlled by software components emulating the electrical behavior of a building along with its Energy Management System. Thanks to the modularity of the GridSim RT framework, several types of building and energy management strategy can be tested and assessed in many scenarios.

As a result of this project, the building electrical processes with their control interface have been modelled and linked to power converters, thus emulating the electrical effect of smart buildings on a distribution grid. Also, simple control strategies are applied and tested.

This enables the testing of low voltage grid control strategies on a full scale flexible laboratory environment, where extreme conditions can be configured and reproduced as needed. This goes beyond the currently used methods of simulations and pilots.

Next step
The developed infrastructure will serve to test and assess Energy Management Systems for buildings.

![GridLab District facility at HES-SO](image)

Figure 13 – GridLab District facility at HES-SO

Further reading

Websites:
- [http://www.hevs.ch/gridlab](http://www.hevs.ch/gridlab)
- [http://gridsim.hevs.ch](http://gridsim.hevs.ch)
- [http://www.semiah.eu](http://www.semiah.eu)
PREDICTIVE CONTROL MODELLING, SIMULATION AND TESTING

Predictive control algorithm for day-to-day electrical and thermal demand

Most predictive algorithms treat either the HVAC systems or the electrical systems first and pay lip-service to other components through thermal or electrical representations. A good model predictive control system will be able to provide end-users, such as big power consumers and grid operators, with a control algorithm capable of optimizing day-to-day electrical and thermal demands. This will (a) give them the capabilities to maximize the utilization of polygeneration devices and flatten or shift peaks in daily demands; (b) support the development of a demand response market where end-users can be active players in the market and make savings through use of polygeneration and storage; and (c) support the provision of better end-user data and general stability to the grid utility and the grid operators.

Goal
The project aims at developing a coherent predictive control algorithm which treats both electrical and thermal interactions on an equal footing and optimizes them utilizing polygeneration devices and storage.

Results
As a result of this project, a multi-level, intra-day predictive control model was developed and tested on a LV-microgrid testbench developed at DESL in EPFL. This model ensures that both electrical flows and thermal interactions are given equal importance in demand response for end-user buildings and LV grids. The optimal system sizing and design for a system with such an algorithm was also performed, ensuring the optimal utilisation of the polygeneration devices installed.

Next step
As a next step, the Predictive Algorithm will be improved to include non-linearities and better stochastics and compatibility of building models with existing control configurations in buildings/for older buildings with fewer control points.

Figure 14 – Optimisation method

State Variables
- Input:
  - Required Comfort for users
  - Internal Temperature
  - State of polygeneration devices (on/off)
  - External Temperature estimates
  - Device sizes

Intra-hourly Electric Flow Optimization

5-min correction of electric flow estimates

Global optimization (1 hour time step)

Global Setpoints
- Output:
  - Hourly Thermal demand
  - Hourly Electrical demand
  - Hourly operation of Polygeneration devices
  - Optimized Operating Cost Temperatures (Internal and External)

Every 25 hours

Global Set-point correction at 15-min

Modification of electric set-point

Figure 14– Optimisation method
HCD 2.0.

An innovative and smart EV home charging system equipped with self-learning algorithms that optimizes energy consumption patterns and electrical network stability

The growing electrification of the individual mobility sector poses new challenge for the power grid. An intelligent regulation of the grid is required in order to maintain its stability. This means that future electric vehicles cannot just plug in and start charging, but they will need to be regulated with innovative functionalities.

Goal
The goal of this project is to upgrade a power charger for e-vehicles with a smart-grid optimization algorithm and new hardware electronics so that the system allows an intelligent charging process, maximal grid integrability in home and building automation systems, increased safety and reduced electricity costs for the end-user. Cost reduction is also a main topic to be taken into account during the project.

Results
A number of EV charger prototypes were successfully built and tested at SUPSI in Trevano (TI), Protoscar in Manno (TI) and Infovel in Mendrisio (TI). These tests demonstrated that the smart EV charger automatically optimizes the charge for grid stability (based on local measures of voltage) and allows a swift penetration of EV chargers in the LV grid, without the need for a central coordination.

Next step
The HCD2.0 algorithms will be included in the Gridsense solution of Alpiq Intec AG and will be commercialized.

Further reading
- Patent: Method for programming energy flow between a grid and an accumulator of an electric vehicle, and corresponding device for programming (PCT/EP2014/068173)
- Website: https://www.aramis.admin.ch/Grunddaten/?ProjectID=32567

Figure 15 – HCD 2.0 prototype
GRIDSENSE

Demand Side Management (DSM) platform for the autonomous and decentralized control of electrical equipment for the Swiss and European DSOs

The increasing share of the inflexible and decentralized power generation technologies in the Swiss Energy mix requires the management of the power demand in order to ensure a stable grid. This can be achieved with the use of DSM solutions that enable the shifting of the demand during the day in order to be aligned with the power production. These DSM solutions are potentially installable in every household with electrical warm water heaters, charging stations for electric vehicles, heat pumps, batteries and/or photovoltaic systems. With an hourly shiftable power of up to 2400MW and a yearly shiftable energy of up to 12.6TWh in 2050, Switzerland has very high DSM potentials.

Goal

The goals of this project are to develop, test and validate a decentralized DSM system and build a prototype system.

Results

A prototype plug-on unit was developed which is able to monitor and steer loads according to a multi-objective optimization scheme. This unit can control electrical equipment such as heat pumps, boilers, electric car charging stations and batteries autonomously and in a decentralized way. It uses artificial intelligence to gauge, learn and anticipate user behavior; and this information is used to ensure optimized energy consumption within a building. The DSM units are supported by a Data Management System which allows configuring the devices remotely and collecting their data and an end user app. A test pilot system was set up in Biel-Benken (BL) in the EBM grid.

Next step

Alpiq Intec AG is now commercializing the product, while SUPSI continues developing new algorithms.

Figure 16 – The Gridsense unit
SWISS2GRID

A grid friendly energy management system that does not require communication and user feedback.

For the improvement of the grid stability due to the increase of the share of renewable energy technologies in the energy grid, emerging innovative solutions related to the storage and demand side technologies aim to substitute conventional solutions such as grid enforcement. However, the investment cost of the former ones plays a key role on their rolling out. Therefore, it is essential to refine the investments that are absolutely necessary for these technologies to provide their users with valuable results.

Goal
This project aims to assess whether the communication cost in DSM is required and demonstrate via thorough simulations and in-depth analysis of measured voltages that fully decentralized DSM is feasible.

Results
For the achievement of the abovementioned goal, a pilot project and demonstrator was set up in a number of residential neighborhoods in Mendrisio (TI), in which 20 houses were equipped with prototype controllers and monitoring equipment.

The S2G pilot and demonstration project demonstrated in a pilot project that a decentralized, local-only voltage measurement approach can be safely adopted for demand side load management as long as there are enough flexible, local loads including batteries to handle also high local PV in-feed peaks and energy balancing over a full day. Under these conditions, on the one hand, the absence of communication and/or centralized control does not result in bad decisions, i.e. no excessive load is put on the transformer. On the other hand, the algorithm systematically improves the stability of the network shifting loads where more appropriate.

A grid friendly energy management system was developed that does not require communication and user feedback. This reduces the investment cost required for a massive coordination of control algorithms for voltage control.

Next step
Alpiq Intec AG decided to invest on the technology and develop the Gridsense solution, starting from the results of the S2G project.

Figure 17 – S2G concept

Further reading
- Website: https://www.aramis.admin.ch/Grunddaten/?ProjectID=29654
CI-NERGY – SMART CITIES WITH SUSTAINABLE ENERGY SYSTEMS

Tools for local stakeholders (politicians, urban planners, utility service companies, grid operators) to make evidence-based decisions for their energy strategy in a given urban context.

There is currently a gap in high level integrated training in the urban energy research field, which is due to the wide range of fragmented disciplines from building physics and energy supply technologies with electrical and thermal engineering up to software engineering and information technology. For the bridging of this gap, the CI-NERGY Marie Curie Initial Training Network (ITN) proposes a highly multi-disciplinary coordinated PhD programme on urban energy sustainability, supporting activities that address the key challenges in cities related to a low carbon future and bringing together renowned academic research institutes and companies from the energy and software technology sector.

Goal
The aim of the related activates undertaken in the frame of FURIES is to train young scientists to develop urban decision making and operational optimization software tools to minimize non-renewable energy use in cities. The research fellows applied their results in two case study cities (Geneva and Vienna), which were chosen for their very ambitious sustainability goals.

Results
As an outcome of these activities, a set of methodologies was developed covering different aspects of urban energy research, such as energy demand estimation, network simulation, co-simulation, demand-response, optimisation. Also, a co-simulation platform was developed coupling different simulation software and a re-useable database was implemented for each case study city, with generic and energy-related data, as well as a 3D CityGML model.

This approach is novel in terms of inter-disciplinarity; linkages between urban and energy planning; and coupling of 3D CityGML semantically enriched databases with urban energy simulation and optimization methods.

Next step
As a next step, the methods will be integrated in a decision support computer framework and a spin-off will be established for the commercial exploitation of the tool with potential clients including utility companies and local authorities of major Swiss urban centers (Geneva, Lausanne, Zürich, Basel…) as well as smaller municipalities.

Figure 18 - Example solution with resulting urban form

Further reading
- Website: http://ci-nergy.eu/
IDEAS4CITIES – SMART HEAT DESIGN

Decision support tools for Swiss industrial services authorities that aim to integrate energy strategies for multi-energy grids (district heating and power network).

For the improvement of the flexibility of the energy grid, the coupling of networks of different energy carries is considered as a solutions that is technologically feasibly, economically viable and socially acceptable. While there is a lot of ongoing work on this topic, the planning tools for decision makers are limited. Standard practice is to design the topology and supply plant(s) of thermal networks based on the density of demand using yearly measured or estimated values.

Goal
The aim of this project is to fill this knowledge gap by developing and validating in use cases a tool that embeds methodologies (a) for characterizing thermal needs and local resources; (b) for sizing energy conversion systems and identifying opportunities for renewable energy integration within local energy distribution networks; and (c) for selecting optimal energy supply solutions.

Results
The coupling of definition of building typologies, with the use of the bSol software and PlanETer database, and of existing planning, simulation and optimization tools allowed for quick simulation of a large number of buildings’ demand for heating/cooling.

The methodology was successfully tested on a neighborhood of the alpine village of Verbier.

The innovation of this work lies in the use of existing planning, simulation and design optimization tools (respectively PlanETer, bSol and OSMOSE developed by each of the academic partners) to base decision making on dynamical information (i.e. well-informed estimations) and thereby to also allow for the integration of (possibly distributed) renewable energy production.

Also, this tool is innovating by considering the urban energy system as a multi-energy system and use the above mentioned tools to forecast the impacts and possibly synergies between thermal and electrical energy infrastructure.

Next step
This research in Smart Heat Design, and in particular this relying on the method of co-simulation, will continue in the frame of the “IntegrCiTy” project, funded by the Era-NET Smart Cities program. Reliable CAPEX and OPEX data will support the further refining of the methodology developed.

Figure 19 - Sequence of operations used to produce a set of optimal integrated energy design solutions.

Further reading
MULTI ENERGY GRID SYSTEM (MEGS)

Methodology for decision makers to design future smart cities, integrate renewable energy sources and reduce environmental impacts

Currently, authorities lack of tools that support them for evidence based decisions regarding the designing of the various energy networks and their interaction. These tools should take into consideration all the various parameters required for such decision and at the same time be simple and user-friendly enough.

Goal

The goal of the project is to develop and prototype a methodology for simulation and optimization of energy grids with multiple energy carriers and loads. The target is a computational framework able to select for a wide range of industrial and residential problems the optimal set of components, their geographical location and their operation planning in such a way that multiple objectives are satisfied.

Results

The mathematical models were developed and linked together using mathematical programming. The innovation of the resulted solutions lies on the combination in a unique tool of multiple aspects of designing an energy system, including part load performance of components, energy and material storage opportunities, geographical location of users, multi-period approaches for user data and network optimization of district heating, electricity lines and any user defined material network.

The collaboration with ABB allowed for the testing of the computer frameworks on real business case models. Preliminary results have shown the importance of simultaneously synthetizing thermal, electrical and mechanical systems.

Next step

As a next step, the computer tool will be validated in Business Case Studies and its capabilities will be extended according to users needs.

Outputs for each location:
- List of selected components, with specified size;
- List of optimal operation scheduling;
- Network configuration and connection costs;
- CAPEX and OPEX contributions of all selected components;

Figure 20 – Outputs of the tool for each location

Further reading
- MEGS: A multi-period MILP model for synthetizing energy networks and designing utilities. (paper under preparation)
CO₂ NETWORK AND ENERGY STORAGE

Methodology for decision makers to design a fully renewable, fully autonomous district energy network

Under Energy Strategy 2050, the Swiss federal government plans to greatly reduce per capita energy consumption, decrease the share of fossil fuels, and replace the nuclear electricity generation by gains in efficiency and use of renewable energy sources. However, a detailed feasibility analysis of this multi objectives target was missing. This work investigates the feasibility of these goals through both improvement of the efficiency of current energy systems and increase in the use of renewable energy sources.

Goal
In this context, the objective of this project is the optimal design of power-to-gas seasonal storage systems for delivery of services. A CO₂ district energy network will be coupled with renewable energy sources to satisfy the heating, cooling, and electricity requirements at different scales.
Also, the city density will be assessed from an economic point of view, which maximizing the building height (minimizes the PV panel area required), while keeping the city - energetically speaking - autonomous.

Results
The case study on the area Rues Basses in Geneva concluded that buildings up to 3 to 4 floor can be built, and the rooftop area is sufficient for PVs which keep the area self-sufficient. The use of geothermal wells instead of a central plant can reduce the electricity consumption by up to 25%.
While the proposed solutions has a higher CAPEX compared to conventional ones, its OPEX is close to zero.
Moreover, mass production of parts of the network such as small scale solid oxide fuel cells due to synergies with other sectors such as auto industry will make them more affordable.

Next step
As a next step, several aspects of the project will be tackled, such as a full waste heat recovery inside the system, waste heat valorization from external sources (e.g. industrial waste heat) and a full economic analysis of the system in order to draw conclusions on the feasibility of the system in different areas (in Switzerland and in the world).

Further reading
REPLICABILITY CONCEPT FOR FLEXIBLE SMART GRIDS (REFLEX)

Guidebook for choosing the most appropriate smart grid solutions depending on the grid topology and customer typology and associate them with the most suitable business models.

The number of smart grid pilot and demonstrators around the world constantly increases. However, there is little to no coordination and knowledge exchange among the actors of these projects. This limits the applicability of these projects’ outcomes to specific sites and, given the high investment cost required for such demonstrations, delays the rolling out of the smart grid technologies.

Goal
ReFlex aims to develop a replicability concept and guidelines for the deployment of technologically feasible, market based and user friendly solutions for smart grids with a high level of flexibility, and to establish a Community of Practice (CoP) for in depth knowledge exchange between regional Smart Grid demo regions across the participating countries providing workshops and demo site visits.
This CoP will bring together the various stakeholders in Europe in order to investigate the scalability and replicability of the different smart grid solutions deployed in Europe, and identify the most suitable business models, taking into account country-specific policies and regulatory frameworks.

Results
The main foreseen outcome is a Guidebook for the replication of technologically feasible, economically viable and user friendly solutions for smart grids. The guidebook comprises a replicability concept and guidelines, covering all three research layers including good practice cases. ReFlex will build on finalized or ongoing demo and pilot projects to furthering them and increase the replicability potential through its reflexive approach. The different solutions for smart grid in Europe will be compared from the three points of view of Stakeholders/Adoption, Marketplace and Technology.

Next step
The next step of this project includes the organisation of workshops involving the various stakeholders and investigation of the scalability and replicability of smart grid project’s results in simulation.
TARGET GRID PLANNING CH LIGHT

Planning tools for cost efficient development of distribution grids

The methods used by large grid companies for target grid planning today require data sets and calculation tools, which are too costly and not adequate for small- and medium-sized distribution grid operators. However, an efficient implementation of the Swiss energy strategy 2050 requires the involvement also of the our 700 smaller grid operators on the grid levels 5 to 7.

Goal
The project aims to make target grid planning applicable also for smaller grid operators for a cost efficient development of distribution grids within the time horizon of the equipment life time. This tool had to take into account the integration of distributed renewables, storage technology and e-mobility into the future distribution grids.

Results
For this purpose, the main technical and economical parameters for target grid planning were identified and described and methods which can be used as guidelines by the systems operators were documented. Also, a GIS-based tool was developed that recognizes the grid topology; as well as easy-to-use tools in Excel for technical and economical assessment and comparison of various grid variants. A tool for the generation of power scenarios for load flow calculations was also provided.

The software solutions to detect the grid topology and to perform technical as well as economical calculations are very user-friendly and allow a data import which is independent of the data bases which are used by the grid operators (e.g. different GIS software, SAP etc.). Additionally, the power scenario generator supports the prediction of future load and generation scenarios. Clear guidelines and easy-to-use tools will significantly facilitate the grid planning compared to the solutions used by large grid companies.

Next step
The developed tools and methods will be tested with distribution grid models of Energie Thun and Energie Service Biel/Bienne. Further optimizations will be included into the software. Also, The tool to generate load- and generation-profiles will be further improved.

Figure 23 – Main topics for target grid planning

Further reading
- Proceedings of 2015 Annual Conference of the SCCER - FURIES
- Web: [http://www.aramis.admin.ch](http://www.aramis.admin.ch) (Project number: SI/501271)
Representative WP1 publications

- 'Editorial' by EPFL, DESL (Paolone) at Sustainable Energy, Grids and Networks (2015) (pdf)
- 'A composable method for real-time control of active distribution networks with explicit power set points.
  I. 'Framework' by EPFL, DESL (Reyes, and Paolone); EPFL, LCA2 (Le Boudec) at Electric Power Systems Research (2015) (pdf)
  II. 'Implementation and validation' by EPFL, DESL (Reyes, and Paolone); EPFL, LCA2 (Le Boudec) at Electric Power Systems Research (2015) (pdf)
- 'Primary Voltage Control in Active Distribution Networks via Broadcast Signals: The Case of Distributed Storage' by EPFL, DESL (Paolone, Christakou, Bahramipanah); EPFL, LCA2 (Le Boudec and Tomozei) at IEEE Transactions on Smart Grid (2014) (pdf)
- 'An Information-Centric Communication Infrastructure for Real-Time State Estimation of Active Distribution Networks' by EPFL, DESL (Romano, Sarri, Pignat, and Paolone) at IEEE transaction on Smart Grid (2015) (pdf)
- 'Information-centric networking for machine-to-machine data delivery: a case study in smart grid applications' by EPFL, DESL (Paolone) at IEEE Network Magazine (2014) (pdf)
- 'Advanced Control of Energy Storage Systems for PV Installation Maximizing Self-Consumption' by ZHAW (Korb, Segundo, Knazkins, Park) at IFAC Symposium on Control of Power and Energy systems in New Delhi, India, (2015)
- 'Improvement of Dynamic Modeling of Supercapacitor by Residual Charge Effects Estimation' by EPFL, DESL (Paolone and Torregrossa); EPFL, PWRS (Cherkaoui, and Bahramipanah) at IEEE Transactions on Industrial Electronics (2014) (pdf)
- 'Macroscopic indicators of fault diagnosis and ageing in electrochemical double layer capacitors' by EPFL, DESL (Torregrossa and Paolone) at Journal of Energy Storage (2015) (pdf)
- 'A model predictive control strategy for the space heating of a smart building including cogeneration of a fuel cell-electrolyzer system' by EPFL, DESL (Paolone, Sossan, Torregrossa and Reyes) at Int.J.Electrical Power&Energy Systems (2014) (pdf)
- 'Fixed-order Decentralized/Distributed Control of Islanded Inverter-interfaced Microgrids' by EPFL, LA (Karimi and Sadabadl) at Control Engineering Practice (2015) (pdf)
- 'Inferring power fluctuations at a low voltage transformer from local voltage measurements in the underlying distribution grid' by SUPSI, ISAAC (Vasco, and Rudel) at Computer Science-Research and Development (2014) (pdf)
- 'Inverter to Grid : Voltage Control Strategies for grid integration of distributed energy resources' by HES-SO, Valais (Gabioud) at 23rd International Conference on Electricity Distribution (2015) (pdf)
- 'Multi-objectives, multi-period optimization of district energy systems: I. Selection of typical operating periods' by EPFL, IPESE (Maréchal) at Computers & Chemical Engineering (2014) (pdf)
  II. Daily thermal storage' by EPFL, IPESE (Maréchal) at Computers & Chemical Engineering (2014) (URL)
  III. Distribution networks' by EPFL, IPESE (Maréchal) at Computers & Chemical Engineering (2014) (URL)
  IV. A case study' by EPFL, IPESE (Maréchal, Ashouri) at Energy (2015) (URL)
- 'Mean and Turbulent Kinetic Energy Budgets Inside and Above Very Large Wind Farms under Conventionally-neutral Condition' by EPFL, WIRE (Porté-Agél) at Renewable Energy (2014) (URL)
WP2
Bulk Multi-energy Grids

Innovation Challenges
The main research challenge of the WP2 were to build a realistic technical model of the Swiss energy system including the transmission systems, which model can be used for planning, operation, and economic evaluation of the system. This model had to comprise:
• location of renewable generation and the limited predictability of these sources;
• location of storage devices, both large scale, i.e. pumped hydro storage, and distributed devices;
• interconnections with regional grids;
• interconnections on the bulk power level, i.e. high voltage lines and gas pipelines;
• possibility to interface it with models for market and other economic simulations
This work had to involve the modelling of individual components, which required interaction with other WPs and other SCCER, such as SCCER-CREST, but also the development of a general system framework taking into account different energy carriers. Innovative geoinformation system had to be used to identify locations for renewable generation and storage devices.

Objectives
The objectives of the WP2 were:
✓ to develop a model of the Swiss bulk energy system that can be used for planning and operation purposes and comprising different energy carriers, i.e. electricity, gas, and heat/cooling; fluctuating energy sources; storage devices; demand side management; transmission grid; spatial distribution and the interconnections with surrounding countries.
✓ to interface this technical model and the economic model of University of Basel (SCCER-CREST) for the development of new electrical market schemes
✓ to use this model for concrete studies aiming at giving direct advice to various stakeholders and decision makers when planning the future Swiss energy system. By using methods for large-scale optimization and simulation it will be possible to analyze realistic and detailed representations of the Swiss system. Multi-stage optimization (Predictive Control with forecasts) will be used to determine optimal usage of storage devices.
Competences of WP2

WP2 is mainly focusing on the transmission grid and the trans-border power exchange. 21 experts are contributing to the implementation of the activities of this work package. These experts cover various aspects of the upper grid layer, including grid dynamics simulation, power generation forecast and large-scale power plants and storage facilities’ integration, multi-energy grids, security and liability, and multi-criteria based planning.

Alike WP1, intra- and inter-SCCER collaborations are completing these internal competences. Within FURIES, WP2 partners collaborate with all the other WPs such as on grid layer’s interaction with WP2, on HVDC with WP3 and the impact of large-scale hydropower plants on the grid with WP4. Furthermore, WP2 partners has a close collaboration with SCCER-CREST on the combination of grid and economic market models and cross-border power trading. WP2 partners also collaborate with other SCCERs such as SCCER-HaE on Power-to-Gas integration into the grid; SCCER-Mobility on power grid simulations; and SCCER-SoE on hydrodynamics and integration of hydropower plants into the grid.

Furthermore, the WP2 has established close links with the industrial partners which are closely related to the focus area of the WP such as the operator of the Swiss transmission grid, SwissGrid; technology companies such as ABB; and research groups from neighboring countries.
Leader of WP2 and Leader of S2.2 Transmission system upgrade

ZHAW, Institute of Energy Systems and Fluid Engineering
Main competences:
• Electrical power systems
• Electrical machines
• Control systems
• Power system dynamics and control
• Integration of decentralized energy sources
• Wide-area monitoring and control
• Smart distribution automation
Web: https://www.zhaw.ch/.../energietechnik-und-smart-grids/

Leader of S2.1 Modelling of large scale multi-energy systems

ETHZ, Power Systems Laboratory (PSL)
Main competences:
• Optimization and control of electric power systems
• Integration of renewable generation into power system operation
• Simulation and modeling of power systems
Web: www.eeh.ee.ethz.ch/en/power/power-systems-laboratory.html

Leader of S2.3 Market coupling

ETHZ, Research Centre for Energy Networks (FEN)
Main competences:
• Optimal Grid Planning and Operation
• Power System Dynamics (Modelling, Simulation and Control)
• Multi Energy Grids
• Reliability and Risk Assessment
• Future Electricity Markets
• Computational Methods and Tools for Power System Analysis
Web: http://www.fen.ethz.ch

Leader of S2.4 Vulnerability and security assessment of the future multi-energy system

ETHZ, Laboratory for Energy Conversion (LEC)
Main competences:
• Turbomachinery Experimental
• Turbomachinery CFD
• Wind Energy
• Plasma Science
• Instrumentation
• Energy Economics and Policy
Web: http://www.lec.ethz.ch

ETHZ, Laboratory of Reliability and Risk Engineering (RRE)
Main competences:
• Mitigating the risk of cascading failures in power systems
• Security of interdependent electric power and gas networks’ operation
• Communication dependencies’ impact in cyber-physical systems
• Resilience in energy-carries networks, robust optimization of design, expansion and recovery
• Risk-based maintenance in networks
Web: http://www.rre.ethz.ch

ETHZ, Institute of Cartography and Geoinformation (IKG)
Main competences:
• WebGIS (3D) mapping
• Spatial planning of Transmission Lines
• Visibility and social impact analysis of renewable projects
• Geographical optimization of energy related projects

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• Geographical optimization of energy related projects

USI, Institute of Computational Science (ICS)
Main competences:
• High Performance Computing, including large-scale discrete and continuous optimization for grids, as well as the numerical modeling of grid components
• Close cooperation with the Swiss supercomputing center CSCS
Web: https://www.ics.usi.ch/index.php/group-schenk

Leader of WP2 and Leader of S2.2 Transmission system upgrade

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Web: http://www.rre.ethz.ch

ETHZ, Institute of Cartography and Geoinformation (IKG)
Main competences:
• WebGIS (3D) mapping
• Spatial planning of Transmission Lines
• Visibility and social impact analysis of renewable projects
• Geographical optimization of energy related projects
Key activities of WP2

WP2 consists of 4 subtasks that cover key aspects of the bulk power systems and includes:
S2.1 Modelling of large scale multi-energy systems (ETHZ-PSL, ETHZ-FEN, USI)
S2.2 Transmission system upgrade (ETHZ-IKG)
S2.3 Market coupling (ETHZ-FEN, Univ. Basel)
S2.4 Vulnerability and security assessment of multi-energy systems (ETHZ-RRE)

During the 2014-2016 period, 39 projects have been initiated in the frame of the abovementioned subtasks of FURIES.

The outcomes of these activities include:

1) A unified simulation, optimization and planning platform to enhance long-term socio-economic benefits for the grid operator, including:
   • Framework & models allowing to deal with various objectives such as optimal planning, optimal economic operation etc.
   • New solvers for large-scale systems

2) A platform to optimize the planning of multi-energy grid systems, including user-friendly methods & tools based on GIS technology which calculates the optimal path for future transmission lines; validated in collaboration with Swissgrid.

3) Modeling & evaluation of the future Swiss energy system, considering its future expansion by renewable energy sources and the markets, including:
   • A combination of a technical grid model and economic market model
   • Probabilistic methods for reserve dimensioning
   • Best practices for reserve dimensioning after integration of significant amount of renewable energy.

4) A framework and models that:
   • quantify the economic impact of electricity disruptions propagated across the grid
   • estimate the risk of cascading outages
   • analyze the impact of power-to-gas on electrical power grid

This section includes further details on three of these projects.
TOWARDS THE NEXT GENERATION OF MULTI-PERIOD OPTIMAL POWER FLOW SOLVERS

A new solver for nonlinear Multi-period Optimal Power Flow problems for significant acceleration of the storage scheduling, reserve allocation and security constrained optimization.

Multi-period Optimal Power Flow (MPOPF) problems arise in various power system applications, ranging from storage scheduling, reserve allocation and security constrained optimization. MPOPF formulations with nonlinear AC network equations are required to accurately model active and reactive power flows but become quickly intractable for a large number of time periods.

Goal
This work aims to address this issue and provide network operation with a fast optimization solver to make large-scale MPOPF formulations tractable. Also, it aims to investigate and interface different application types (storage, reserve allocation, security constraints).

Results
The structure of the KKT system associated with the optimality conditions was revisited, and a new Schur-complement based approach was proposed tailored to its particular structure. The new approach brings significant savings in both computational time and memory allowing the solution of extremely large-scale MPOPF problems on a common laptop. This allows the users to tackle completely new problem classes that previously required heuristics or approximations to solve. For instance, end users can perform reserve/storage scheduling or sizing of a full year horizon. The method can be extended to security constrained formulations, allowing the parallel optimization of thousands of full network security constraints to obtain optimal N-1 stability in large networks such as the continental European grid.

Speedups achieved in several benchmark cases lie between two and three orders of magnitude compared to over conventional AC-MPOPF solvers with an increasing rate with the number of time periods.

The resulted MATPOWER is a package of MATLAB m-files and interfaces are provided for using the sparse linear solver PARDISO.

Next step
As a next step, the solver will be extended beyond storage scheduling to general purpose MPOPF formulations.

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Figure 24 – Modelling of the swiss power grid (map) and prediction of the Swiss household loads for a week of 2035

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Funding
SCCER-FURIES

Academic partners
USI (ICS) (olaf.schenk@usi.ch);
ETHZ (FEN)

Project Duration
2014-2016 (2 year)

Project Scope
Transmission grid Planning

Work Packages
WP2

Further reading
- Website: www.pardiso-project.org
AFEM INFRA – INFRASTRUCTURE FOR FUTURE ELECTRICITY MARKETS

Precise location-based assessment of renewables potentials and their impacts on the high voltage transmission system’s stability

The policy makers, system operators, and market participants need to have an holistic understanding on the impact of renewable energy on the Swiss energy system in order to take related policy or investment decisions. However, they are currently missing of a tool that considers all the aspects of such a system and provide clear evidences enabling informed decisions.

Goal
AFEM-INFRA aims to quantify the exploitable potential of stochastic renewable energy sources and the feasibility of their grid integration.

By utilizing detailed Geographic Information Systems (GIS)-based analysis, its objectives are to evaluate and optimize the wind and solar resource potentials and optimize the paths for new transmission lines. AFEM-INFRA aims also to assess the security and reliability of the grid infrastructure with the use of a comprehensive time-domain network model of the Swiss transmission system and evaluate the need for additional flexible generation resources and future transmission system improvements.

Results
The GIS enabled the consideration of natural and social constraints for wind and PV installations. Also, the Weather Research and Forecasting model for high-resolution RES predictions on a continental scale was applied for the first time in power system simulations. The subjective judgment in the transmission line planning was avoided through the development of robust statistical methods for the weighting in a multi-criteria decision analysis. Also, a reserve methodology is applied that advances what is seen in all operating reserve markets today and is in line with the most state of the art research-based methods.

As a result, it was proven that (a) the distribution of suitable regions for wind energy is clustered in the western part of Switzerland; (b) properly incorporating measures of the real-time variability and forecast uncertainty of added wind and solar capacity is critical to ensure adequate operating reserves are procured; and (c) for increasing the social acceptance of new transmission lines, it is crucial to develop methods to automate the planning process.

Next step
The analysis from AFEM-INFRA is under integration with the models of AFEM-MODEL (dispatch model) and AFEM-FUTURE (capacity planning) to create an analysis framework for evaluating future market and policy options for achieving renewable integration goals.

Figure 25 – GIS-based analysis of the solar potential of rooftop PV

Classification annual irradiation

<table>
<thead>
<tr>
<th>kWh/m²·yr</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1000</td>
<td>medium</td>
</tr>
<tr>
<td>&lt;800</td>
<td>unsuitable</td>
</tr>
<tr>
<td>&gt;1300</td>
<td>very high</td>
</tr>
</tbody>
</table>

Further reading
APPLICATION OF 3D GIS FOR TRANSPARENT AND SUSTAINABLE PLANNING OF ELECTRIC POWER SYSTEMS

On-line 3D GIS-based tool for quick and robust planning of Transmission lines based on an objective multi-criteria approach

Defining the optimal path of transmission lines is a time-consuming planning task, which is often impacted by strong social opposition. Furthermore, currently the planning involves experts-based multi-criteria approach which involves a risk of biased decisions.

Goal
The scope of this project is the development of an integrated 3D GIS web-platform to define the optimal path of a new transmission line, to enhance the communication among all stakeholders involved in a project and to reduce social opposition. An improved 3D visualization to be utilized for community-based decision-making will demonstrate to the stakeholders the impact of the new project on the surroundings.

Results
In the frame of this project, a demo on-line planning tool for transmission lines siting was developed. This tool allows users to select the weights to assign to different geographical layers, e.g. protected areas, during the process of selection of the optimal transmission line path. Automatic transmission line siting is done by gathering weights for geographical layers through expert knowledge. This increases the subjectivity of the analysis and bounds the results to the opinions of the experts involved. The tool developed here allows users to fully customize the decision making process, thus allowing for full control.

Next step
As a next step, the on-line tool will be further developed by expanding it beyond the test area.

Figure 26 – Screenshot of the optimal path for a transmission line generated by the on-line planning tool.

Further reading
• Website: https://netzausbau.ethz.ch/
Representative WP2 publications

- 'An integrated pan-European ancillary services market for frequency control' by ETHZ, PSL (Andersson) at Energy Policy (2014) [URL]
- 'The global grid' by ETHZ, PSL (Andersson) at Renewable Energy (2014) [pdf]
- 'A Probabilistic Framework for Reserve Scheduling and N-1 Security Assessment of Systems with High Wind Power Penetration' by ETHZ, PSL (Andersson) at IEEE Transactions on Power Systems (2014) [URL]
- 'Stabilization of Large Power Systems Using VSC–HVDC and Model Predictive Control' by ETHZ, FEN (Demiray, Fuchs) at IEEE Transactions on Power Delivery (2014) [pdf]
- 'Review of grid applications with the Zurich 1 MW battery energy storage system' by ETHZ, PSL (Andersson) at Electric Power Systems Research (2015) [URL]
- 'Improved rotor angular speed measurement - a key for proper power grid stabilization (conference proceedings)' by ZHAW (Korba, Knazkins) at IEEE PES General Meeting 2014 [URL]
- 'Optimal placement of wind turbines on a continuous domain: an MILP-based approach (conference proceedings)' by ETHZ, IKG (Raubal and Grassi) at 2015 American Control Conference, Chicago, IL, USA (2015) [URL]
- 'Assessment of the wake effect on the energy production of onshore wind farms using GIS' by ETHZ, IKG (Raubal and Grassi) at Applied Energy (2014) [URL]
- '3.4.1 Methoden, Netze zu erneuern, auszubauen, umzubauen und zu Dezentralisieren; 5.3.1 Methoden zur Solarund Windpotenzialanalyse; 5.4.1 Berechnung optimaler HSL-Pfade und Korridore für Hochspannungsleitung; 6.7 Potenzial von Solarkraftanlagen;' by ETHZ, IKG (Grassi) at 3D-GIS und Energie, by Runder Tisch GIS E.V.(2015) [pdf]
- 'Statistical Learning Approach for Wind Speed Distribution Mapping: The UK as a Case Study' by ETHZ, IKG (Raubal, Veronesi and Grassi) at Springer International Publishing, In AGILE: Geographic Information Science as an Enabler of Smarter Cities and Communities (2015) [pdf]
- 'Eine 3D entscheidungsunterstützende Plattform zur transparenten und nachhaltigen Planung von elektrischen Versorgungsnetzen' by ETHZ, IKG (Raubal) at 3D-GIS und Energie, by Runder Tisch GIS E.V.(2015) [URL]
- 'High Resolution Simulations of Increased Renewable Penetration on Central European Transmission Grid (conference proceedings)' by ETHZ, LEC (Abhari, Chokani, and Singh) at IEEE Power Energy and Society General Meeting (2015) [URL]
- 'Increasing On-Shore Wind Generated Electricity In Germany’s Transmission Grid' by ETHZ, LEC (Abhari, Chokani, and Singh) at Journal of Engineering for Gas Turbines and Power (2015) [URL]
WP3
Multi-terminal AC-DC Grids and Power Electronics

Innovation Challenges
The main research challenges of the WP3 were related, but not limited to, High Voltage Direct Current (HVDC) line design, operation, fault location and optimization. Multi-terminal DC transmission is not yet commercially used, but it is anticipated to be a relevant option for the system expansion or reinforcement in the near future. The deployment of this novel solution needs to be robust in order to minimise technical risks and to ensure the interoperability of these systems. Three classes of High Voltage Direct Current (HVDC) breakers have been discussed in the literature: mechanical, static and hybrid.

Additionally, the principles and technologies for isolating and accurately detecting the faults clearly differ from existing AC solutions. Fast measurement and fault detection systems are not yet available. Research had to be undertaken on the improvement of the fault behaviour and topology of HVDC converters to prepare them for use in multi-terminal DC grids along with the identification of the limit performances of existing alternative HVDC circuit breakers.

Further research activities are also required in modular power electronic converters. In mixed frequency insulation material, the lack of basic understanding for the dielectric stress distribution and its effects will become an increasing hindrance.

Objectives
The objectives of the WP1 were:
✓ to undertake standardization work (including procedures) for the acceleration of Switzerland’s connection to multi-terminal DC networks;
✓ to facilitate the emergence of a common DC fault management concept for the European interconnected network;
✓ to investigate key power electronic technology issues that had to be solved for the establishment of cost efficient and reliable converters for transmission applications
✓ to validate a modular power conversion architecture along with its associated control structure for increasing flexibility and performance of the future Swiss electricity network.
Competences of WP3

WP3 is mainly focusing on HVDC; the impact of power electronics on the grid; and ancillary services from the LV to the upper grid. **31 experts** are contributing to the implementation of the activities of this work package with background mainly on the power electronics aspect of the power system. One of the key competence of WP3 lies on the established FURIES AC/DC lab network. This network enables the development and testing of a wide variety of AC/DC technologies and consists of test facilities including:

- the ETHZ UnACo & Power EI labs focusing on hybrid DC circuit breakers and optimized solid-state transformers;
- the EPFL MV power lab working on fault location and Galvanically Isolated Modular Conversion (GIMC) and
- the HES-SO reduced scale ACDC lab working on the development and testing of the soft-open-point for congestion and fault management.

Also, WP3 partners validate their innovative solutions on the grid in close collaboration with WP1 and WP2. Therefore, they have links with DSOs, TSOs and power companies and access to a wider pool of capacities.

WP3 partners collaborate with other SCCER such as CREST and FEEB&D in the frame of demonstration projects; and HaE (storage) in the frame of training activities such as the PhD Summer school Eurotech.

Furthermore, WP3 partners have put in place training activities for capacity development of young scientists and practitioners such as:

- CAS ERTA Smart Grid module by HES-SO
- CAS in grid management involving FURIES Partners, such as ewz, ETHZ-FEN, Romande Energie, Swissgrid, HES-SO
- Courses at ETHZ and HES-SO
- Ad-hoc courses offered to various organisations (TSO, public administration) at HES-SO
**Chapter 3 – Multi-Terminal AC-DC Grids and Power Electronics**

**Leader of WP3 and Leader of S3.1 Multi-terminal HVDC system design and operation & S3.2. Fault clearing in multi-terminal HVDC**

<table>
<thead>
<tr>
<th>Name</th>
<th>Institute and Research Institute</th>
<th>Main Competences</th>
<th>Web</th>
</tr>
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<tbody>
<tr>
<td>HES-SO Fribourg / HEIA-FR, Institute for Applied Research into Energy Systems</td>
<td>High voltage engineering and testing, Power system modelling, including harmonic analysis, Power system control &amp; protection, including digital substation, AC/DC power systems</td>
<td><a href="https://energy.heia-fr.ch/">https://energy.heia-fr.ch/</a></td>
<td></td>
</tr>
</tbody>
</table>

**Leader of S3.4 Low voltage grid control Enhancement & S3.5 Storage system in MV for grid ancillary services**

<table>
<thead>
<tr>
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<th>Institute and Research Institute</th>
<th>Main Competences</th>
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**Leader of S3.3 Enabling technologies**

<table>
<thead>
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<th>Institute and Research Institute</th>
<th>Main Competences</th>
<th>Web</th>
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</thead>
<tbody>
<tr>
<td>EPFL, Power Electronics Laboratory (PEL)</td>
<td>High power MV electronics, Converter’s modelling, simulation, design, optimization and control, Power semiconductors and magnetics, Electrical energy generation, conversion and storage</td>
<td><a href="http://pel.epfl.ch">http://pel.epfl.ch</a></td>
<td></td>
</tr>
</tbody>
</table>

**Leader of S3.4 Low voltage grid control Enhancement & S3.5 Storage system in MV for grid ancillary services**

<table>
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**ETHZ, High Voltage Laboratory (HVL)**

<table>
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<th>Main Competences</th>
<th>Web</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETHZ, High Voltage Laboratory (HVL)</td>
<td>High Voltage Gaseous Insulation, High voltage DC Insulation, Current Interruption in HV systems, Upgrading of existing overhead-line by optimized used of “dynamic line rating” or conversion of multi-circuit AC towers to hybrid HVAC/HVDC.</td>
<td><a href="https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html">https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html</a></td>
<td></td>
</tr>
</tbody>
</table>

*HES-SO Fribourg / HEIA-FR, Institute for Applied Research into Energy Systems*

Main competences:
- High voltage engineering and testing
- Power system modelling, including harmonic analysis
- Power system control & protection, including digital substation
- AC/DC power systems

Web: [https://energy.heia-fr.ch/](https://energy.heia-fr.ch/)

*HES-SO Vaud, Institute of Energy and Electric Systems (IESE)*

Main competences:
- High Voltage Power Electronics Converters
- Power Electronics Systems modelling and simulation
- Digital control systems
- Low Voltage grid measurements and control systems

Web: [http://iese.heig-vd.ch/](http://iese.heig-vd.ch/)

*EPFL, Power Electronics Laboratory (PEL)*

Main competences:
- High power MV electronics,
- Converter’s modelling, simulation, design, optimization and control
- Power semiconductors and magnetics
- Electrical energy generation, conversion and storage

Web: [http://pel.epfl.ch](http://pel.epfl.ch)

*EPFL, Power Electronic Systems Laboratory (LEM)*

Main competences:
- New power electronics converter topologies and actuator concepts
- Advanced modulation and control of power electronic converters
- Advanced sensing and monitoring of converters and machines
- Ultra-compact -efficient converter systems
- Solid-state transformers

Web: [https://www.pes.ee.ethz.ch/](https://www.pes.ee.ethz.ch/)

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Main competences:
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- Ultra-compact -efficient converter systems
- Solid-state transformers

Web: [https://www.pes.ee.ethz.ch/](https://www.pes.ee.ethz.ch/)

*ETHZ, High Power Electronic Systems (HPE)*

Main competences:
- Converter’s modelling, optimisation and design
- Numerical modelling of components for converter systems
- Development of advanced passive components
- MV test facility for power electronic converter systems

Web: [https://www.hpe.ee.ethz.ch/](https://www.hpe.ee.ethz.ch/)

*ETHZ, High Voltage Laboratory (HVL)*

Main competences:
- High Voltage Gaseous Insulation
- High voltage DC Insulation
- Current Interruption in HV systems.
- Upgrading of existing overhead-line by optimized used of “dynamic line rating” or conversion of multi-circuit AC towers to hybrid HVAC/HVDC.

Web: [https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html](https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html)

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Web: [https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html](https://www.eeh.ee.ethz.ch/en/power/high-voltage-laboratory.html)
Key activities of WP3

WP3 consists of 5 subtasks that cover key aspects of Multi-terminal AC-DC grids and power electronics and includes:
S3.1. Multi-terminal HVDC system design and operation
S3.2. Fault clearing in multi-terminal HVDC
S3.3. Enabling technologies
S3.4. Low Voltage grid control Enhancement
S3.5. Storage system in MV for grid ancillary services
During the 2014-2016, 11 projects have been initiated in the frame of the abovementioned subtasks of FURIES.
One of the key achievements of the WP3 is the establishment of the FURIES AC/DC lab network. Furthermore, the following achievement have resulted of the above mentioned collaborations and infrastructure:
• Characterization of various converter structures for fault clearing
• Testing of network resonances use-cases with DSOs
• Identification of sensitivities of DC breaker concepts to key parameters, e.g. inductance of the faulted circuit
• Development of flexible test current source for initial tests with 5.5 kV / 1.4 kA
• Design and construction of a medium-frequency transformer
• Concept and design of 10 kV DC, 500 kVA demonstrator of GIMC
• Validation of model-less approach for distributed control of DER
• Development of a reduced scale Modular Multilevel Converter
This section includes further details on representative projects of WP3.
AGREFLEX – AGGREGATION OF FLEXIBLE ELECTRICAL LOADS, ECONOMIC AND REGULATORY ANALYSES

Solutions for control of group of flexible loads as a single resources

With the increase of the share of distributed generation into the Swiss energy mix, the maintenance of grid’s stability requires more and more the use of the flexibility of the power systems’ elements related to power production; storage and consumption. However, the distributed nature of these elements challenges their control.

Goal
The goal of the “AgreFlex” project is to design solutions enabling control of groups of flexible loads as a single resource modelled as a battery. Such a resource would then be managed by a Virtual Power Plant (VPP) controller.

Results
For this purpose, the following steps have been undertaken. Firstly, the estimation of shiftable power and energy at the scale of Switzerland was analyzed. Then, aggregation algorithms requiring a limited exchange of control information between the controlled sites and the aggregator were designed. And several simulations were performed based on the designed aggregation algorithms. Finally, the results of the simulations were verified based on the real case measurements.

As a results, three opportunities for new suppliers were selected (a) balance the load through the adjustment market; (b) limit the conventional development of the electrical grid by a congestion management; (c) catch opportunities on the energy market.

Also, it was proven that the seasonal variability is not particularly significant. As shown in Figure 27, the average cost of the positive tertiary power during a period of four hours and considering a probability of fifty percent, is estimated at 3 CHF/MWh.

Next step
These results will be further tested in simulations in laboratory and implemented in experimental prototype.

Figure 27 – Prices distribution of the TRL+ from 2011 to 2014.
STOSYS - ELECTRICAL ENERGY STORAGE - CHARACTERIZATION AND INTEGRATION IN THE GRID MANAGEMENT

Tools for design and operation of power storage system for integration of Renewable Energy Sources into the grid.

Developed countries promote the renewable energy production systems which are thriving; in particular Photovoltaic. Due to their dependence on weather conditions, these have a stochastic production that makes their integration into the power grid difficult. Optimal integration of Energy Storage Systems (ESS) can address this issue.

However, control of the renewable energy production through ESS is a major challenge because uncoordinated massive integration will lead to destabilize the grid operation, increase losses, degrade the voltage profile, decrease life duration of the grid elements, etc. and so caused a high economic loss.

Goal
This project aims to develop tools to improve integration of Renewable Energy Sources into the grid in order to increase their economic viability and decrease their impact on the grid.

Results
For this purpose, the most common and promising ESS technologies were characterized and modeled; tools for ESS integration in the grid were developed for management, optimal sizing and technical-economic analysis of batteries for constant production of PV systems; and tools for electrical distribution networks planning for the management of the thermal loads.

The innovation will allow to integrate more easily the RES and will increase the part of green energy production and consumption.

Next step
As a next step, different technical tools will be tested and studies and demonstration activities will be undertaken in order to increase the readiness level of this technology.

Figure 28 – Synoptic of a Grid-connected PV/Battery hybrid system

Further reading
STORAGE SYSTEM IN MV FOR GRID AUXILIARY SERVICES

Innovative interface of storage systems for MV applications, making use of modular converters and avoiding the 50Hz main transformer.

Utility grid system operation requires network services. Nowadays they rely heavily on large power plants. However, centralized production is gradually replaced by decentralized production facilities (IPDs). This will result to additional costs for future network operations (DSO). IPDs capable of providing these services would increase the economic efficiency of distributed generation and would offer an opportunity to aggregate these services for the DSO.

Goal
The project has two main objectives:
1) to undertake theoretical studies on the most promising ancillary services
2) to develop and test a storage system based on a Modular Multilevel Converter (MMC) structure

Results
For this purpose, the ancillary services selected include:
1a) with/without less conventional generators (rotary) and more storage, without degradation of quality of service.
1b) including a large number of players without overloading the control centers and/or communication systems.

Also, for the tests a Statcom converter was developed based on a MMC in reduced scale, designed to interface a battery with the average voltage network without 50Hz transformer. Also, a suitable lay-out of the Gridlab was designed and configured to one or more scenarios consistent with the theoretical studies, including the Statcom MMC and possibly a serial compensator.

As a result, operational studies according to objectives a) and b) were finalized; a MMC converter was developed; and the serial compensator (LVSR) was adapted to the needs of the project. As a last step of this project, the relevance of these solutions to the revision of the Electricity Supply Act (LApEL) will be studied. These results will support DSOs to develop a strategy for managing future network services in case of a high penetration of IPD.

Next steps
Test of the serial compensator and its potential to solve current problems with DSOs.

Figure 29a– Case study: LV of District of Corminboeuf (FR)  
Figure 29b– MMC laboratory set-up

Further reading
Techno-economic analysis of intelligent substations

The massive integration of renewable energy technologies into the grid, as indicated by the Swiss energy strategy 2050, will require the adaptation of the power grid. This concerns among else the substations which should become more intelligent, enforced with functionalities required for the real-time monitoring and control of the LV grid. This will enable the grid operators to maintain efficiently the security and quality of supply of their network under these new conditions.

Goal
The goal of this project is to identify the best intelligent substation in terms of techno-economic aspects by comparing various intelligent substations solutions.

Results
For the achievement of this goal, various scenarios related to the use of smart substations were studied, for instance for PV control or EVC control. Four different scenarios were selected and further analyzed on a techno-economic basis. This analysis considered the material costs, workforce, maintenance, as well as the reliability of the system and its potential unavailability.

It was demonstrated that a real-time management and control system of a photovoltaic central inverter is a promising solution. However, the integration of smart devices requires high level of knowledge of the system. Currently, the high integration of these devices into the LV network and their actual reliability raises concerns.

For this project, a principle of telemetry and remote control of a MV/LV substation was developed. Also, the close collaboration with a DSOs, i.e., Services Industriels de Genève, enable the validation of the results.

Next step
As a next step, the results will be further simulated on the lab and tested in a substation.

Figure 30 – Cost allocation for the different scenarios studied
Tools to develop EMC standards to avoid harmonics interferences.

With the increased use of power electronics, TSO and DSOs are facing the increasing significance of a known issue: harmonic pollution. Due to its switching nature, each power electronic converter injects harmonics into the network.

**Goal**
This project aims to reduce the EMC interferences between the harmonic pollution due to power electronics in the distribution level and Power Line Communication used by smart grid equipment.

**Results**
This systemic approach takes into account the grid frequency-dependent impedance and the dynamic behavior of decentralized storage and generation inverters. All the elements of a standard distribution network (LV power lines, MV/LV transformer, loads) have been modeled in a large frequency band (CENELEC A).

A real case of distribution area (Avusy Qoattes, Services Industriels de Genève) is modeled and a special tool to measure the network spectral impedance, developed in a related project, will be used to validate this model.

The used methods called Frequency Scan and Resonant Mode Analysis (RMA) can be applied on the distribution systems, with a large frequency band of validity, and compared with other software solution, they take into account more EMC phenomena (like Skin Effect, earth return path, etc.). The use of RMA method allows DSOs to predict if there will be some harmonics interference problems, and were they come. The harmonics propagation along the network elements can be simulated too.

**Next step**
As a next step, the models will be validated by comparison with measurements; a harmonics propagation study will be undertaken; and recommendations for standards and DSOs will be developed.

**Figure 31** – Modelling of a real case of distribution area (Avusy Qoattes of SIG).
AC/DC INTERACTIONS: RESONANCE PROBLEMS IN POWER NETWORKS IN PRESENCE OF HARMONIC POLLUTION

Prediction of resonance behavior of different operational topologies and of the future network configuration

Apart from avoiding harmonic pollution (see “CEM SMARTGRIDS – Electromagnetic Compatibility between smart grids and decentralized generation and storage systems” project), its prediction is also important for future network configuration.

Goal
The goal of this project is to analyze resonance behavior of current and expanded DSOs’ networks, and to predict possible resonance problems; identify their origin; and investigate their effects on the centralized control carrier signal. In case of TSO, in the real case study, Pradella case, the changes in resonance response are aimed to be analyzed.

Results
For this purpose, real TSO’s and DSOs’ networks and their various operational topologies are analyzed, considering several voltage levels. The frequency behavior of the DSO’s expanded network is predicted and possible resonance problems compare to its current configuration are detected. The effects on the centralized control carrier signal is examined.

The findings of this study are that the changes in configuration of studied DSO’s network will not lead to appearance of new resonance at 475 Hz (see figure) and thus will not affect the centralized control carrier signal (CCCS). However, the first resonance peak (around 375 Hz) is close to the frequency used for CCCS, and changes in operation topology could delay this peak to the right.

The changes in configuration of the TSO’s network (Pradella case) will have a great influence on the resonance response of the power system. The resonance in the Pradella area will decrease dramatically. Prediction of the resonance behavior of the network allows to avoid resonance problems in the studied network, such as amplification of the carrier signal. It also provides an information on the best location of active filter installation.

Next step
As a next step, the impact of the DSO’s network undergrounding on the CCCS will be investigated.

Further reading
INFLUENCE OF HARMONICS ON MTDC / AC NETWORK STRUCTURES

Identification of weak nodes in term of resonance in a power transmission system

Nowadays, there is an interest in underground cable transmission lines in extra high and high voltage level networks. The undergrounding of the transmission system can lead to the decrease of the resonance frequencies resulting in high overvoltages and possible power system component damages. It is therefore necessary to analyze possible resonance problems in a mixed transmission power system (comprising both overhead and underground lines).

Goal

The objective of this work is to analyze possible resonance problems in a mixed power system and to define the factors that affect the resonance frequency in power system. This work is also aimed at defining the impact of one voltage level network on another.

Results

In this project several scenarios were performed for the Swiss power transmission system: case of the actual power system comprising solely overhead lines and three cases of mixed power systems with underground cables. In order to gain a better understanding of the nature and extent of the resonance, a resonance mode analysis was executed. The main conclusions drawn include that the introduction of underground cables in the power transmission system leads in certain cases to a dramatic reduction of the resonance frequency. Also, potential resonance problems can be anticipated based on the participation factors of the nodes to be connected with future underground lines. Identification of weak nodes provides valuable information to avoid resonance frequency drop when undergrounding transmission lines in the power system.

Next step

The resonance of DSOs networks will be analyzed.

![Figure 33 – Swiss power transmission system.](image)

Further reading

FAULT CLEARING IN MULTI-TERMINAL HVDC

Novel test source for flexible pulse-current creation for circuit breaker testing

For the safe operation of future HVDC multi-terminal grids, HVDC circuit breakers are a key component. Advances in HVDC switching technology will enable the Swiss energy industry to take a leading role in the world-wide transition from fossil to renewable energy sources.

While first HVDC networks are already in operation, hybrid/DC circuit breakers are still in the prototype phase.

Goal
The presented project aims to identify the capabilities of different HVDC circuit breaker topologies and investigate optimization potential.

Results
In the scope of this project, short circuit current interruption in multi-terminal HVDC systems were investigated over a broad range, from grid level to individual components, combining expertise in power system, power electronics and high voltage engineering. The conducted simulations showed the impact of grid topologies on the development of fault currents. Furthermore, different power electronic circuits for enabling a fast current breaking in a mechanical switch were simulated and compared. On the component level, a model gas circuit breaker was developed that is used to investigate the interaction of mechanical switches and power electronic devices.

In addition, a novel test source is developed to allow flexible pulse-current creation for circuit breaker testing.

Figure 34a – Model gas circuit breaker to investigate the interruption behaviour in HVDC applications.

The novel test current source is commercialized in cooperation with a Swiss industry partner. It is expected that leading test labs are interested in purchasing these test sources. Similar designs can be used to operate sources and magnets in accelerator technology of particle physics labs.

Next step
In the future, further simulations regarding the optimization of HVDC circuit breaker topologies are planned and new concepts for hybrid circuit breakers based on power electronic converters and mechanical breakers are investigated. In parallel, the test bench for the built model gas circuit breaker is upgraded to investigate its interruption capability and its interaction with power electronic circuits.

Figure 34b– Unipolar Arbitrary Current Source for Hardware in the Loop Tests

Funding
SCCER, private industrial funding

Academic partners
ETHZ (HVL, HPE) (fhjele@ethz.ch)

Industrial partners
ABB AG

Non-FURIES partners
Ampegon Switzerland

Project Duration
2014-2017 (3 year)

Project Scope
HVDC

Work Packages
WP3

Further reading
• Schultz, T., & Franck, C. (2016). Interruption Capability Investigations of a Model Gas Circuit-Breaker for HVDC Switching Operations, 21st International Conference on Gas Discharges and Their Applications (accepted for publication)
**DRY-TYPE INSULATION SYSTEMS UNDER MIXED-FREQUENCY MV STRESS**

*Alternative dry-type insulation material featuring high potential with respect to MF stress resilience*

The recent developments in Silicon Carbide (SiC) solid-state switches open up new possibilities in medium-voltage (MV) power electronic converter design and applications. Such solid-state transformers (SSTs) are promising alternatives to conventional low-frequency distribution transformers in certain applications, providing active grid-grid, grid-load or grid-source interfaces linking different voltage and/or frequency levels (including DC). However, comparatively higher power loss densities and the broadband medium-frequency (MF) voltage stress raise issues with respect to the endurance of the concerned insulation systems due to the temperature and frequency dependence of the (di)electric properties and the active degradation mechanisms.

**Goal**

This project aims at combining inputs from the physics of dielectrics, electro-thermal stress analysis simulation and experimental investigations to identify and quantify the active degradation processes and use this knowledge to develop design criteria for resilient insulation systems exposed to the stresses occurring in MV MF transformers.

**Results**

As a results, a test bench was built up for laboratory investigations of the effects of MF voltage stress; a arbitrary waveform dielectric spectrometer was setup for offline aging diagnostics; and a virtual prototyping software for MF transformers (thermal, (di)electric, magnetic) was developed. The innovation of this approach lies on the identification of an alternative dry-type insulation material featuring high potential with respect to MF stress resilience; the innovative insulation concepts for common/differential mode separation in MV insulation and electromagnetic shielding of MF transformers; and the accurate, fast, and comprehensive method for the evaluation of the dielectric losses of materials subject to fast transients.

**Next step**

Test bench and dielectric spectrometer will be used to assess voltage endurance and aging of potential dry-type insulation materials in various electrode configurations. Also, MV prototype of a 10 kV/50 kHz MF transformer with an insulation coordination will be designed for fast transients.

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**Further reading**

- [http://p3.snf.ch/project-154005](http://p3.snf.ch/project-154005)

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**Fig. 35a** – MF/MV transformer used in a SST.

**Fig. 35b**– Developed test bench for investigations of specimens under various thermo-electric stresses and electrode geometries.
Representative WP3 publications

- 'Conception of a Modular Multilevel Converter in a Multi Terminal DC/AC transmission network (conference proceedings)' by HES-SO, IESE (Carpita, Siemaszko); HES-SO Fribourg (Favre-Perrod) at 2015 ECCE Europe, Geneva, Switzerland (2015) (URL)
- 'Resonance Analysis of a Transmission Power System and Possible Consequences of its Undergrounding (conference proceedings)' by HES-SO, Fribourg (Favre-Perrod, Galland, Leu) at 10th International Conference on Deregulated Electricity Market Issues in South Eastern Europe, Budapest (2015) (URL)
- 'Spectral Grid impedance and electromagnetic interferences in the 2 to 150kHz frequency range' by HES-SO, Valais (Roggo) at International Journal of Distributed Energy Resources (2015) (pdf)
- 'Multi-Terminal HVDC Networks - What is the preferred topology?' by ETHZ, HVL (Franck and Bucher); ETHZ, PSL (Andersson and Wiget) at IEEE, Transactions on Power Delivery (2014) (pdf)
- 'Analytic Approximation of Fault Current Contribution from AC Networks to MTDC Networks During Pole-to-Ground Faults' by ETHZ, HVL (Franck and Bucher) at IEEE, Transactions on Power Delivery (2015) (pdf)
- 'Analytic Approximation of Fault Current Contributions from Capacitive Components in MTDC HVDC Cable Networks' by ETHZ, HVL (Franck and Bucher) at IEEE, Transactions on Power Delivery (2015) (pdf)
- 'Fault Current Interruption in Multiterminal HVDC Networks' by ETHZ, HVL (Franck and Bucher) at IEEE, Transactions on Power Delivery (2015) (pdf)
- 'Characterization of the Voltage and Electric Field Stresses in Multi-Cell Solid-State Transformers (conference proceedings)' by ETHZ, HVL (Franck); ETHZ, PES (Kolar) at IEEE Energy Conversion Congress and Exposition, Pittsburgh, PA, USA (2014) (URL)
- '10kV SiC-Based Isolated DC-DC Converter for Medium-Voltage-Connected SSTs (conference proceedings)' by ETHZ, PES (Kolar) at 30th Applied Power Electronics Conference and Exposition, Charlotte, NC, USA (2015) (pdf)
- 'Protection of MV/LV Solid-State Transformers in the Distribution Grid (conference proceedings)' by ETHZ, PES (Kolar, Guillod), ETHZ, HVL (Franck) at Annual Conference of the IEEE Industrial Electronics Society (2015) (pdf)
- 'An Update on Experimental Data Obtained at the Säntis Tower (conference proceedings)' by EPFL, EMC (Rachidi); EPFL, DESL (Paolone) at IEEE International Conference on Environmental and Electrical Engineering, Rome, Italy (2015) (URL)
Innovation Challenges
The previously described evolution of the electrical grid infrastructure imposes new constraints to the transmission and distribution network that can be only fulfilled by developing new efficient, cost-effective and environmental friendly grid components. A strong requirement for the new components is to have less environmental impact during production, operation and disposal (“green technology components”). The main research challenge of the WP4 is the development of new concepts and technologies for future grid components capable to fulfill the needs and conflicting constraints of the future power systems.

Objectives
The objectives of the WP4 were:
✓ to improve the switching components for Very Fast Transients (VFTs) in power systems applications with particular reference to materials used to achieve the electrical insulations
✓ to investigate the networking and communication among monitoring and control components of power systems (e.g. smart meters, intelligent electronic devices etc.)
✓ to improve the reliability of the testing methods for high voltage components; deeper understanding of novel material behavior, lower operational costs for electricity suppliers and consequently for customers as well.
✓ to study the optimal design of reversible pump-turbines and PVs and their integration into the grid.
Competences of WP4

WP4 is mainly focusing on the grid components, including transformers but also PV-inverters, hydropower turbines; and monitoring infrastructure. 34 experts are contributing to the implementation of the activities of this work package with capacities on electrical, mechanical and micro-engineering; computer science and physics. These knowledge competences are complemented with infrastructure such as testing facilities for PV-inverters.

Also, WP4 partners have access to a wider range of competences through close collaboration with WP1 and WP2 on the impact of components on the grid. In this frame, they collaborate with various companies, including DSOs such as BKW, Romande Energie, and Elektra Fraubrunnen AG; power technology and components companies, such as ABB, Siemens, Alpiq, and Andritz hydro.

Furthermore, WP4 partners have links with all the other SCCERs that are close to their focus area, such as SCCER-CREST on socio-economic aspects of the components; SCCER-HaE (storage) on PV-inverters; and SCCER-SoE (supply of electricity) and SCCER-Mobility on the impact of hydropower components and EVs, respectively, on the grid.

Furthermore, WP4 partners have put in place training activities for capacity development of young scientists and practitioners such as:
- PV prevention for “fire brigade instructors”
- Workshops “planning of plushouses”
- CAS Strom im Haus
- Courses at BFH, FHWN, HSLU, HSR and USI
Leader of WP4 and Leader of S4.1 Modelling and experimental investigation of VFT in DC installations

Prof. Dr. Jasmin Smajic

HSR, Computational and Applied Electromagnetics Group
Main competences:
- Electromagnetic field simulations
- Simulation-based product development and design optimization
- High voltage measurements in modern laboratory
- 30kW test bench for electric machines
Web: [http://www.iet.hsr.ch/Computational-Electromagnetics.12232.0.html](http://www.iet.hsr.ch/Computational-Electromagnetics.12232.0.html)

Deputy leaders of WP4 and Leader of S4.6. PV-MMPT/ PV-inverter test bench/ accreditation of PV inverter test/ lightning arc detection

Prof. Dr. Urs Muntwyler

BFH, PV-Lab
Main competences:
- Test PV systems with field campaigns/IR-drones/U-I equip./flasher&e-lumin.
- Simulate and plan PV production profiles and their grid impact
- Predict load profiles and simulating complex systems in the “prosumer-LAB
- Test of components <1 MV in HV test facility and surge current test chamber
Web: [http://www.pvtest.ch](http://www.pvtest.ch)

Leader of S4.2 Life-cycle optimization of power system components and reliability analysis

Prof. Dr. Nicolas Schulz

FHNW, Power Systems Engineering Group
Main competences:
- Distributed DSM systems modeling
- Centralized/Distributed energy storages: Control algorithms
- MV&LV grids simulation and control methods for grid stabilization
- Power grid components: Reliability
Web: [http://www.fhnw.ch/technik/last](http://www.fhnw.ch/technik/last)

Leader of S4.3 Addressing instability of hydro power plant during their design

Prof. Dr. Ernesto Casartelli

HSLU, Fluid Mechanics & Hydraulic Machines
Main competences:
- On-site hydro power-plant measur. (IEC Expert) and monitoring
- High-end CFD analysis&customized code develop., 1000-cores own cluster
- Large own lab with various measur. and visualization techniques, incl. IEC volume flow calibration
Web: [https://www.hslu.ch/.../?pid=54](https://www.hslu.ch/.../?pid=54)

Leader of S4.4 Embedded systems for the electrical grids real-time monitoring

Prof. Dr. Miroslaw Malek

USI, Advanced Learning and Research Institute (ALaRI)
Main competences:
- Cyber-physical and embedded systems including: grid monitoring, dependability, load and disturbance prediction for proactive grid management, predictive maintenance, security and real time
Web: [http://www.alari.ch/](http://www.alari.ch/)

Leader of S4.5 Integration and Intelligence of Storage, Mobility and PV

Prof. Dr. Vinzenz Härri

HSLU, Integral, Intelligent and Efficient Energy Systems
Main competences:
- Energy Systems Engineering
- Fast System Integration and Prototyping
Web: [https://www.hslu.ch/.../iiee/](https://www.hslu.ch/.../iiee/)

Leader of S4.7. High Performance Methods for Coupled Problems Parallel Approaches to Simulation and Optimization

Prof. Dr. Rolf Krause

USI, Institute of Computational Science
Main competences:
- High Performance Computing, including large-scale discrete and continuous optimization for grids, as well as the numerical modeling of grid components
- Close cooperation with the Swiss supercomputing center CSCS
Web: [http://ics.usi.ch/.../prof-rolf-krause.html](http://ics.usi.ch/.../prof-rolf-krause.html)
Key activities of WP4

WP4 consists of 7 subtasks that cover key aspects of power systems’ components and includes:
S4.1. “Green” and “Smart-grid-compatible” Power System Components
S4.2. Life-cycle Optimization and Reliability Analysis
S4.3. Addressing Instability of Hydro Power Plant During Their Design
S4.4. Embedded Systems for the Electrical Grids Real-time Monitoring
S4.5. Integration and Intelligence of Storage, Mobility and PV
S4.6. PV-Multi-Maximum Power Tracker MMPT/ PV-inverter test bench/ accreditation of PV inverter test/ lightning arc detection
S4.7. High Performance Methods for Coupled Problems Parallel Approaches to Simulation and Optimization

During the 2014-2016, 21 projects have been initiated in the frame of the WP4 subtasks of FURIES, resulting to the following key achievement:

• Development and validation of an optimized sensor for VFT measurements in gas insulated substations
• Validation in real transformer of the HF-simulation of transformer winding
• Development of a multi-physics (electric-thermal-mechanical) simulation model of high-power semiconductor modules intended for applications such as HVDC
• Investigation of source of instability of pump storage plants (PSP) for the design of more stable turbines
• Development of a dynamic power system fault injector to compensate lack of real-life failure related data
• Development of test facilities and procedures for PVs including PV-Multi Maximum Power Tracker (MMPT); accreditation PV inverter test; PV-inverter battery test bench; and lightning arc detector test procedure
• Development of a multi-physics Coupling Library with Interface to different simulation tools

Further details on representative projects of WP4 are provided on the following pages.
PROGRID: PROACTIVE METHODS FOR CONTINUOUS OPERATION OF THE POWER GRID

Alternative dry-type insulation material featuring high potential with respect to MF stress resilience

Further improvement of availability of power distribution service requires novel methods in grid operation management. Proactive grid management can complement the existing (reactive) one by predicting disturbances to prevent them or to mitigate their effect.

Goal
This project aims at exploring the concept of proactive grid operation management by: (i) proposing a unified approach to Smart Grid dependability, and identifying and classifying disturbances in Smart Grid, (ii) identifying the most indicative features for disturbances’ prediction and adapting a proper prediction algorithm, and (iii) evaluating the effect of failure prediction accuracy on system’s availability.

Results
For this purpose, the following steps were undertaken: (1) modeling the system structure and classification of disturbances; (2) data conditioning, feature extraction and feature selection; (3) prediction algorithm selection and evaluation; (4) analysis of the prediction impact on system’s availability. These activities resulted to the introduction of a classification of various types of power systems’ disturbing events such as faults, errors and failures, and the development of a taxonomy for the classification of faults. Also, a comprehensive methodology was proposed for proactive management of failures in Smart Grid based on data analytics inspired by well-established solutions of computer engineering. A generic model of proactive management was defined and the availability equation was extended with parameters that characterize the quality of failure prediction and proactive actions.

Next step
This solutions will be demonstrated and validated in a real-life active distribution grid.
MULTI-MPPT PV INVERTER TEST BENCH

Construction and test of a multistring PV inverter test bench

In the past few years, PV inverters with more than one maximum power point tracker, so called multi-MPPT PV inverters, have become market standard. These devices allow the connection of multiple sub PV arrays and perform a separate MPP tracking on each of these sub arrays. Usually, one module string per MPP tracker is being connected. The benefits of such systems are a better performance under inhomogeneous conditions, i.e. if the PV array is partially shaded or if the strings have multiple orientations. Also, multi-MPPT PV inverters allow more flexibility in the layout of the PV array, because the strings do not necessarily all have the same number of PV modules.

Goal
This project aims to develop a multi-PPT PV inverter test bench; to reach a high thermal stability; and the multistring PV array simulator to have a very fast settling time.

Results
For the achievement of these goals, a multi-PPT PV inverter test bench with 3x15 kWp with linear approach was developed and tested. The Multi-MPPT PV Inverter Test Bench passed all the tests. It reach a high thermal stability better than 0.01% even if the measurement is being performed out of a cold start. This is an outstanding value. Also, the multistring PV array simulator has a settling time of less than 50 microseconds. This is about 20 times faster than the fastest switched mode PV array simulators. The Multi-MPPT PV Inverter Test Bench allows - for the first time - the measurement of multi-string PV inverters in real conditions with up to three unbalanced input power strings. This gives the developer of such devices more information about the behavior with unbalanced PV input power; and their installers can plan more efficient PV plants.

Next step
As a next step, the test norm for Multi-MPPT PV inverters will be presented at the PV Konferenz in Staffelstein, Germany, in March 2017. Also, further tests; and tests on EMC of PV inverters and optimizers are planned for 2017-2020.

Further reading
• Web: [http://www.pvtest.ch](http://www.pvtest.ch)
ACCREDITATION OF INVERTER TEST FACILITY

The 1st certified PV inverter test bench in Switzerland

The implementation of the Swiss Energy Strategy 2050 requires the massive integration of photovoltaic systems into the Swiss power network. These PV systems, which are almost exclusively imported, are tested with methods not always certified and transparent. This result to a deviation between expected and real power outcome which affects the confidence of PV investors.

Goal
This project, which is closely linked with the “Multi-MPPT PV Inverter Test Bench” project mentioned before, aims to describe and define a quality measurement environment for PV inverter tests within Bern University of Applied Sciences BFH (QM pilot quality system at BFH).

Results
The Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf, has tested PV inverters for more than 20 years. This project focuses on the accreditation of the PV inverter test. In the last decades, five different test benches with 12-, 20-, 25-, 100- and 3x15 kWp were developed. The procedure is now integrated into the QM pilot system of BFH which will enable the addition of further test procedures.

The Multi-MPPT PV Inverter Test Bench passed all the validation tests and is now ready for use by research laboratories and the PV industry in Switzerland. PV inverter tests are now carried out in a certified environment and offer confidence to the customer with regard to the quality of the tests and the test results.

This is the first and only such infrastructure in Switzerland.

Next step
As a next step, the test norm for Multi-MPPT PV inverters will be presented at the PV Konferenz in Staffelstein, Germany, in March 2017. Also, further tests; and tests on EMC of PV inverters and optimizers are planned for 2017-2020.

Fig. 38 – PV-module test at the BFH-PV lab

Further reading
• Web: http://www.pvtest.ch
PV INVERTER AND BATTERY INVERTER TESTS

PV inverter and battery test bench and test norms

For the smoothening of the PV power production and the enhancement of the own consumption of houses with PV installations, stationary batteries are increasingly installed. However, these PV-storage systems can serve multiple purposes and improve the economic performance of the PV installations.

Goal
This project aims to develop a “PV inverter and battery” test facility and a related EN test norm.

Results
For the achievement of this goal, a PV inverter and battery test bench was developed based on existing infrastructure at the PV LAB at BFH in Burgdorf, i.e., PV inverter test benches. First measurements of the dynamic battery-inverter units performances are currently being conducted, and the knowledge acquired is transferred and cross-checked with international partners. Data sheets are developed and a proposal for an EN Test norm is underway.

Real measurement of “battery-PV-inverter” units enabled a better understanding of the function and the parameters of such devices. One of the results is that a poor dynamic response could result to system operation modes with low efficiency (<60%). Also, the EN-test norm enable the industry to be aware of the real performance of such systems and to improve them. For instance, PV planers can integrated in their work the real data of such devices. The outcomes of this project will enable the owners of PV installations to improve the economic performance of their investments, by for instance increasing their own self-consumption on PV power. Also, utilities and others can learn to use the “PV-battery-inverter devices” to stabilize the grid and to optimize the economy of the electricity in their grid.

There are more than 15 possibilities for the different stakeholders to use the unit for improving different parameters (e.g., voltage control, power control, production of regulation power etc.).

Next step
As a next step, the test norm will be developed by the end of 2016, jointly with international partners, and a “round robin” test cycle will be undertaken with three other institutes for 2016/2017.

A software will be developed to semi-automatize some of the test procedures and an artificial load will be integrated to speed up the test procedures. The testing of small (<10 kWh) and big units (>>(10 kWh) will continue during the 2017 – 2020 period. Tests of bidirectional EV-batteries are also planned in view of performing the same function as a stationary battery (2017-2021).

Further reading
• Web: http://www.pvtest.ch

Fig. 39 – PV laboratory established test configuration and measures several batteries for a local utility company
ARC FAULT DETECTOR (AFD)

Arc fault detector for safer PV installations

PV installations have thousands of contacts in which relative high DC currents, and high DC voltages occur. Each fault of such a contact could cause an arc and potentially cause a fire which could destroy the installation and even a house. However, there are not many arc detectors on the market and those that exist do not protect sufficiently the PV installations.

Goal
This project aims to develop arc fault detectors either integrated in PV inverters and regulators or as a single device.

Results
Arc fault detectors have been developed by the Photovoltaic Laboratory (PV LAB) of Bern University of Applied Sciences BFH for more than 20 years. In the frame of this project, a new approach was developed including the building up of an arc generator, which always produces the same arc. This speeds up the development process of the arc fault detectors. Measurements were taken in two campaigns in 2014 and 2016. The innovation of this solution lies on the fact that the “arc generator” can produce similar arcs that simulate critical situations much better than the arc generated by the widely used UL-norm. This gives a higher protection of PV installations and all the investments around them (e.g., houses).

Next step
This project will be followed up by an industrial collaboration with a Swiss SME in 2017-2018.

Further reading
- Web: [http://www.pvtest.ch](http://www.pvtest.ch)
**SWISS TRANSFORMER: APPLICATION AND SUSTAINABILITY OF SiC SST IN THE SWISS ELECTRICAL GRID**

*Integration and application of solid-state transformers in the existing electric grid*

Silicon carbide (SiC) -based power electronic transformers (SSTs) can play an important role on the stabilization of the power grid with strongly fluctuating electricity supply from PV and wind power plants. However, research is still needed on the development of technologies for the realization of SiC-based high-power semiconductor switching elements, and for the optimization of hardware concepts for SiC-based power electronic transformers (SSTs).

**Goal**

This project is part of the same program with the STT project mentioned under WP3. This project aims to assess the application of SiC SSTs in low- and medium voltage grids by grid simulations; to develop control algorithms; and assess the overall sustainability of grid-based SiC SSTs.

Target customers are DSOs operating both, MV and LV grids with strong decentralized feed-in by wind and PV.

**Results**

As a result of the project, simulation models and control algorithms for SSTs were developed for voltage control of LV grids with a high penetration of decentralized PV generation. Also, the application of SST was assessed in MV grids in order to stabilize voltage, compensate reactive power and minimize grid losses. Based on these outcomes, decision makers and end-users can decide whether and how SSTs will bring the required functionalities for grid operation and stabilization. Furthermore, they obtain information about how many SSTs should be used in a specific grid, at which locations and which control scheme to apply.

**Next step**

A sustainability model of SiC SSTs applied in the Swiss electric grid will be established; and reliability data of the underlying SiC power semiconductors will be acquired. The rolling out of this technology is foreseen for beyond 2025.

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**Fig. 41**– Overview of 2 LV grids in Rheinfelden AG, with calculated distributed PV potential (displayed columns), as enabled by SiC SSTs.

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**Further reading**

- C. Hunziker, N. Schulz, “Potential of Solid-State Transformers as Key Technology for Future Smart Grids”, poster presentation at the SCCER-FURIES 3rd Annual Conference 2015 (Lausanne)
- Web: [http://www.swiss-transformer.ch/](http://www.swiss-transformer.ch/)
Representative WP4 publications

- 'Simulation and Measurement of Lightning-impulse Voltage Distributions Over Transformer Windings' by HSR (Smajic) at IEEE Transactions on Magnetics (2014) (pdf)
- 'Simulation Based Design of HF Resonators for Damping Very Fast Transients in GIS' by HSR (Smajic) at IEEE Transactions on Power Delivery (2014) (pdf)
- 'Herausforderungen in Planungs- und Umsetzungsprozessen von PV-Gebäudehüllen.' (conference proceedings) by BFH, PV-Lab (Prof.Muntwyler) at BIPV-Konferenz Staffelstein (2015) (pdf)
- 'Ultrafast Multi-MPPT PV Inverter Test Bench (conference proceedings)' by BFH, PV-LAB (Muntwyler; Schuepbach) at EU PVSEC 2014 (URL)
- 'Towards 100% Renewable Energy Supplies (conference proceedings)' by BFH, PV-Lab (Prof.Muntwyler) at 10th International Conference on Ecological Vehicles and Renewable Energies, Monaco, Monte Carlo (2015) (URL)
- 'Grey-box modeling of a low pressure electric boiler for domestic hot water system' by FHNW, IAST (Schulz) at Applied Thermal Engineering (2015) (URL)
- 'ExCovery – A Framework for Distributed System Experiments and a Case Study of Service Discovery (conference proceedings)' by USI, ALaRI (Malek) at 28th International Parallel & Distributed Processing Symposium, Workshops and Phd Forum (2014) (pdf)
- 'A multi-level spectral deferred correction method' by USI, ICS (Krause) at BIT Numerical Mathematics (2014) (pdf)
- 'A space-time parallel solver for the three-dimensional heat equation' by USI, ICS (Krause) at Advances in Parallel Computing (2014) (pdf)
- 'Convergence of Parareal for the Navier-Stokes equations depending on the Reynolds number' by USI, ICS (Krause) at Numerical Analysis (2013) (pdf)
- 'Inexact spectral deferred corrections' by USI, ICS (Krause) at Numerical Analysis (2014) (pdf)
- 'Parareal for diffusion problems with space- and time-dependent coefficients' by USI, ICS (Krause) at Numerical Analysis (2014) (pdf)
- 'Numerical Simulation of skin transport using Parareal' by USI, ICS (Krause, Kreienbuehl) at Numerical Analysis (2015) (URL)
- 'Parareal convergence for 2D unsteady flow around a cylinder' by USI, ICS (Krause, Kreienbuehl) at Numerical Analysis (2015) (URL)
- 'Time parallel gravitational collapse simulation' by USI, ICS (Krause, Kreienbuehl) at Journal of Computational Physics (2015) (URL)
- 'Transient Simulation of Speed-No Load Conditions With An Open-Source Based C++ Code' by HSLU (Casartelli) at 27th IAHR Symposium on Hydraulic Machinery and Systems (2014) (pdf)
- 'A Conceptual Solution for Integration of EV Charging with Smart Grids (conference proceedings)' by USI, ALaRI (Lukovic) at International Conference on Smart Grid and Clean Energy Technologies (2014) (pdf)
- 'Smart Charging Cell for Smart Cities (conference proceedings)' by USI, ALaRI (Malek, Dr.Lukovic) at 2nd IEEE International Workshop on Intelligent Energy Systems (IWIES) (URL)
- 'Responsiveness of Service Discovery in Wireless Mesh Networks (conference proceedings)' by USI, ALaRI (Malek) at 20th IEEE Pacific Rim International Symposium on Dependable Computing (2014) (URL)
Further information

For further information about the SCCER-FURIES’s partners, and technical and social activities, please visit the website:  
http://sccer-furies-epfl.ch

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