ETH zürich

Integration of RES in the Swiss electricity grid

Challenges, solutions and methods

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FEN

Project overview

- Financed by CCEM, Swisselectric Research
- Phase 1: Distribution grid aspects (2014-15)
- Phase 2: Transmission grid aspects (2016-17)

Project partners

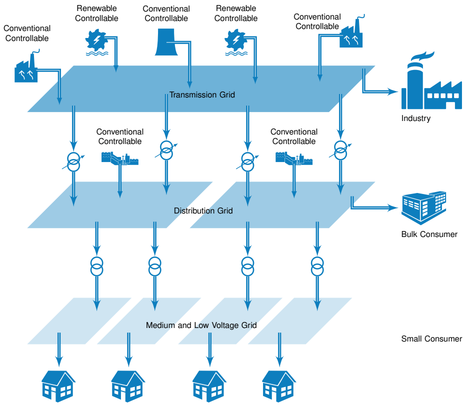
- ETH Zurich (Research Center for Energy Networks, FEN)
- Paul-Scherrer-Institut (Technology-Assessment-Group, TAG)
- Paul-Scherrer-Institut (Energy-Economics-Group, EEG)
- Hochschule Luzern (HSLU)
- CKW, Axpo

Overall goal: Develop a general planning and strategy tool for distribution grids .

Outline

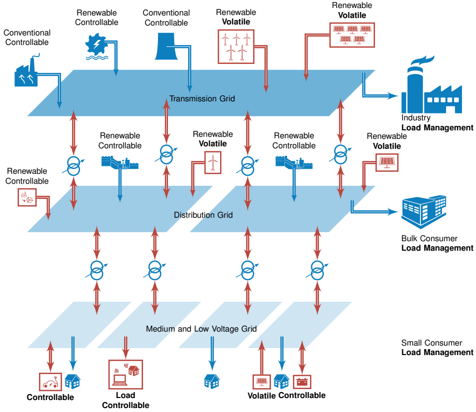
Outline

Grid operation today



- Predictable loads, prices and production capacities
- Sufficient stability reserves in the grid
- Unidirectional load flow
- Established operational procedures

Grid operation future



- Limited predictability of loads, prices; volatile production
- Reduced stability reserves in the grid
- Bidirectional load flow, production on the distribution grid level
- New operational procedures required

Challenges for the distribution grid operator

Especially uncertainty regarding:

- the development of future network structure.
- the development of future production capacity and demand profiles.
- new regulatory framework (Swiss and Europe wide).

As a result uncertainty regarding future *operating procedures* and *investment decisions*.

Goals of the project

- Systematic investigation of existing approaches regarding their applicability for the Swiss distribution grids.
- Quantification of costs, risks and chances of each approach.
- Determine conclusions and recommendations for the Swiss distribution and transmission grid operators.

Main result is a road map for a concrete network example and a general software tool for the investigation of other networks.

Outline

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Grid components

Trafos   Loads   PV-Sources   Batteries

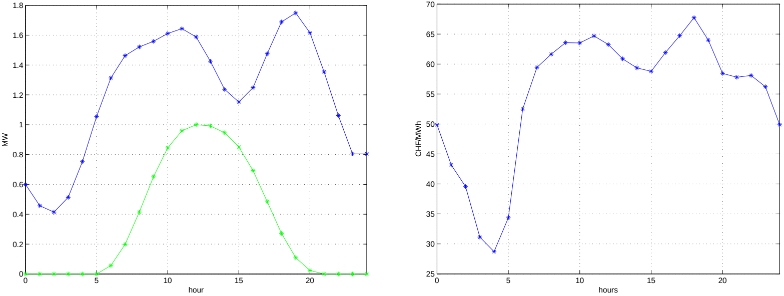


Figure: Load profile (left, blue), PV profile (left , green), Price profile at the trafo (right)

Classical distribution grid

- Aggregated loads at the trafo
- Load and price profile are given

Controllable quantities: none

Classical distribution grid - example

- Load and losses compensated by the trafo

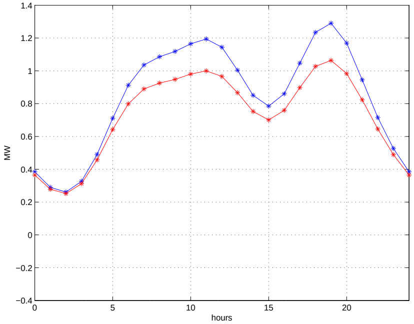
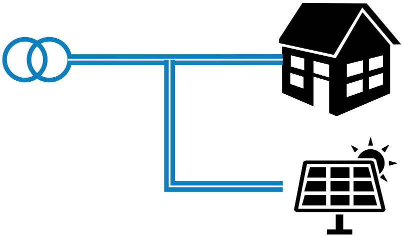


Figure: Load profile (red) and trafo power (blue).

Classical distribution grid with PV

- Aggregated loads at the trafo
- Profiles of Load, PV and price are given



Controllable quantities: none

Classical distribution grid with PV - example

- Load and losses compensated by the trafo and the PV source

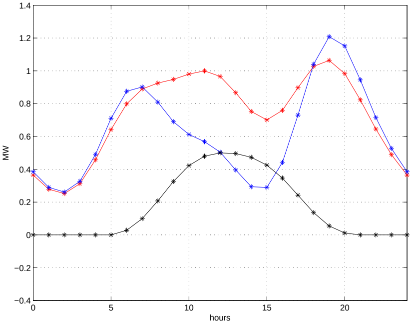
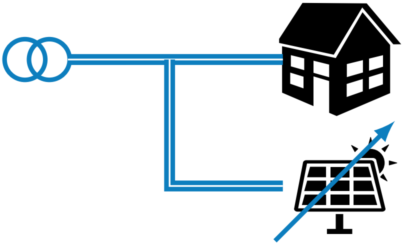


Figure: Load profile (red) and trafo power (blue), PV-Power (black).

Distribution grid with controllable PV

- Aggregated loads at the trafo
- Profiles of Load, PV and price are given



Controllable quantities: PV curtailment

Distribution grid with controllable PV - example

- Load and losses compensated by the trafo and the PV source
- PV peak power brings network to its limits (thermal or voltage).

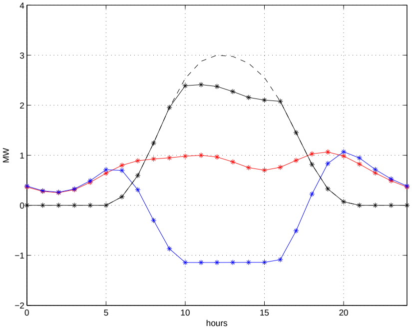
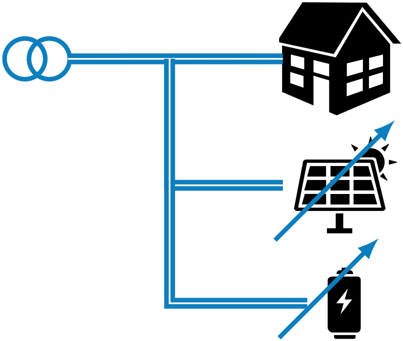


Figure: Load profile (red) and trafo power (blue), PV-Power (black), available PV power (black dashed).

Distribution grid with controllable PV and batteries

- Aggregated loads at the trafo
- Profiles of Load, PV and price are given



Controllable quantities: PV curtailment, battery power

Distribution grid with controllable PV and batteries - example

- Load and losses compensated by the trafo and the PV source
- PV peak power brings network to its limits (thermal or voltage).
- Battery allows increased usage of PV and cheap electricity from the feeder.

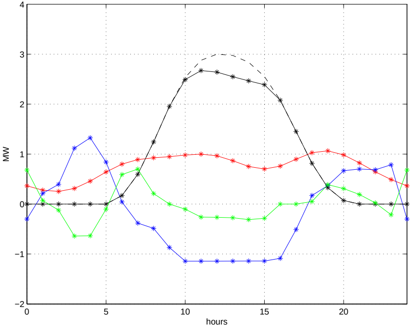


Figure: Load profile (red) and trafo power (blue), PV-Power (black), available PV power (black dashed), battery power (green).

Distribution grid with controllable PV and batteries - example

- Planning algorithm considers state-of-charge, power limits, efficiency of the batteries.
- Planning algorithm can be repeated hourly to include new predictions (weather, price, demand, ...).

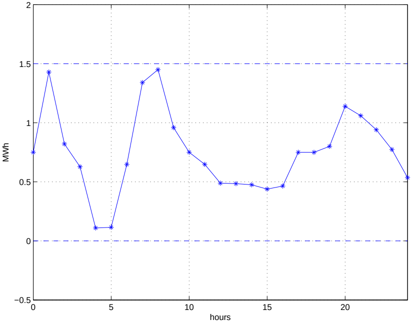


Figure: Battery state-of-charge (blue) and charge limits (blue dashed).

Comparison of energy costs

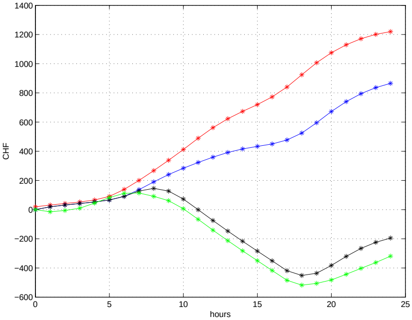


Figure: Cumulative energy costs no PV (red), with PV (blue), with controlled PV (black), with controlled PV and storage (green).

Grid operation - Mathematical problem formulation

$$J^* = \left(\min_{u_1,\ldots,u_N} \sum_{i=1}^{N} l_i(x_i, u_i) \right)$$

$$\text{s.t. } \forall i = 1, \ldots, N: \; g(x_i, u_i) \leq 0, \quad h(x_i, u_i) = 0,$$

- Nonlinear multi-period AC power flow problem as extension to the software Matpower (no DC power flow approximation necessary)
- Efficient Parallelization possible with MATPOWER / IPOPT / PARDISO (`http://www.pardiso-project.org`)
- Further improvement of the solution speed possible by exploiting the problem structure

Outline

Overview

- Investigation of CKW distribution grids near Luzern.
- Assumption: High increase of PV injection in the distribution grid

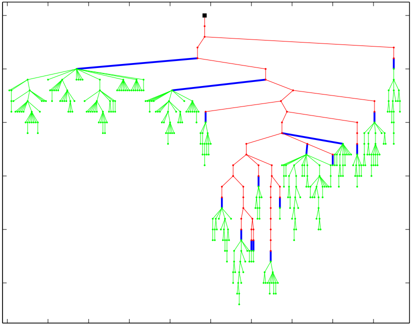


Figure: Distribution grid example Trafos (black and blue), 20 kV lines (red), 400 V lines (green).

Solution approaches for PV integration

Several academic methods and general approaches with reference systems available:

- Grid extension, operation and business as usual
- Usage of storage elements
- Load management, smart metering
- Production management and control

Grid planning - Mathematical problem formulation

$$J^* = \min_{p} \left(\min_{u_1,\dots,u_N} \sum_{i=1}^{N} l_i(x_i, u_i, p) \right) \quad (1)$$

$$\text{s.t. } \forall i = 1, \dots, N : \; g(x_i, u_i, p) \leq 0, \quad h(x_i, u_i, p) = 0, \quad (2)$$

- Planning parameter p includes grid extension, degree of PV curtailment and size/location of the storage units
- Can be included in the basic multi-period OPF problem formulation
- Is solved for a scenario of family of scenarios

Outline

Outline

PV-injection without storage

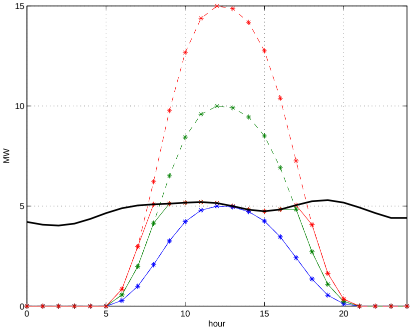


Figure: Distribution grid example Sursee: Maximum grid capacity (black), maximum PV-Injection without PV-curtailment (blue), increased PV-injection with PV-curtailment (green), strongly increased PV-injection with PV-control (red), available PV-capacity (dashed).

PV-injection without storage

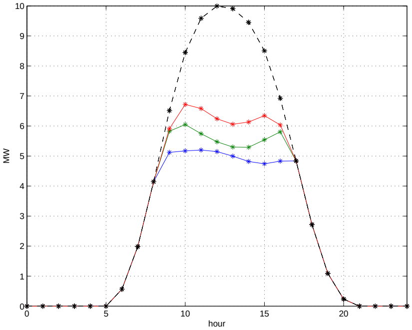


Figure: Distribution grid example Sursee: Maximum PV injection without storage (blue), increased PV-injection with storage for 30 minutes PV (green), with storage for 60 minutes PV (red), available PV-capacity (dashed).

Placement and sizing of storage units

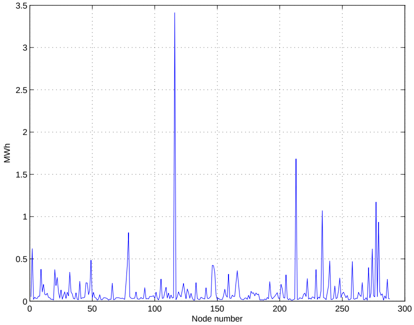


Figure: Distribution of the storage sizes at different nodes of the grid for a total storage capacity of $E_{\text{total}} = 33\text{MWh}$.

$\rightarrow$ *Storages are placed in the entire grid.*

Placement and sizing of storage units

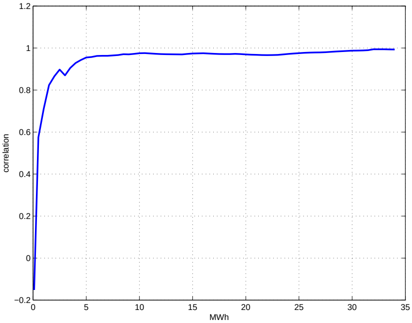


Figure: Correlation between optimal storage distribution and installed PV capacity $P_{\text{PV,rated}}$ at every node, as a function of the total storage capacity E_{total}.

$\rightarrow$ *Storages are sized according to the size of nearby PV units.*

Comparison of PV curtailment, storage and network extension

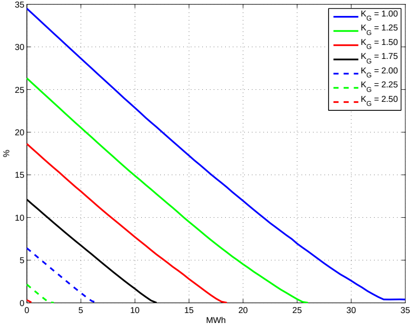


Figure: Ratio of curtailed PV power as function of the total storage capacity E_{total} for different degrees of grid expansion K_G.

$\rightarrow$ *Grid extension results in strong reduction of PV curtailment.*

Decision surface for PV integration strategies

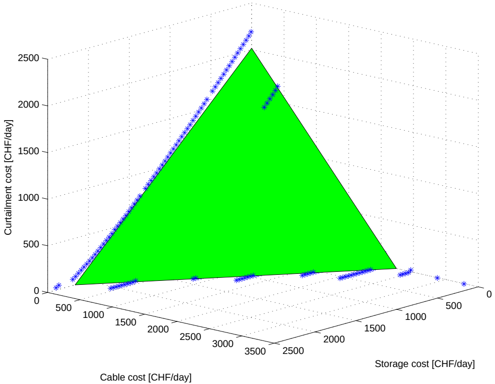


Figure: Daily operational grid costs for different strategy combinations. Individual simulations (blue stars) and approximation by a decision surface. Assumed cost parameters are the average electricity cost of $\bar{c} = 55$CHF/MWh, grid degradation costs of $p_G = 55$CHF/(km · day) and storage degradation costs of $p_S = 70$CHF/(MWh · day) .

Comparison of PV integration strategies

Trade-off between storage costs p_S, grid degradation costs p_G and electricity costs $\overline{c}$.
Minimum sum of all three costs is always an extreme point of the decision surface (corresponds to a single pure strategy).

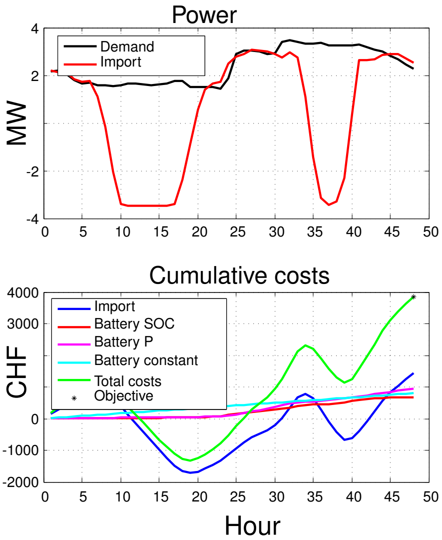
Linear criterion for the optimality of each strategy:

$p_\mathsf{S} < 1.29 p_\mathsf{G}$ and $p_\mathsf{S} < 1.16\overline{c}$:	Use only storage units.
$p_\mathsf{G} < 0.77 p_\mathsf{S}$ and $p_\mathsf{G} < 0.90\overline{c}$:	Use only grid extension.
$\overline{c} < 1.12 p_\mathsf{G}$ and $\overline{c} < 0.86 P_\mathsf{S}$:	Use only PV curtailment.

Without the linear approximation the minimum total cost is also reached at a combination of different strategies.

Outline

Simulation example for fixed cost parameters



Two-day simulation example of the CKW grid Ettiswil with an increased PV production and high demand: Power demand and import (top). Cumulative electricity and operational costs (bottom).

Fixed simulation parameter

Parameter are fixed before the simulation.

- Simulation of the Sursee region (summer and winter day, 48 hours)
- PV integration potential of today's grid is determined and increased
- Load profile of the households are maximized and simulated with coincident factor (25% base load and random distribution)

Variable simulation parameter

Only a range of simulation parameters has to be selected.

- Electricity price (20 - 80 CHF/MWh)
- Battery cost model: $J = b\bar{E}(SOC - a)^2 + cP + d\bar{E}$
  storage size $\bar{E}$
  State-of-charge SOC
  Load power P
  Parameter $\{a, b, c, d\}$ can be fitted to multiple battery models and technologies.
- Grid extension is a constant increase of the trafos, lines and cables .
- PV curtailment is not remunerated, but enters the planning decision through opportunity costs.

Full operational costs

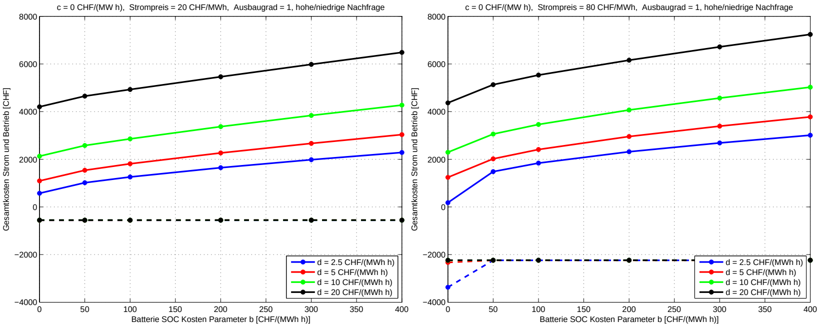


Figure: Optimal grid planning with variable battery parameters. High demand (solid lines) and low demand (dashed lines). Low electricity price (left) and high electricity price (right). No grid extension.

Sizing of installed storage units

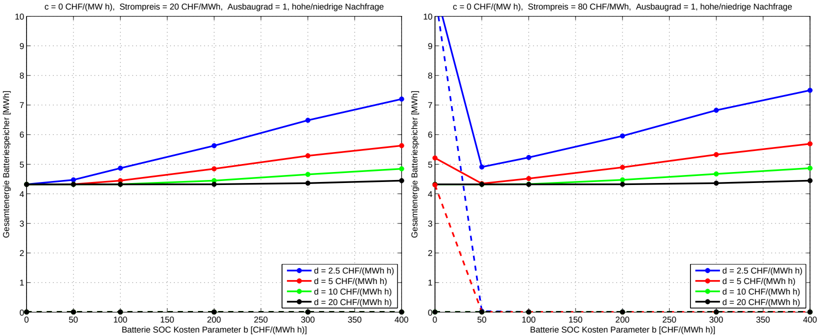


Figure: Optimal grid planning with variable battery parameters. High demand (solid lines) and low demand (dashed lines). Low electricity price (left) and high electricity price (right). No grid extension.

Curtailed PV power

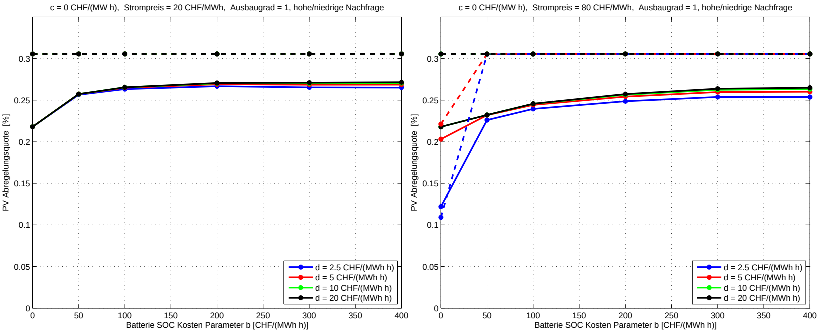
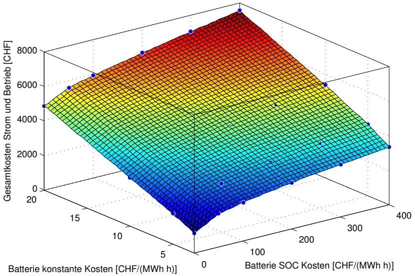


Figure: Optimal grid planning with variable battery parameters. High demand (solid lines) and low demand (dashed lines). Low electricity price (left) and high electricity price (right). No grid extension.

Results

- Simulation results form a decision surface, depending on multiple simulation parameter.
- Based on the decision surface, the grid owner can quickly make planning decisions for selected parameter values.



- Location and size of the storages are determined by the optimization.
- Control of the controllable quantities are part of the optimization.

Selected observations

- Storage technologies are only interesting for further decrease of storage costs or higher electricity costs.
- Evaluation of the grid extension depends on the costs of the individual grid components.
- High potential for controlled loads and PV components (currently simulated without additional costs).

Outline

Summary

- Unified problem formulation for the grid operation and planning.
- Optimal usage of available assets to compute a Pareto decision surface
- AC power flow extension for planning and multi period scenarios .
- Large multi-period simulations of AC power flow problems (1000 nodes, 1000 time steps) become tractable with dedicated solvers.

Ongoing work

Quantitative:

- Comparison of economic and CO2 objective

Qualitative:

- Robust plan with scenario uncertainty
- Long term transfer of the methods to general distribution and transmission grids

Thank you for your attention

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