CINELDI

Centre for intelligent electricity distribution
- to empower the future Smart Grid

Mobile and stationary batteries in the distribution grid: Where are the largest benefits?

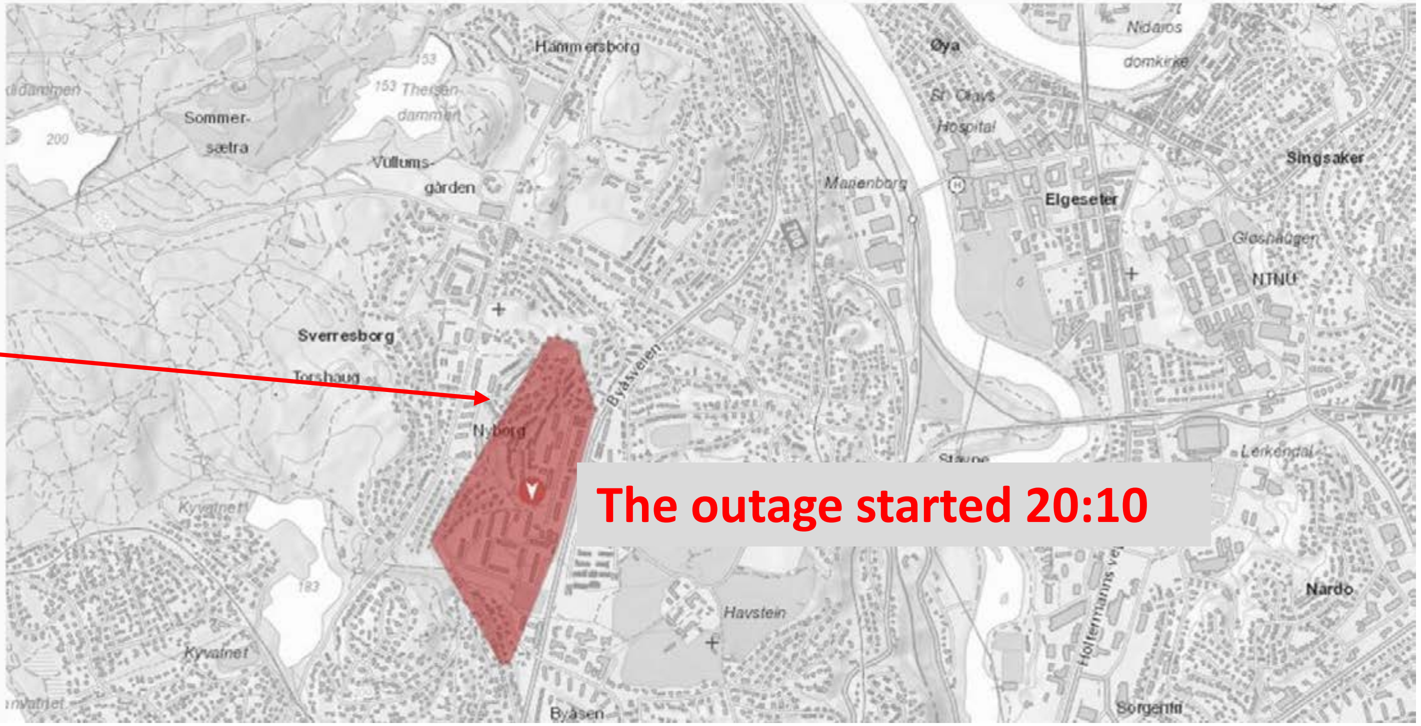
CINELDI DAYS 2019, Trondheim

Magnus Korpås, NTNU

I plugged in my Model 3
for the first time at 18:19…

Nesten 1000 abonnenter var rammet av strømbrudd i Trondheim

Et stort antall av Trønderenergis abonnenter på Havstad var uten strøm.



The outage started 20:10

Overview of presentation

- Categorisation of mobile and stationary battery types
- Batteries for what?
- Cost-benefit analyses from CINELDI and CINELDI-related research
- Lessons learned so far
  - Value of batteries and flexible EV charging in the grid
  - Value of accurate problem formulation and modelling
  - Value of fast-computing algorithms

Stationary battery types

- Off-grid systems
- Behind-the-meter batteries
  - PV-battery systems for households, larger buildings, (neighbourhoods?)
- Grid-scale batteries
  - Battery systems for small and large wind farms
  - Battery systems for grids at distribution/regional/transmission level

Mobile and vehicle battery types

- Electric passenger cars
- Larger vehicles and ferries
- Mobile batteries (Batteries “on wheels”)

https://www.greentechmedia.com/articles/read/the-business-case-for-mobile-batteries-in-new-york#gs.44l5wc

Multiple uses of stationary batteries

- Behind-the-meter batteries
  - Self-consumption of PV
  - Price arbitrage
  - Grid services by aggregation
- Grid-scale batteries
  - Grid investment deferral or postponement
  - Smoothing of wind power fluctuations (same owner)
  - Grid services
  - Short-term balancing
  - Price arbitrage
  - Capacity adequacy

Multiple uses of vehicle batteries for flexibility

- Electric vehicles
  - Self-consumption of PV
  - Price arbitrage
  - Grid services by aggregation
- Larger vehicles and ferries
  - An interesting duality:
    - Electric ferries and heavy duty vehicles needs A LOT of electric power
    - This yields more grids or local batteries to support the instant power needs
    - At the same time: When stand-by, these vehicles could also support the grid
    - Here, industry, policy makers and research must join forces to find least-cost solutions!

Cost-benefit analyses of mobile and stationary batteries in the grid

- Practical problem 1: The utilization of battery storage is very case-specific, so it is tempting to do tailor-made («ad hoc») calculations of the costs and benefits.
  - Can you trust the results?
- Practical problem 2: There is no standard, or recommended, approach
  - Battery assessments are not straightforward, because of the inter-temporal links, mulitple possible usages, battery degredation effects, large degrees of freedom related to sizing, etc
  - A LOT of research activities going on, but methods and models differ quite much

EV batteries vs stationary batteries for prosumers. What is the best choice?

Problem formulation

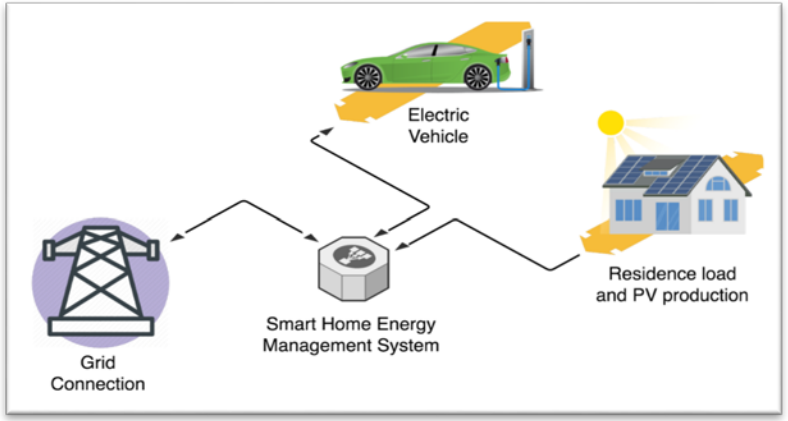
Minimize the annual energy costs for a prosumer with PV and a) Powerwall b) Tesla Model S under different grid tariff structures

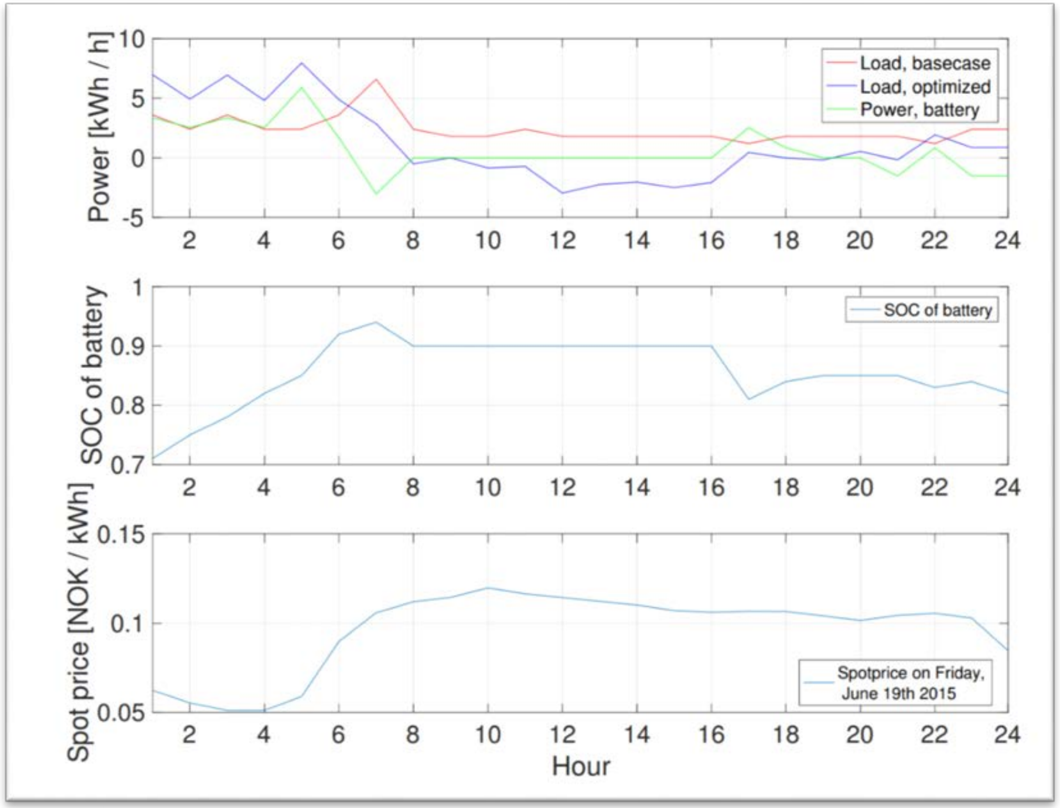
Approach

- Use formal optimization (dynamic programming) for each hour of the year
- Not considered: Uncertanties, degradation and investments

Bjarghov, S; Korpås, M; Zaferanlouei, S (NTNU) *Value Comparison of EV and House Batteries at End-user Level under Different Grid Tariffs*. IEEE ENERGYCON 2018

EV batteries vs stationary batteries for prosumers. What is the best choice?





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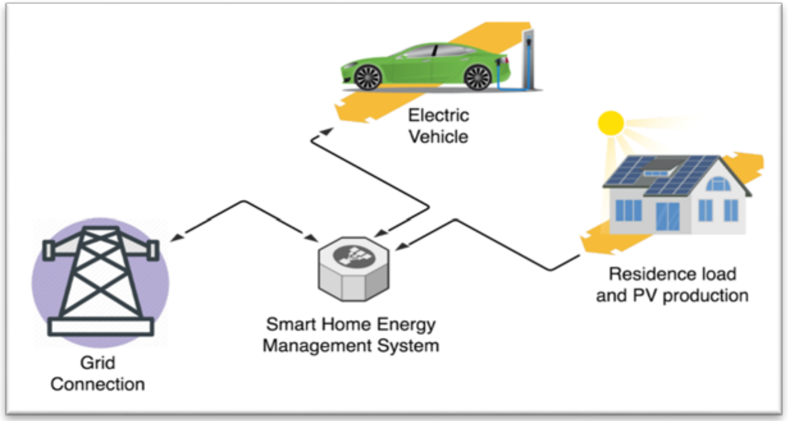

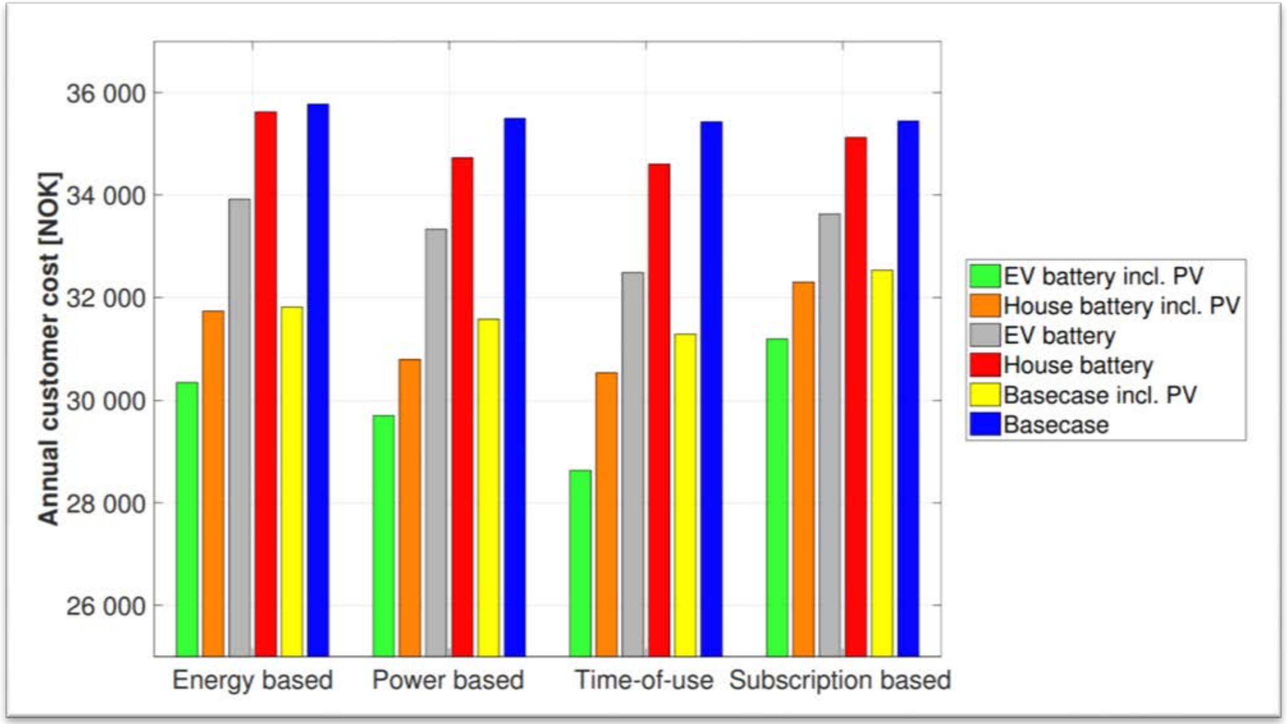

- ✓ Value of house batteries are 1 – 3 %
- ✓ Value of EV batteries are 5 – 8 %

Bjarghov, S; Korpås, M; Zaferanlouei, S (NTNU) *Value Comparison of EV and House Batteries at End-user Level under Different Grid Tariffs*. IEEE ENERGYCON 2018

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Battery storage for medium-sized swimming facility. Is it profitable?

Problem formulation

Minimize the total cost of electricity for the facility, including the cost of energy and peak power demand, while ensuring the longevity of the battery

Approach

- Use formal optimization (mixed-integer programming) for each hour of the year, including investments and battery degradation.
- Extensive sensitivity analysis for uncertanties in parameters
- Not considered: Short-term uncertanties

Berglund, F; Zaferanlouei, S; Korpås, M; Uhlen K; (NTNU) *Optimal Operation of Battery Storage for a Subscribed Capacity-Based Power Tariff Prosumer : A Norwegian Case Study*. Submitted to Applied Energy, 2019

CINELDI

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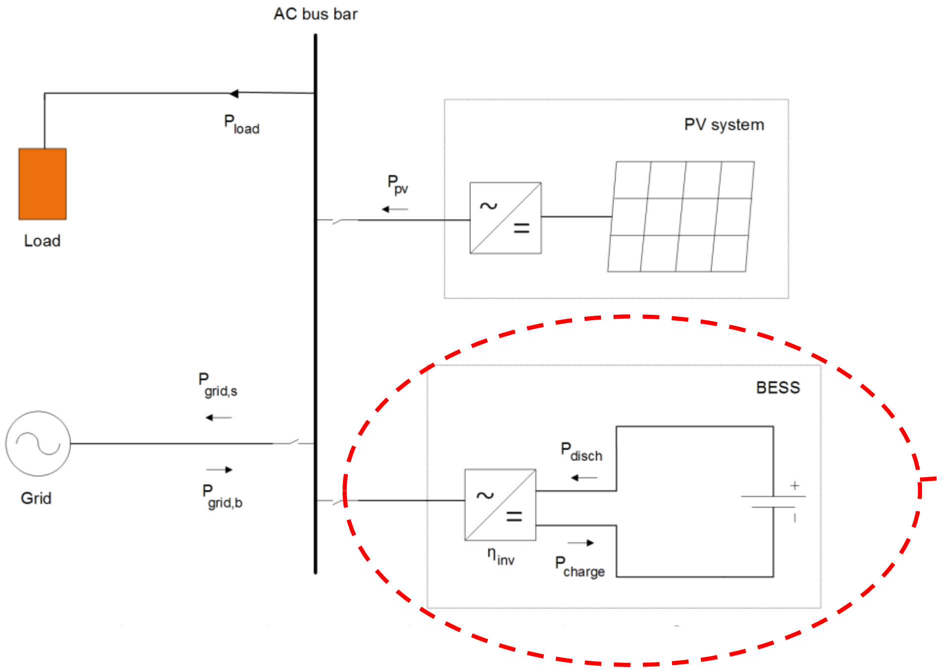
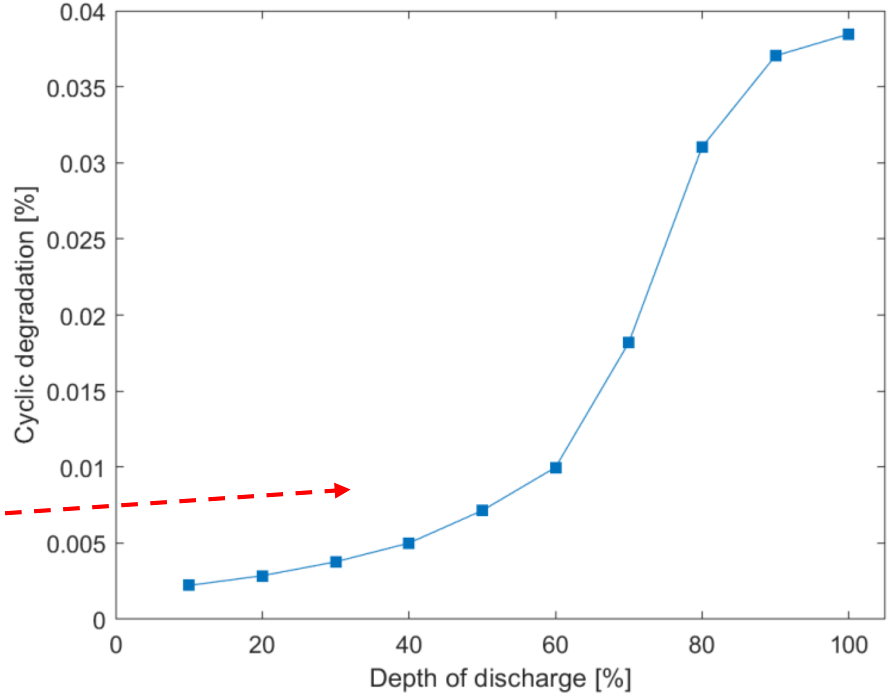


Degradation model



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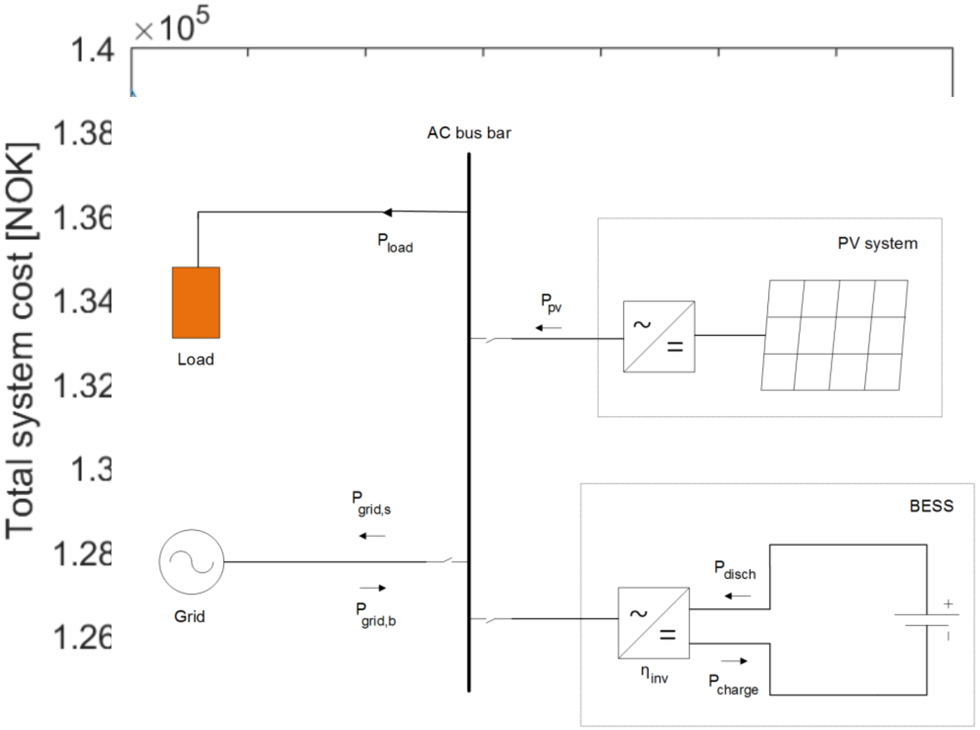
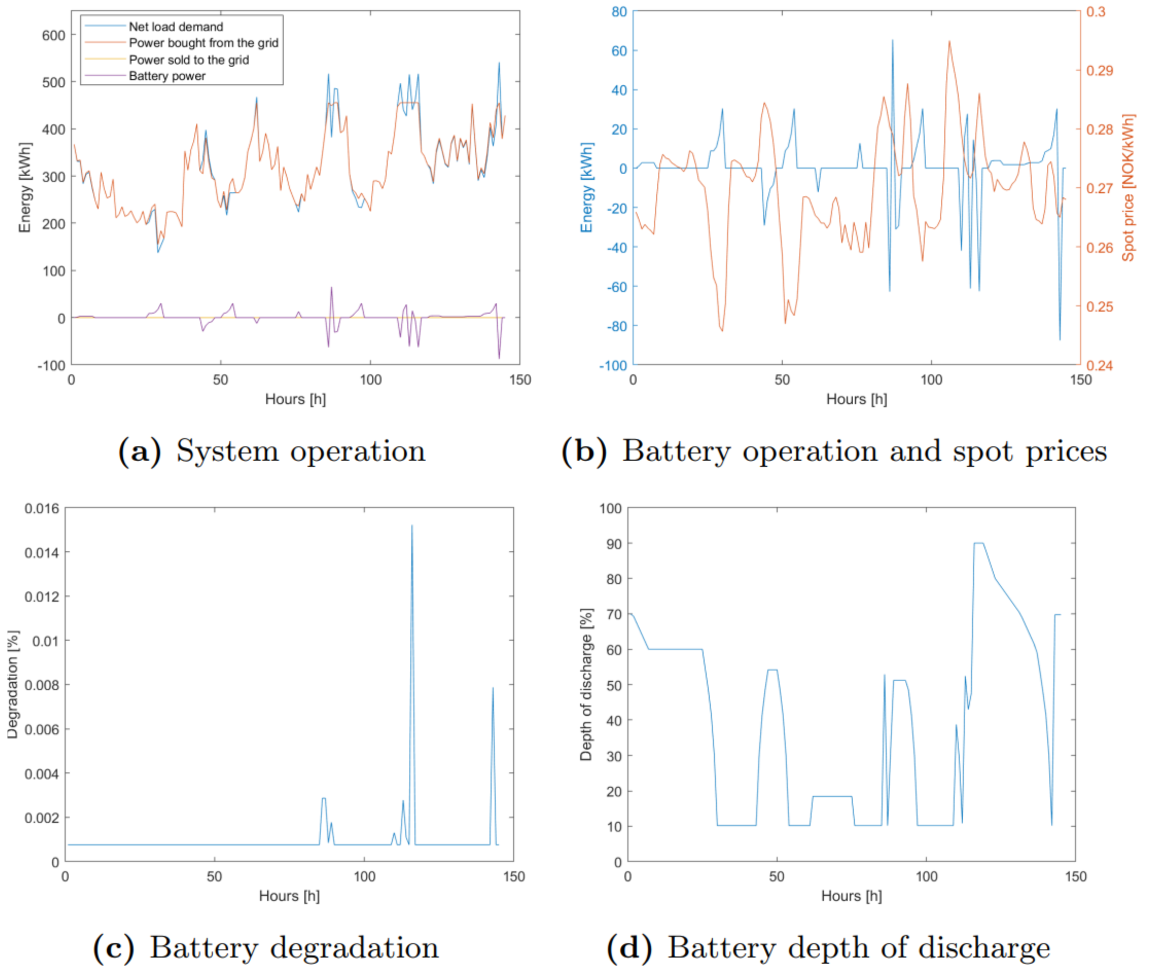


- ✓ Total costs are reduced by 0.5-1.0 %
- ✓ For a 2030 scenario: 4-5 %



(a) System operation

(b) Battery operation and spot prices

(c) Battery degradation

(d) Battery depth of discharge

Berglund, F; Zaferanlouei, S; Korpås, M; Uhlen K; (NTNU) *Optimal Operation of Battery Storage for a Subscribed Capacity-Based Power Tariff Prosumer : A Norwegian Case Study*. Submitted to Applied Energy, 2019

Predictive control of energy storage: Can we improve the computational speed?

Problem formulation

- Storage operation strategies are today a compromise between optimality and computational speed

Approach

- Re-formulate the optimziation problem to a search algorithm using methematical theory
  - Proven theoretically to give exact the same result as the original piece-wise Linear Programming formulation
  - The new algorithm runs up to 100 000 (!) times faster than state-of-the-art solvers

Xu, B (MIT); Korpås, M (NTNU); Botterud, A (MIT); O'Sullivan F (MIT); *A Lagrangian Policy for Optimal Energy Storage Control*. Submitted IEEE Conference on Decision and Control, 2019

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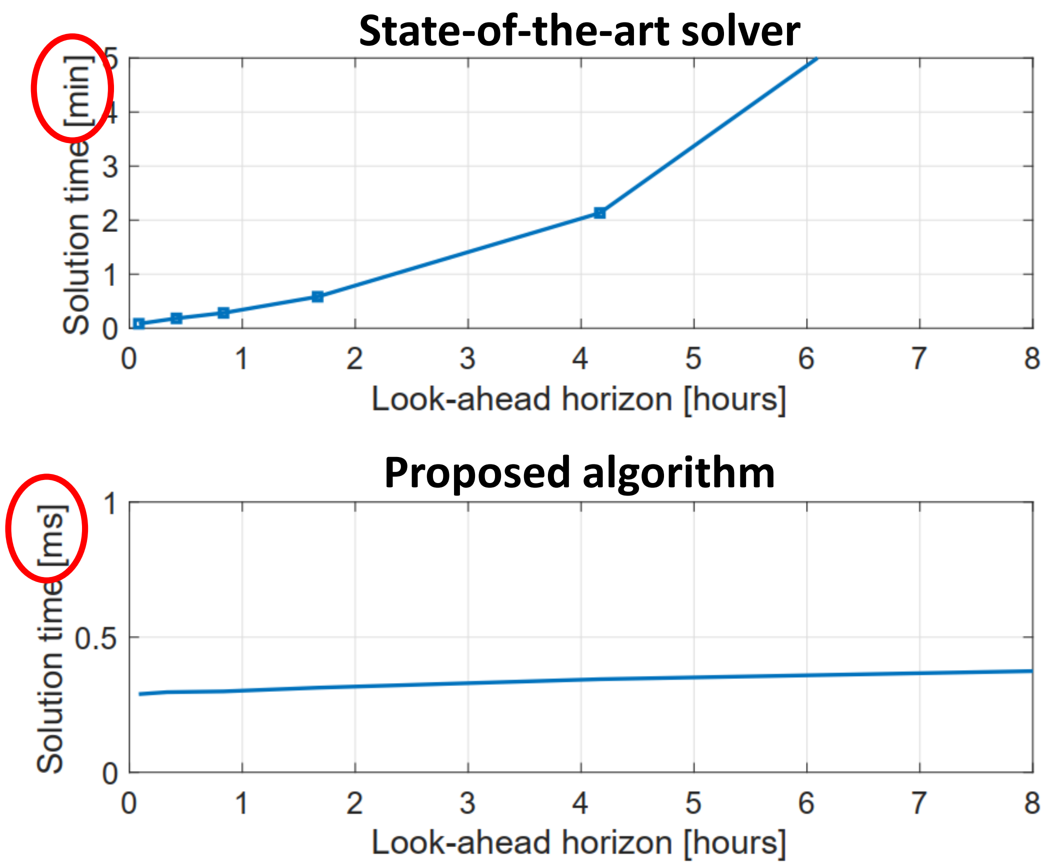

Xu, B (MIT); Korpås, M (NTNU); Botterud, A (MIT); O'Sullivan F (MIT); *A Lagrangian Policy for Optimal Energy Storage Control*. Submitted IEEE Conference on Decision and Control, 2019

Incorporating energy storage in optimal power flow. How to value energy stored for later use?

Problem formulation

- Maximize the value of energy storage in grids with high amounts of uncertain wind and solar power

Approach

- Explicity take into account uncertain wind and solar forecasts
- Use a «water value» approach for setting the end-value of storage
- Realistic grid representation by AC Optimal Power Flow
- Not considered: Degradation, investments, computational speed

Sperstad, IB (SINTEF); Korpås, M (NTNU); *Energy Storage Scheduling in Distribution Systems Considering Wind and Photovoltaic Generation Uncertainties*. Energies, Vol. 12(7), 2019

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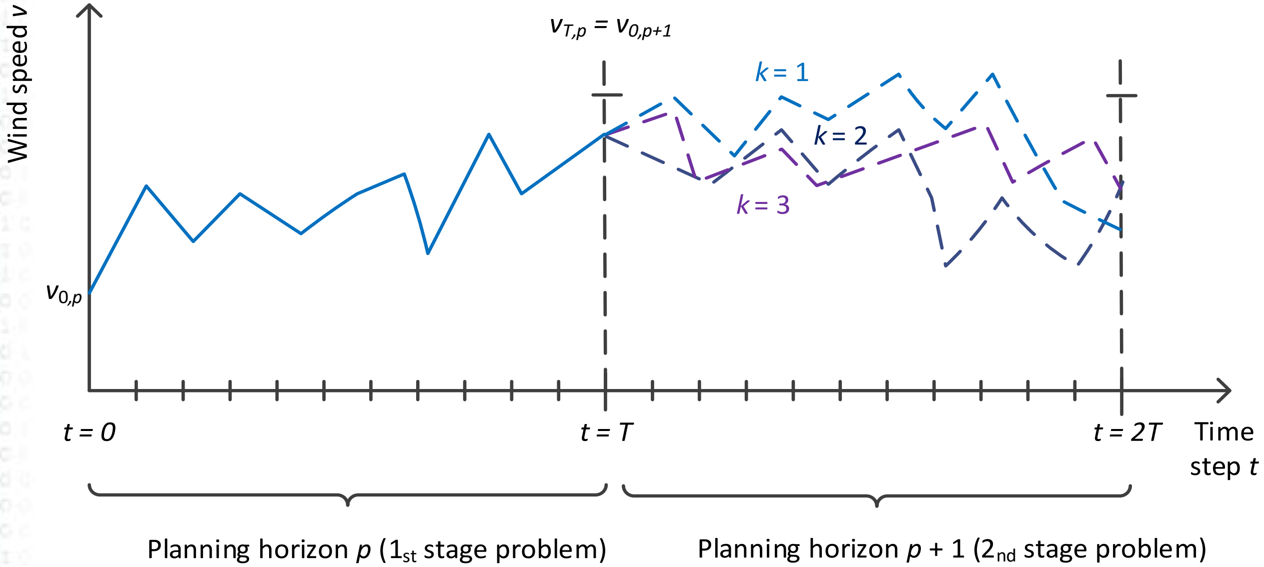

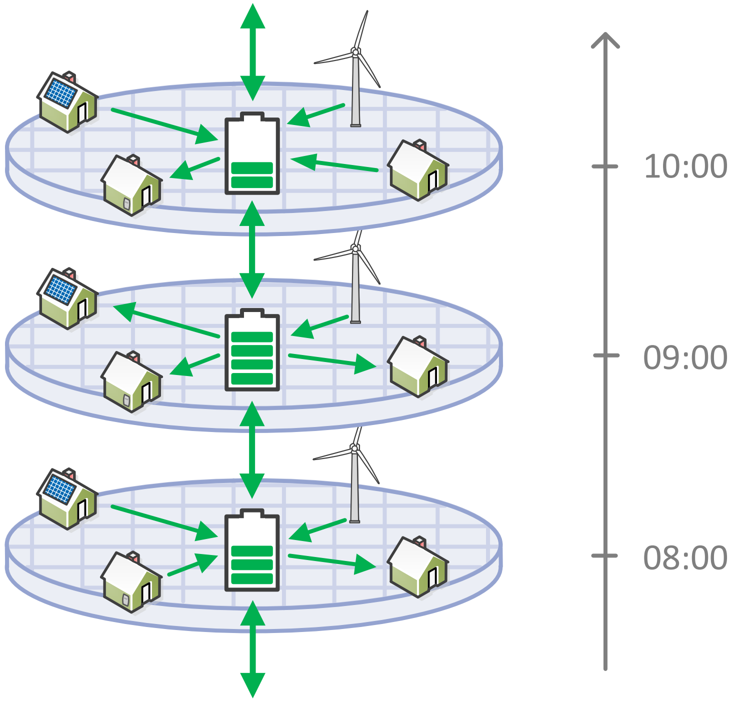

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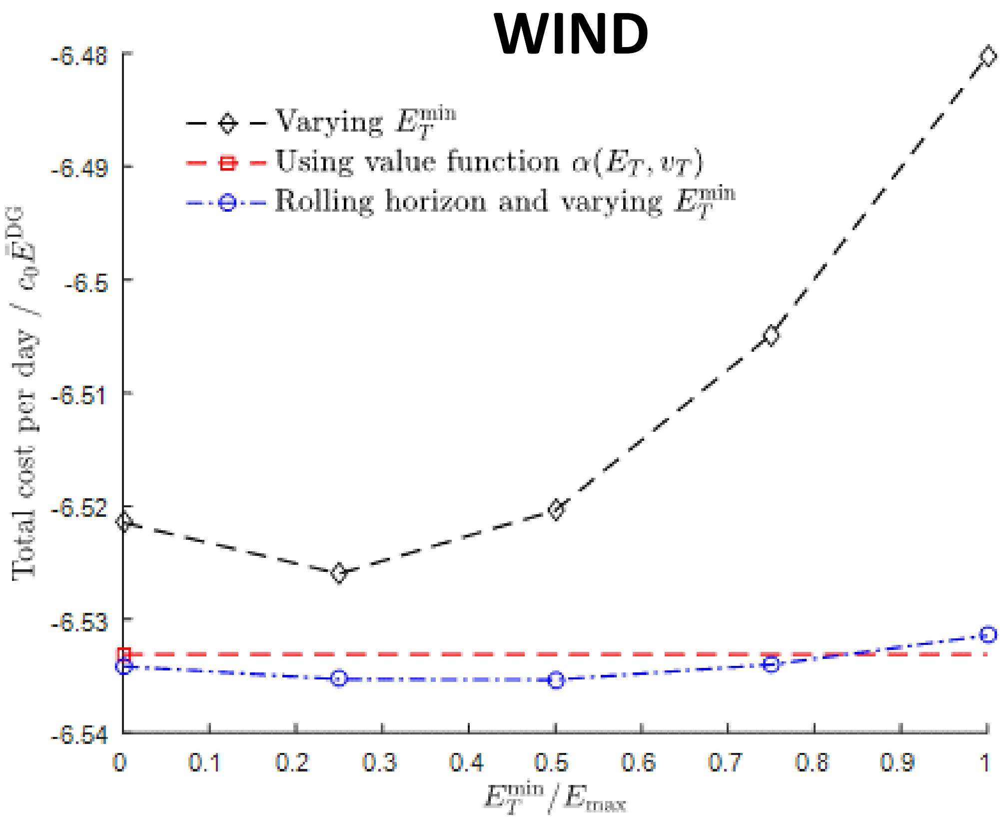

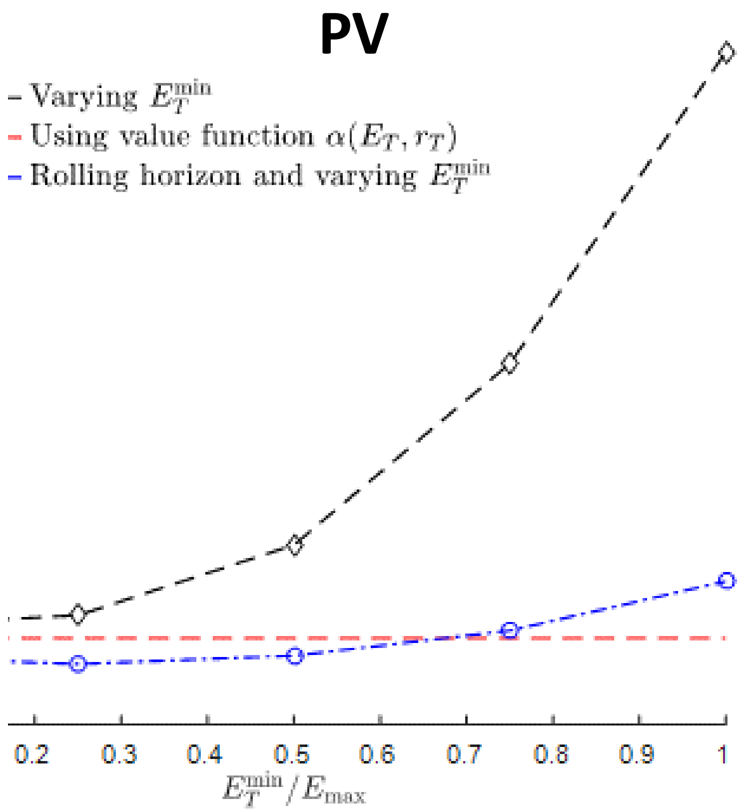

Sperstad, IB (SINTEF); Korpås, M (NTNU); *Energy Storage Scheduling in Distribution Systems Considering Wind and Photovoltaic Generation Uncertainties*. Energies, Vol. 12(7), 2019

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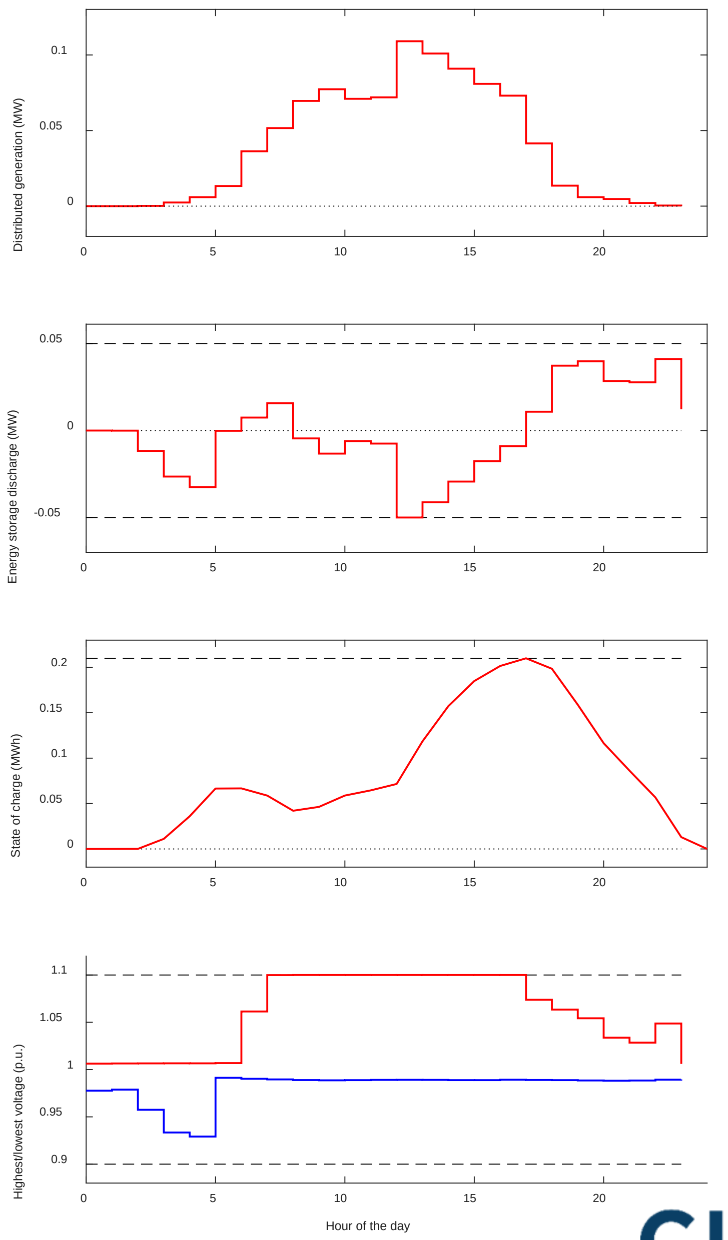
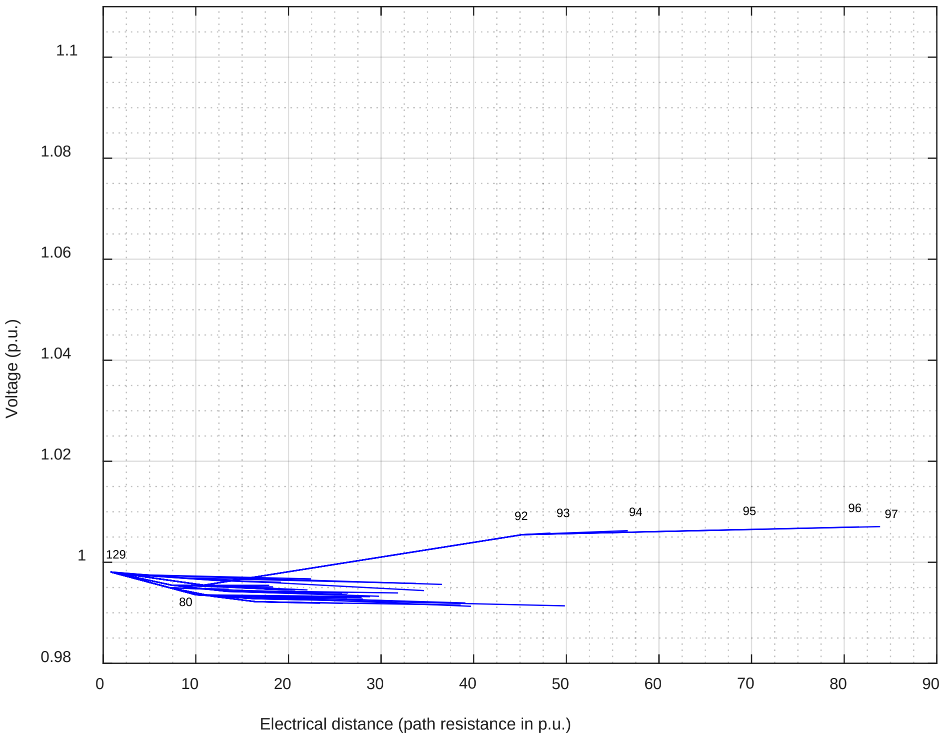
Results from DOPF

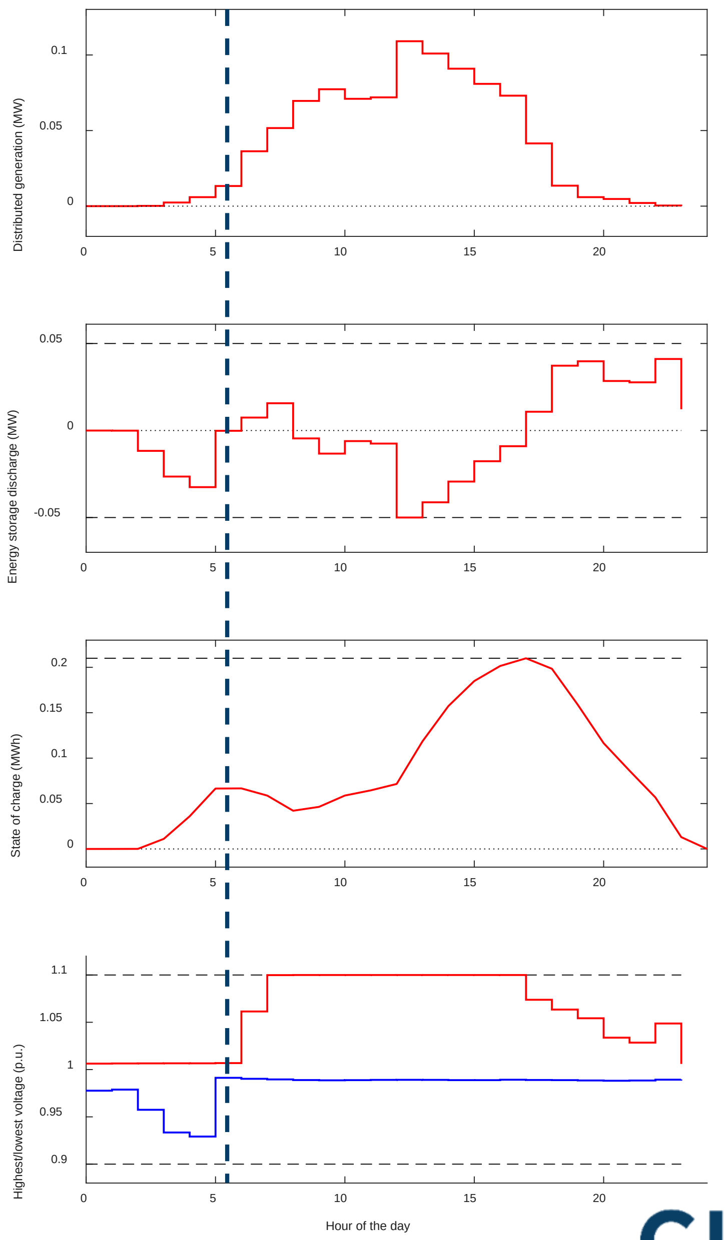


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 05.00–06.00:

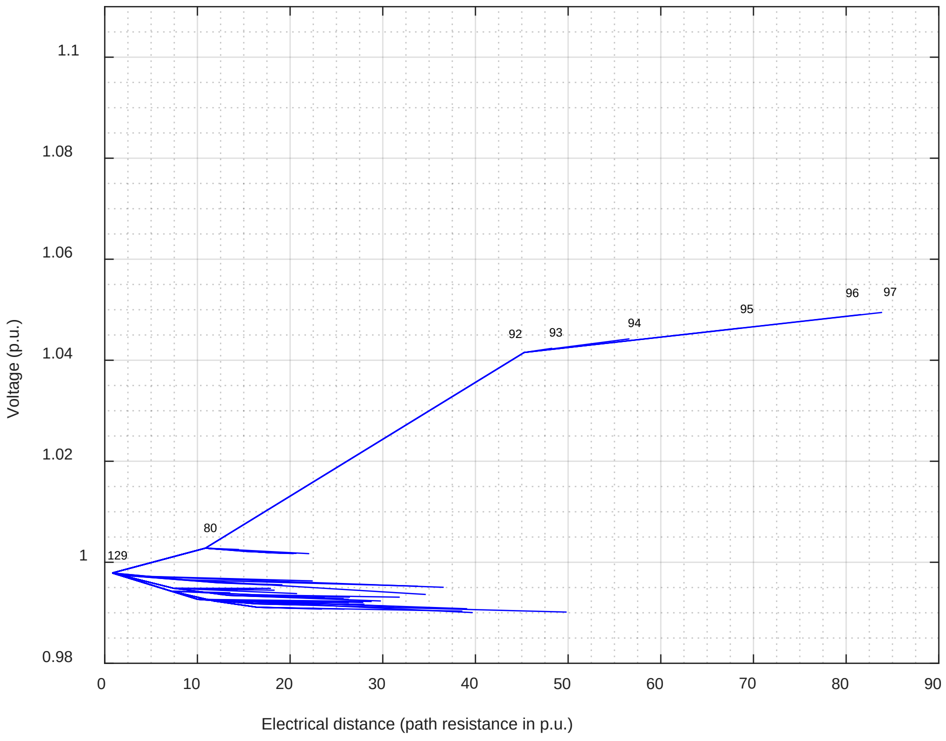


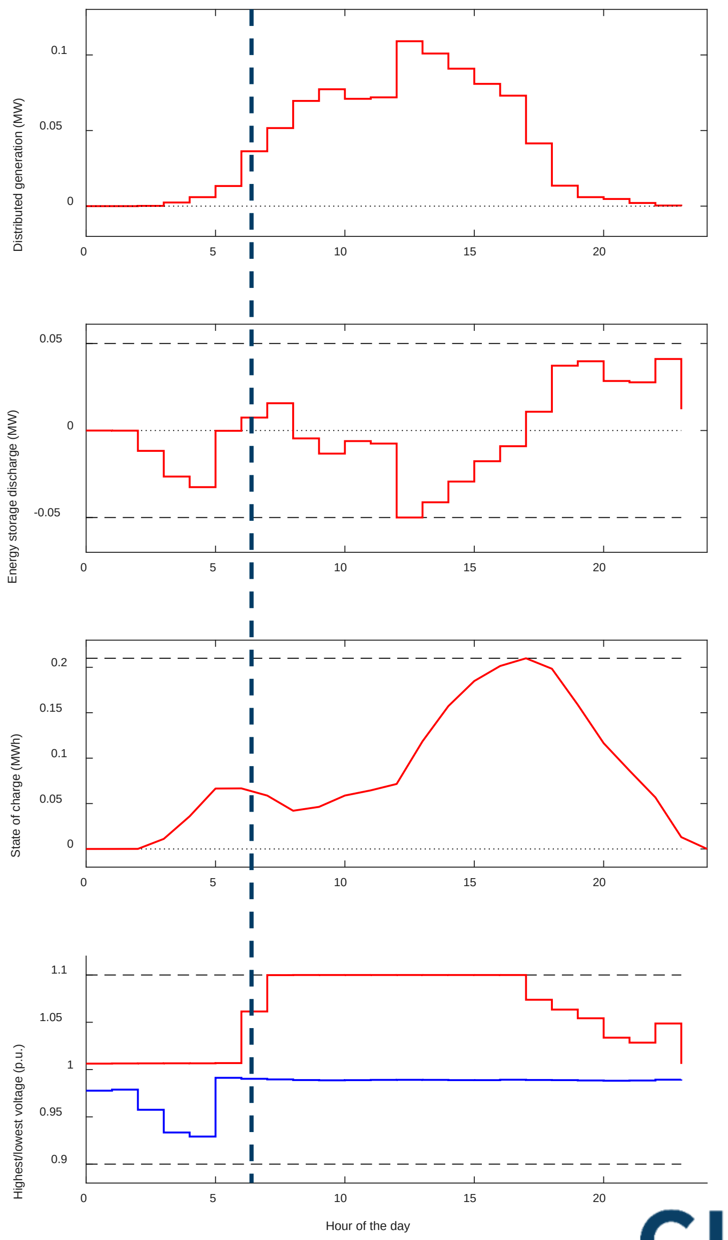


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 06.00–07.00:

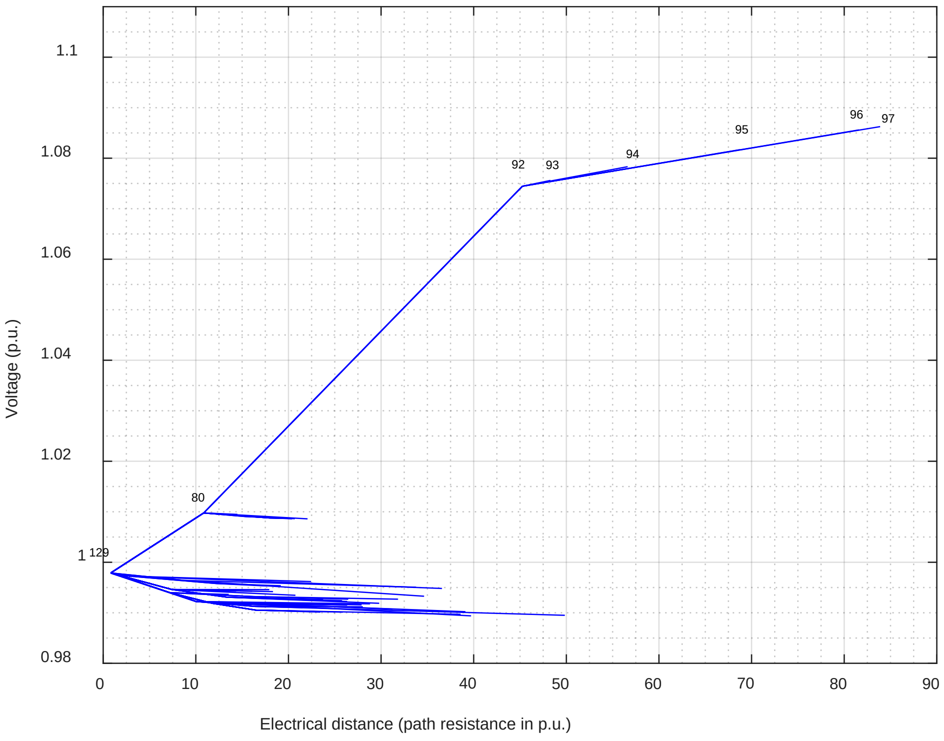


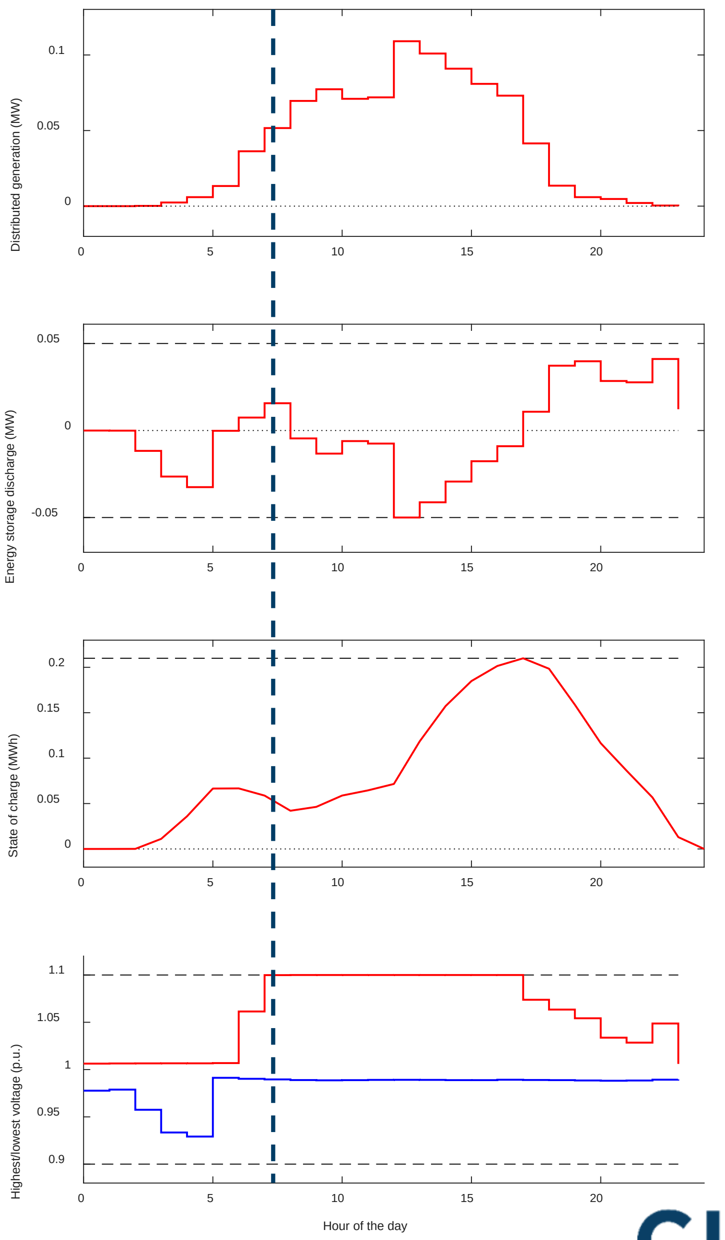


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 07.00–08.00:

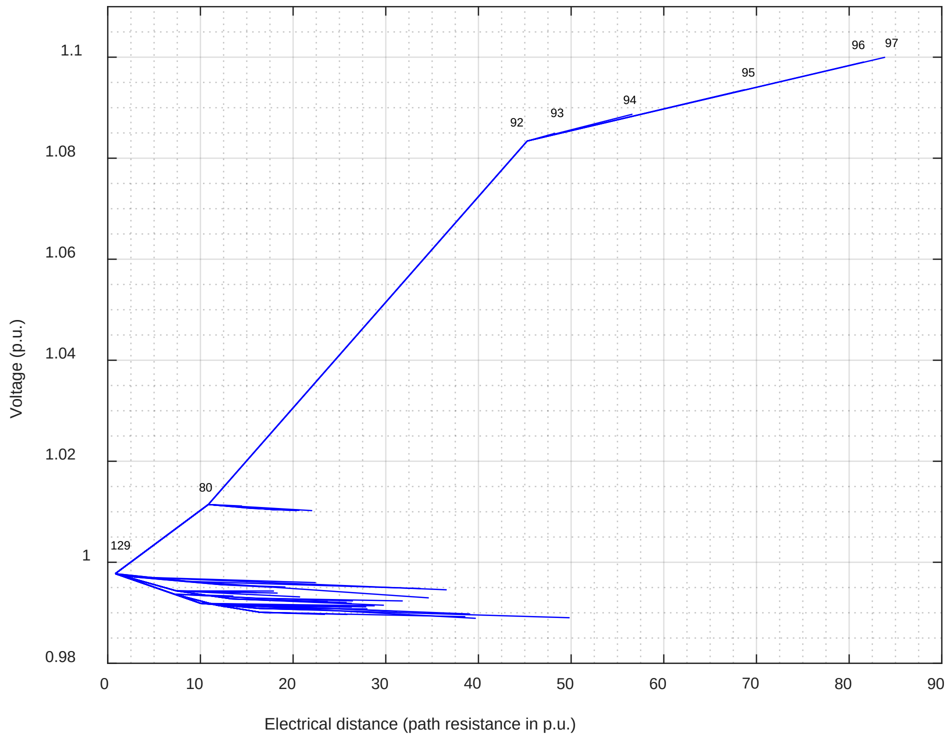


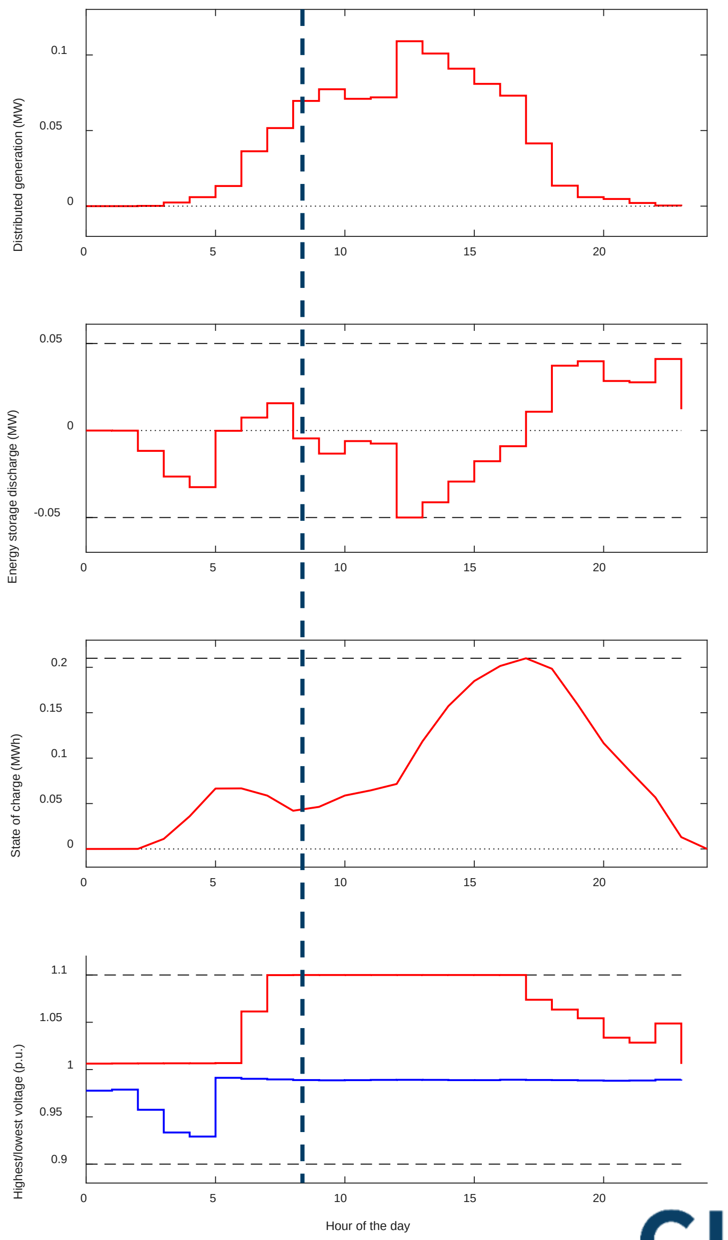


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 08.00–09.00:

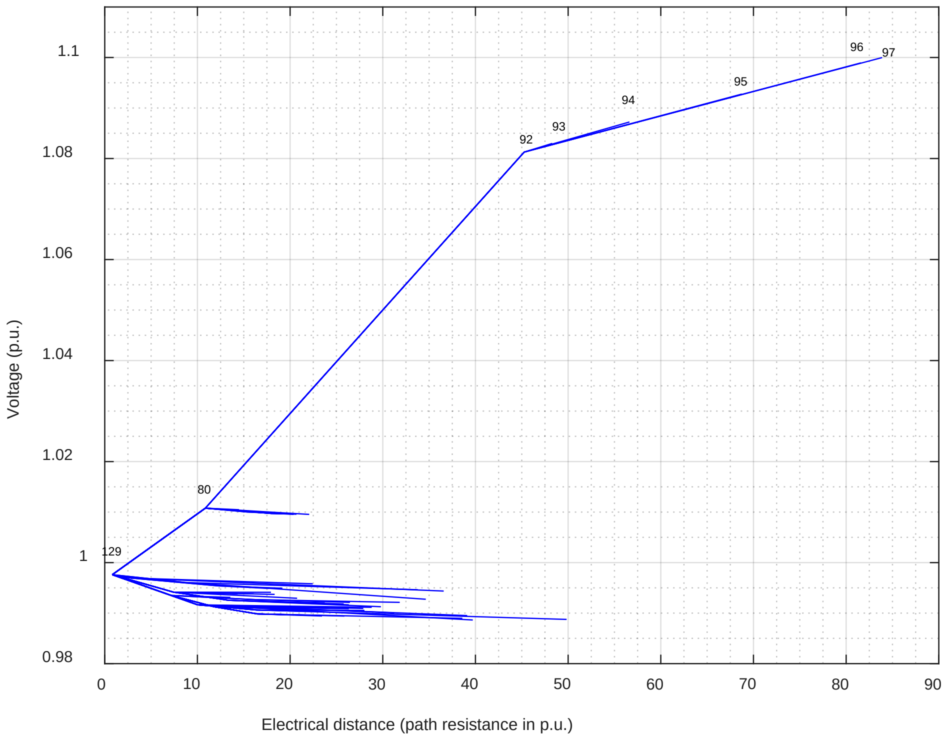


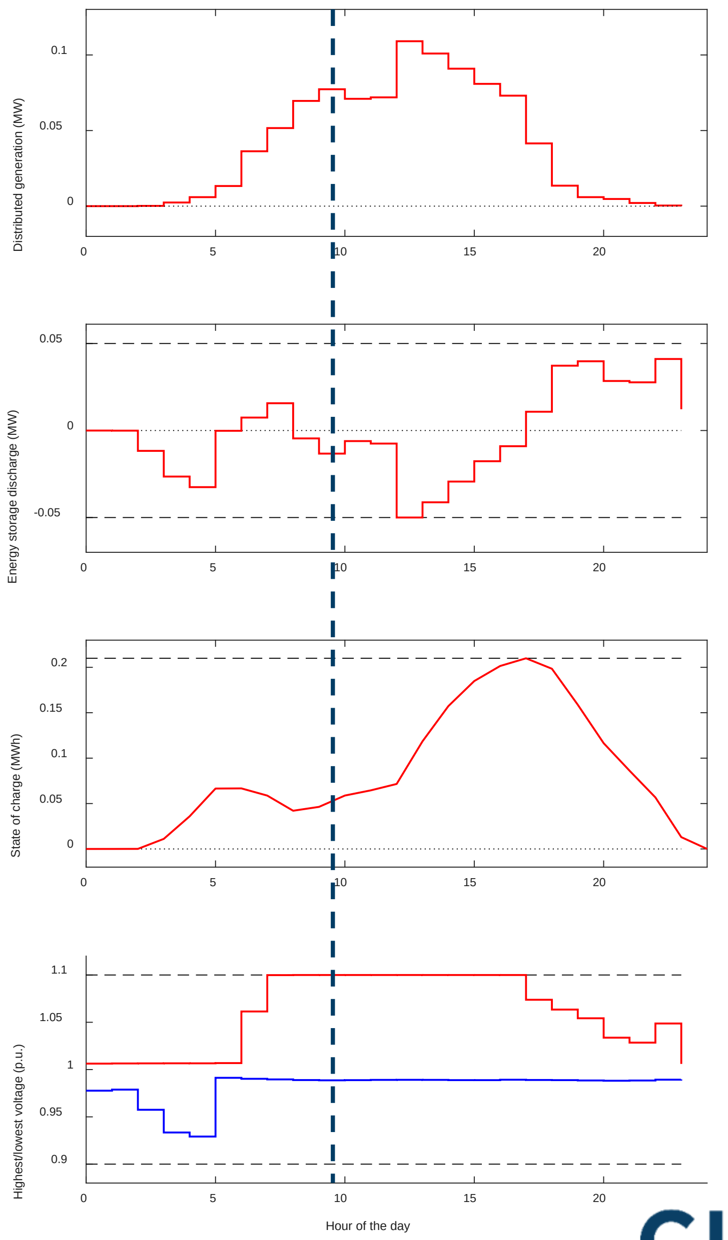


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 09.00–10.00:

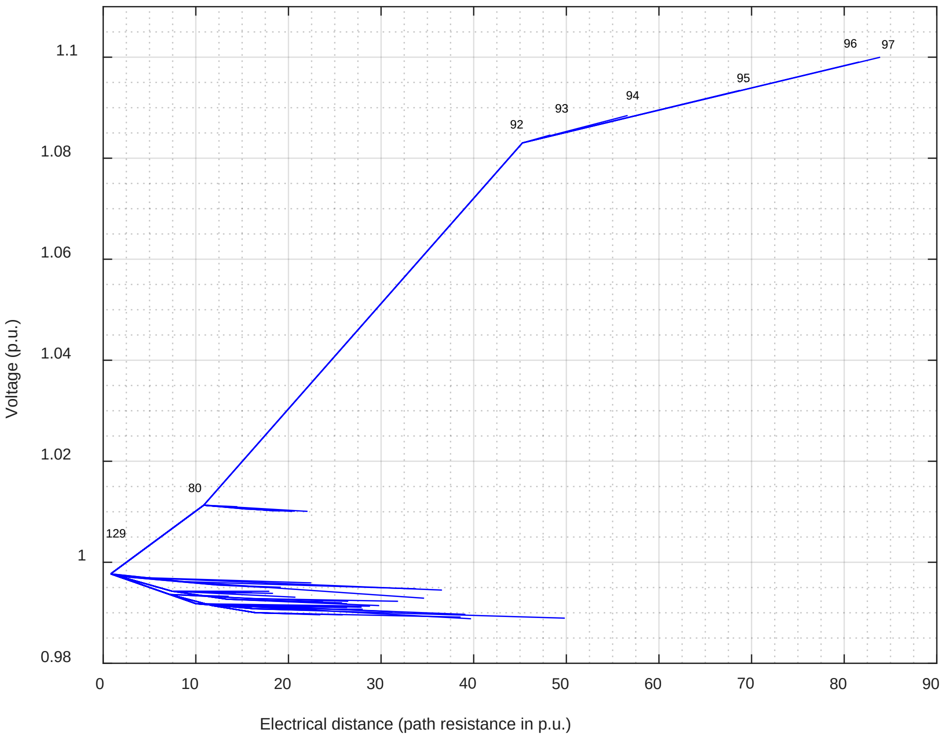


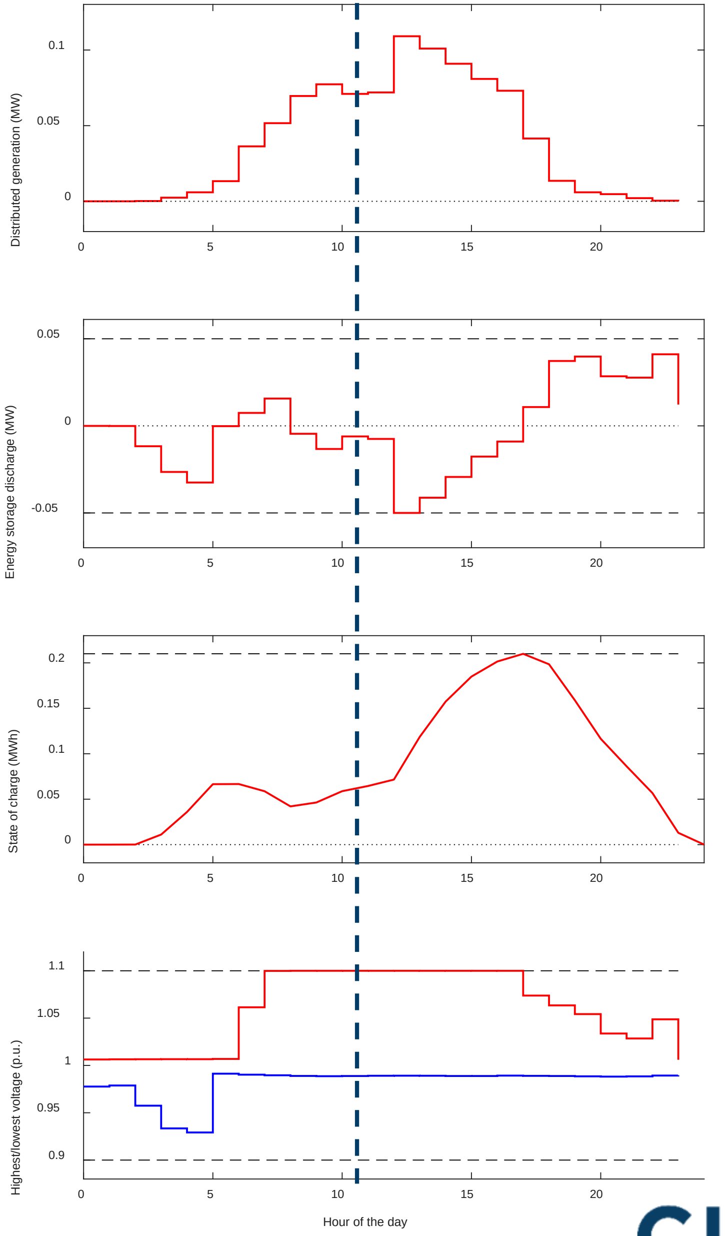


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 10.00–11.00:

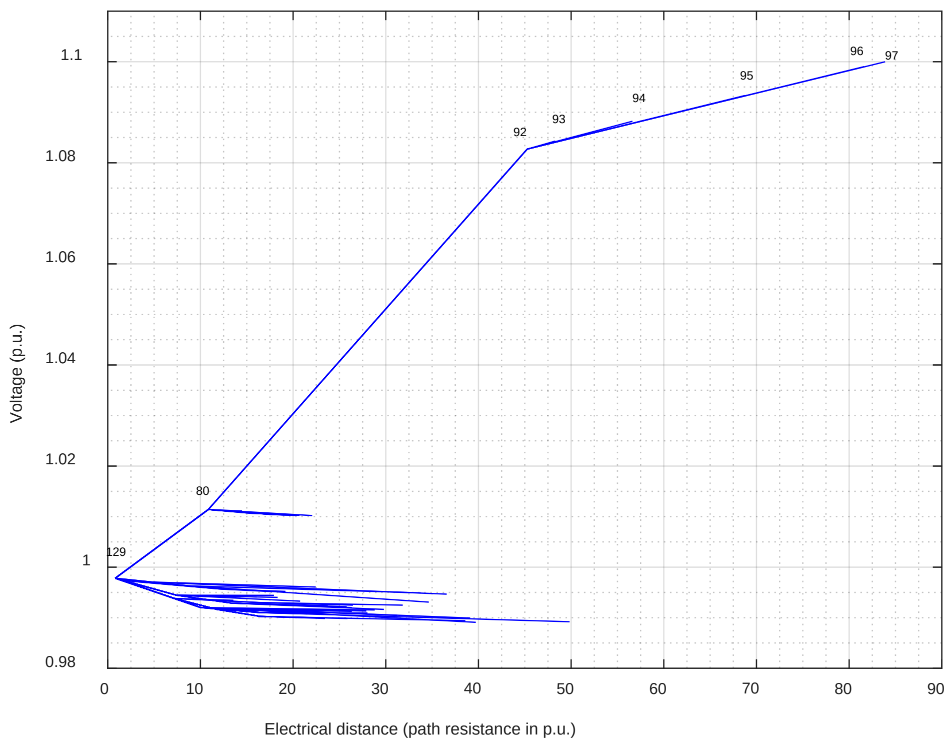


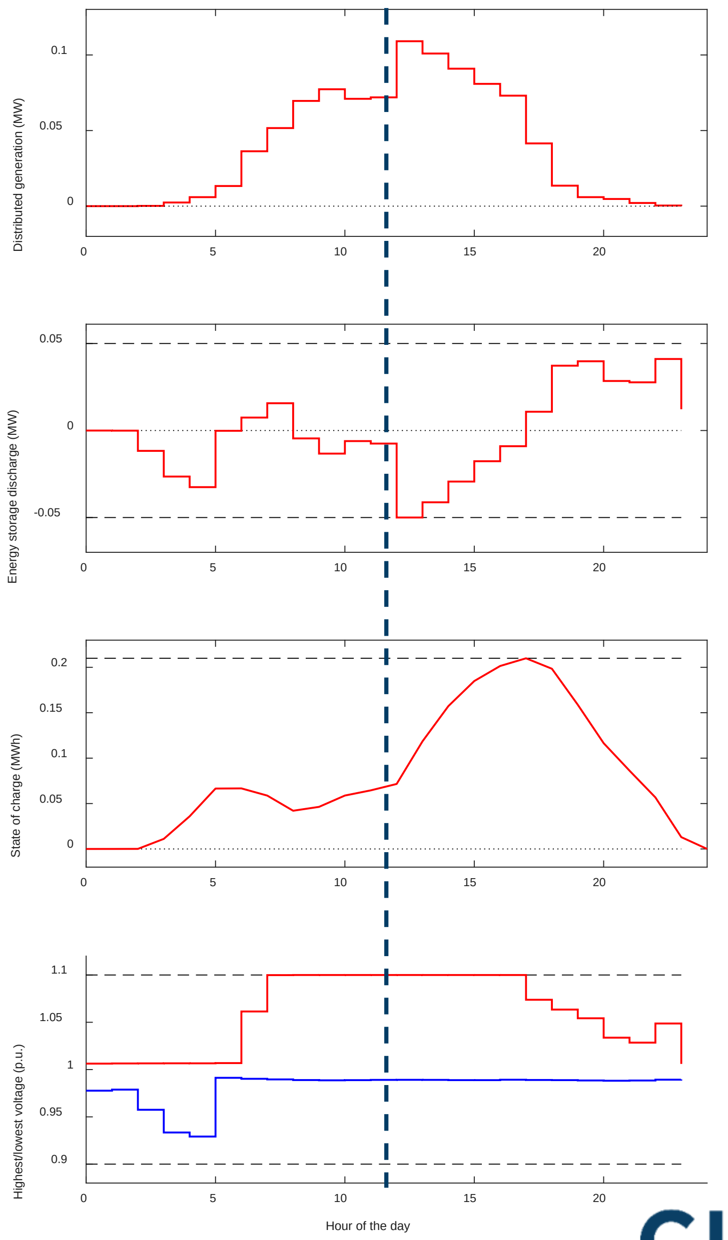


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 11.00–12.00:

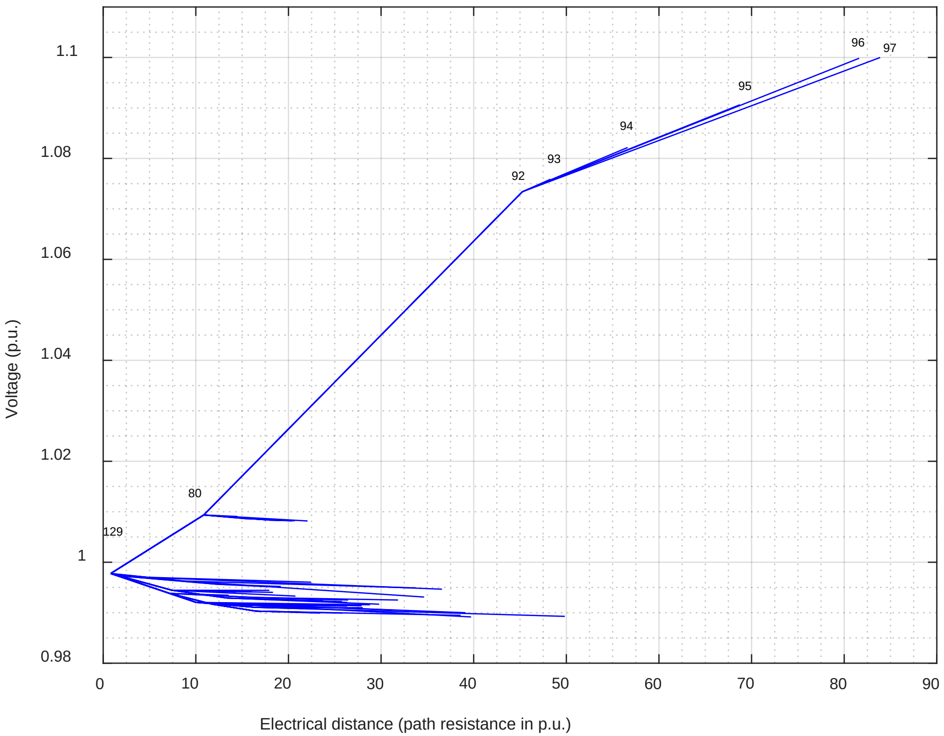


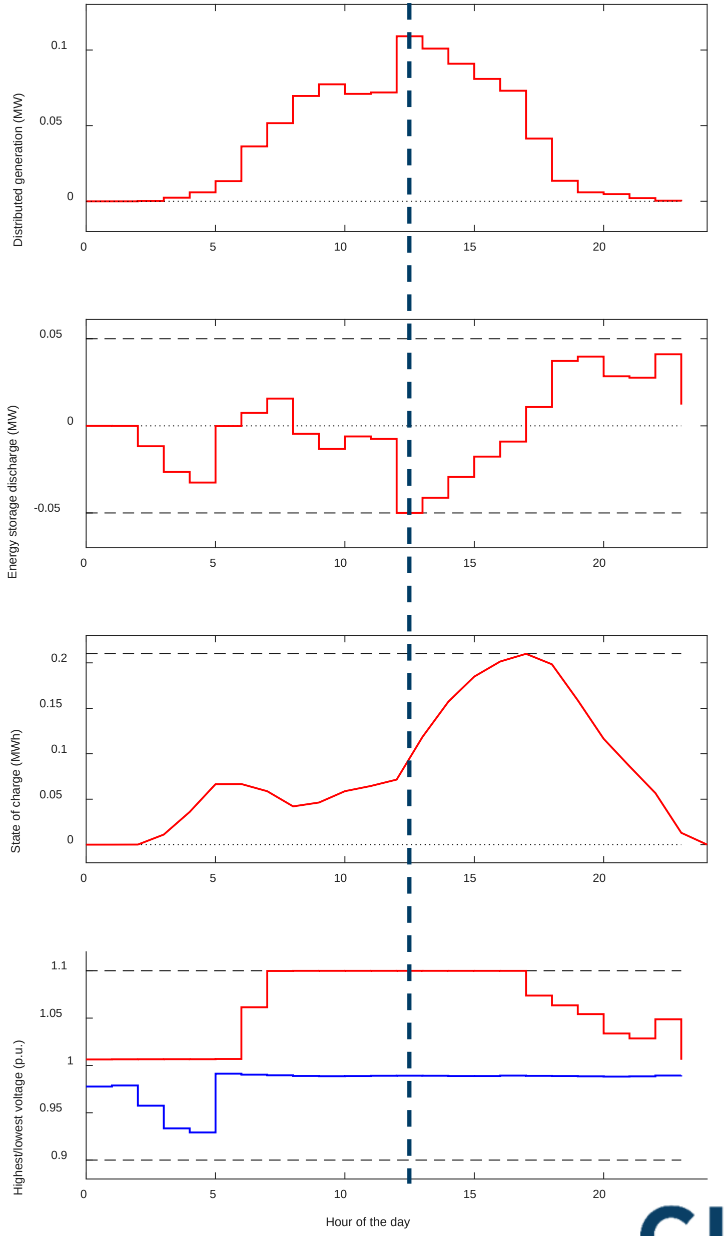


Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Results from DOPF

Kl. 12.00–13.00:





Sperstad, IB (SINTEF); Korpås, M (NTNU); Energies, Vol. 12(7), 2019

Incorporating energy storage in optimal power flow. Can we improve the computational speed?

Problem formulation

- Maximize the value of batteries, EV flex and V2G in grids with high amounts of wind and solar power

Approach

- Realistic grid representation by AC Optimal Power Flow
- Novel fast solution method tailor-made for non-linear ACOPF
- Not considered: Degradation, investments, uncertanty

Zaferanlouei, S; Farahmand, H; Korpås, M (NTNU); Ongoing work, 2019

Incorporating energy storage in optimal power flow. Can we improve the computational speed?

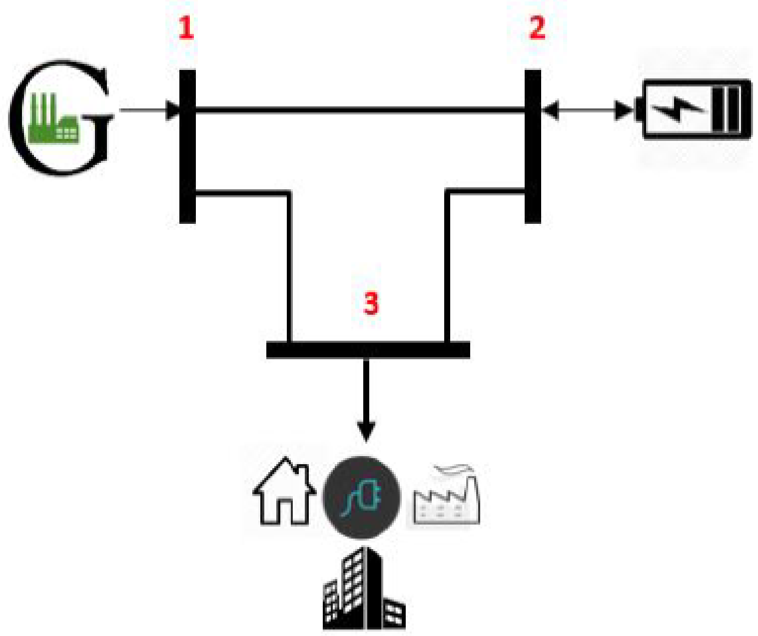


TABLE II. COMPUTATIONAL TIME FOR DIFFERENT SOLVERS AND WITH THE SAME CONVERGENCE CRITERIA

Implemented environment	Solver	Computational time (sec)
MATLAB	FMINCON	0.411
GAMS	CONOPT	0.408
GAMS	CONOPT4	0.592
GAMS	COUENNE	0.637
GAMS	IPOPT	0.538
GAMS	IPOPTH	0.517
GAMS	KNITRO	0.461
GAMS	MINOS	0.413
GAMS	PATHNLP	0.472
GAMS	SNOPT	0.385
MATLAB	The Proposed Method	0.056

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Zaferanlouei, S; Farahmand, H; Korpås, M (NTNU); Ongoing work, 2019

Lessons learned: Where are the benefits of storage?

- For prosumers, V2G seems more attractive than stationary storage
  - Grid tariffs must reflect the value/cost for grid owner. Not straightforward
- Cycling degradation limits the attractiveness of price arbitrage
- Better to exploit other opportunities such as
  1) TSO Frequency control: Causes only small variations in storage levels)
  2) DSO Grid deferral: Only needed in peak hours. Can therefore be combined with 1)
- Supercharging stations, heavy-duty vehicles and E-ferries are challenging for the grid operator
  - The economic (and environmental) consequences of using stationary batteries to compensate vehicle charing must be better understood
  - What flexibility can large vehicles and ferries offers when they are not in use?

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Lessons learned: How do we analyse the benefits of mobile and stationary storage in the grid?

- Storage and EV flexibility is not straightforward to analyse
- Tempting to use ad-hoc methods and assumptions
- Simulations show that such simplifications can give misleading results, e.g. lack of degradation modelling, lack of grid details
  - Further modelling improvement is acheived by proof-of –concepts in Lab and Demos
- Theoretical «correct» methods for grid analysis with storage can become untractable for computers for on-line operation
  - Reformulation of the mathemathical problem can improve speed A LOT!
  - Potentially very attractive for software used by storage operators, aggregators and grid operators

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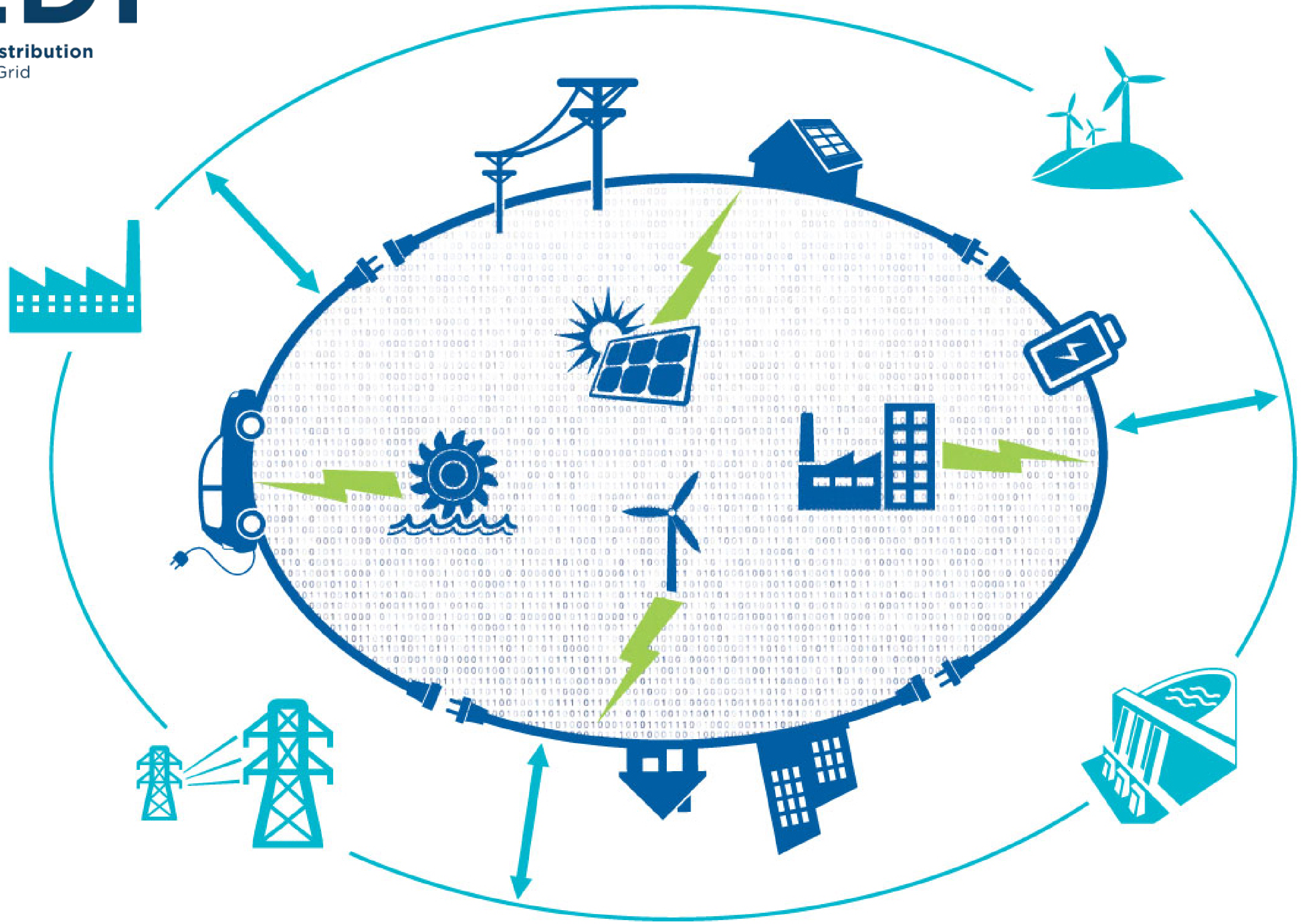
- to empower the future Smart Grid



This work is funded by CINELDI - Centre for intelligent electricity distribution, an 8 year Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research, 257626/E20). The authors gratefully acknowledge the financial support from the Research Council of Norway and the CINELDI partners.

without degradation cost