SummerSoc
Service Oriented Computing

June 17-23, 2019
Crete, Greece

Open Challenges in Modern Energy Systems

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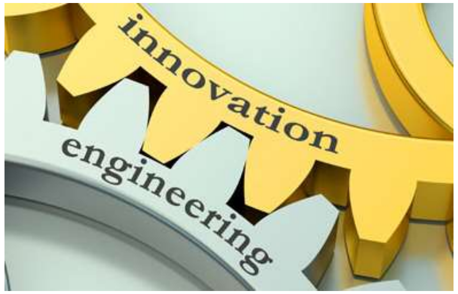
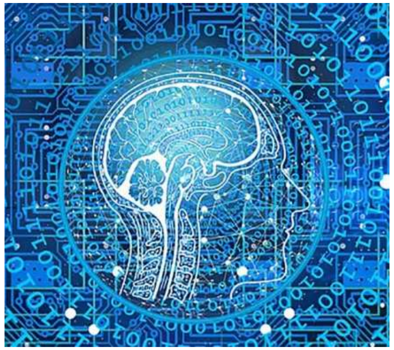
- A non-exhaustive overview

- Bridging a gap between Service Oriented Computing and real needs of researchers and engineers

Many problems
and naïf solutions

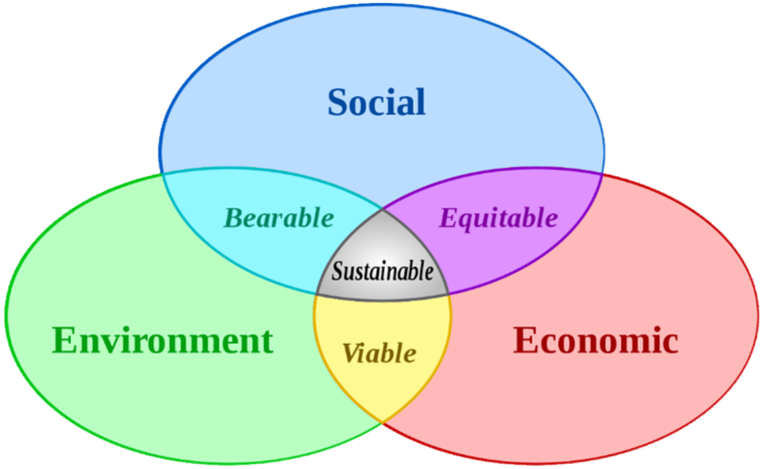


Computational skills,
looking for applications
and new challenges



Our new mantras:

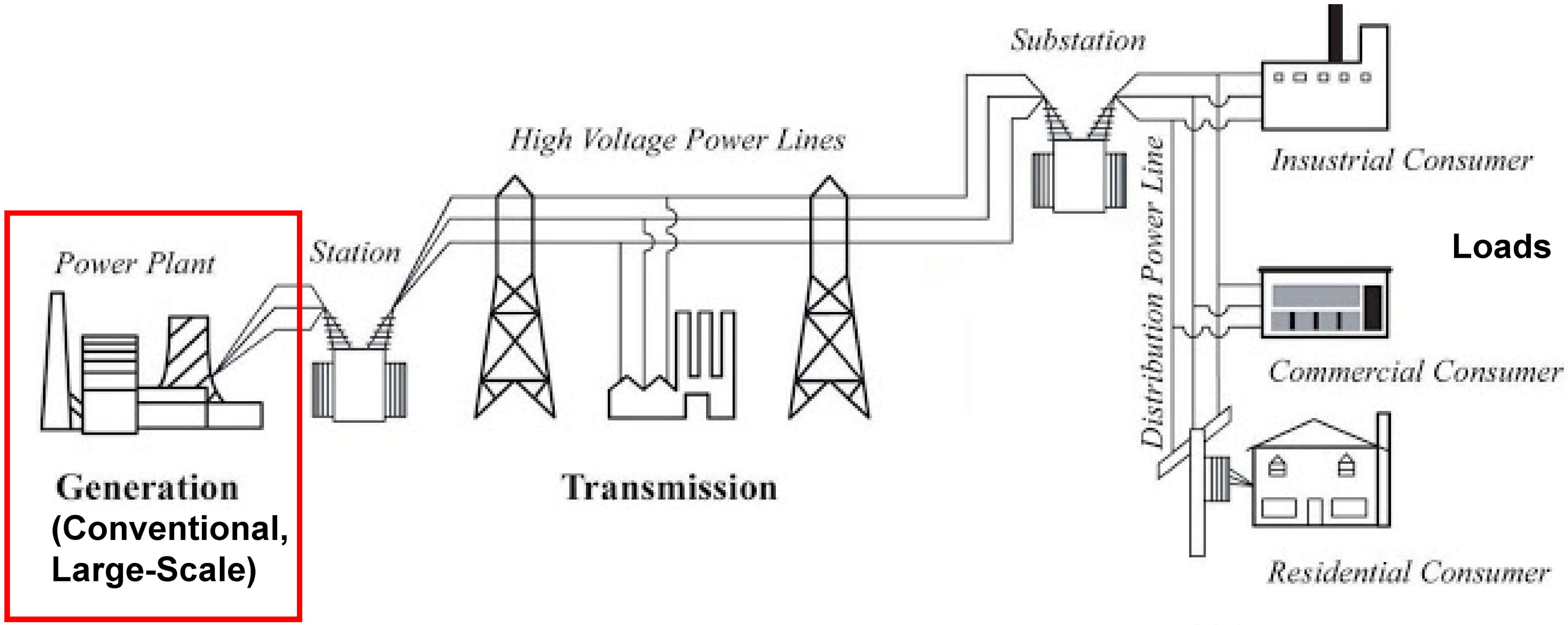
- **Sustainability**
- Electricity for **everybody**
- Use better what you have: **optimize**!
- **Distributed** resources and intelligence
- ….



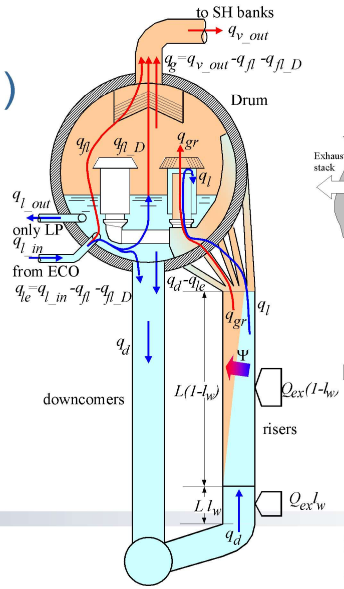
A short review of calculation/optimization problems in modern power systems:

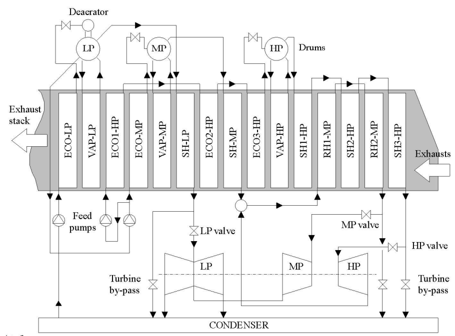
- "**classical**" problems → reducing computational time
  from off-line to real-time, from steady-state to dynamic
  system extension & complexity: adequacy of algorithms?
  from deterministic to probabilistic
  higher Quality of Supply
  multi-objective optimization

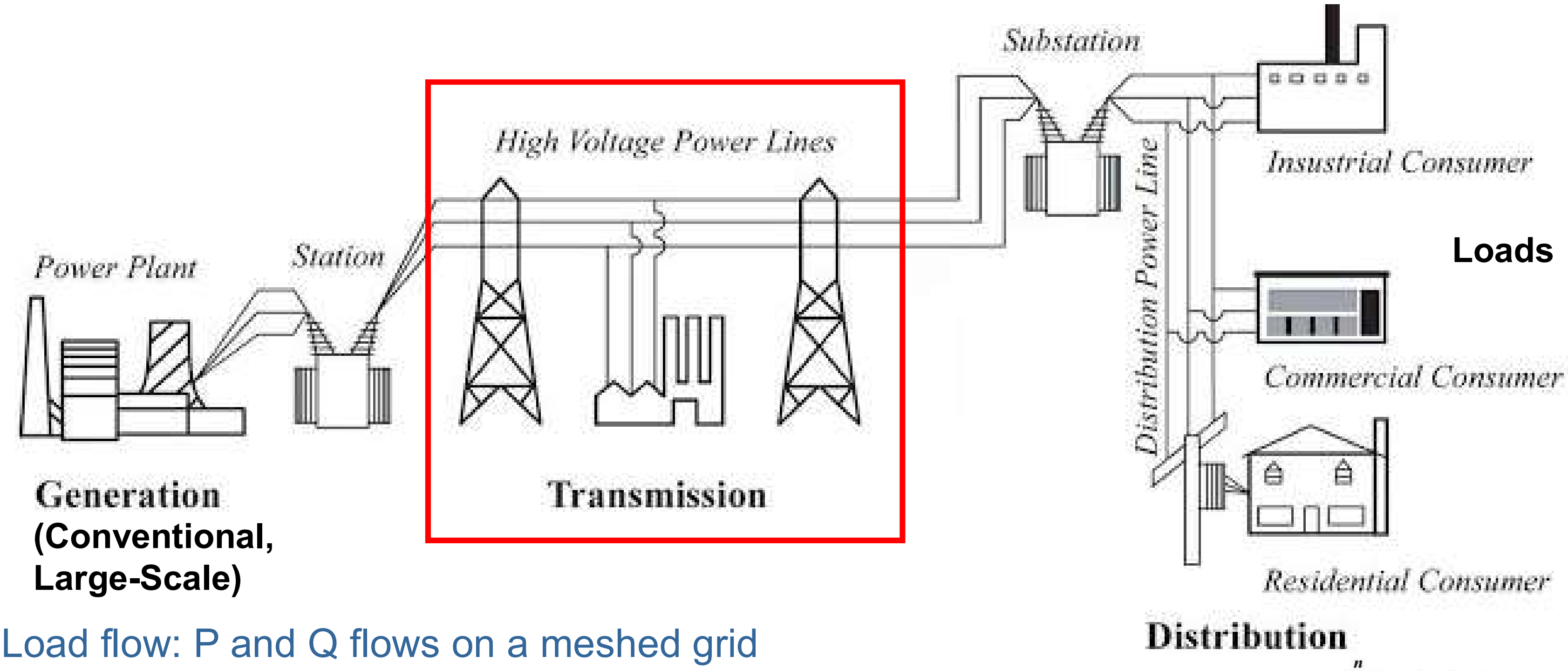
- "**new**" challenges → integrating **non-programmable RES** (up to 100%?)
  rural electrification of developing countries: **new models**?
  from centralized approach to P2P
  CO_2-free economy ↔ increase of energy demand, ….



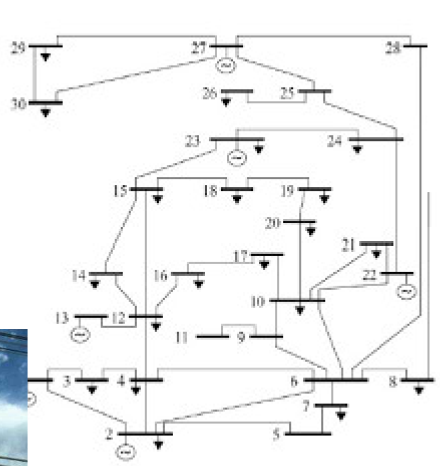
- Thermodynamics (cycles, 3D models of components, …)
- Emissions (NO_x, SO_x, GHG,…)
- Energy efficiency, reliability and availability
- Control systems (prime mover and exciter), stability
- Flexibility (technical min, ramp [MW/min], startup, …)
- Black-startup capability
- ….







- Load flow: P and Q flows on a meshed grid
- Optimal Power Flow
- Dynamic Thermal Rating of overhead lines
- New conductors (HTLS, IG cables…)
- Flexible AC Transmission Systems
- Magnetic and visual impact, maintenance
- …



$$P_i = \sum_{k=1}^{n} |Y_{3i}||V_i||V_k| \cos(\theta_i - \theta_k - \gamma_{ik})$$

$$Q_i = \sum_{k=1}^{n} |Y_{3i}||V_3||V_i| \sin(\theta_i - \theta_k - \gamma_{ik})$$

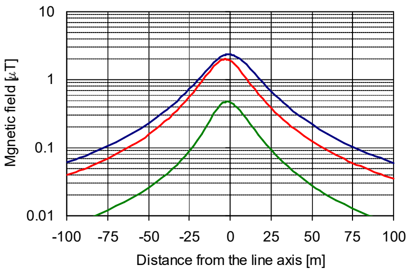
P, Q, V, θ *i=1..n*

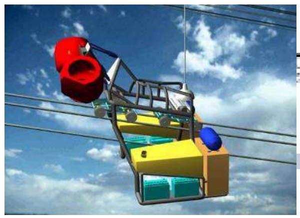
n= many thousands

Newton-Raphson

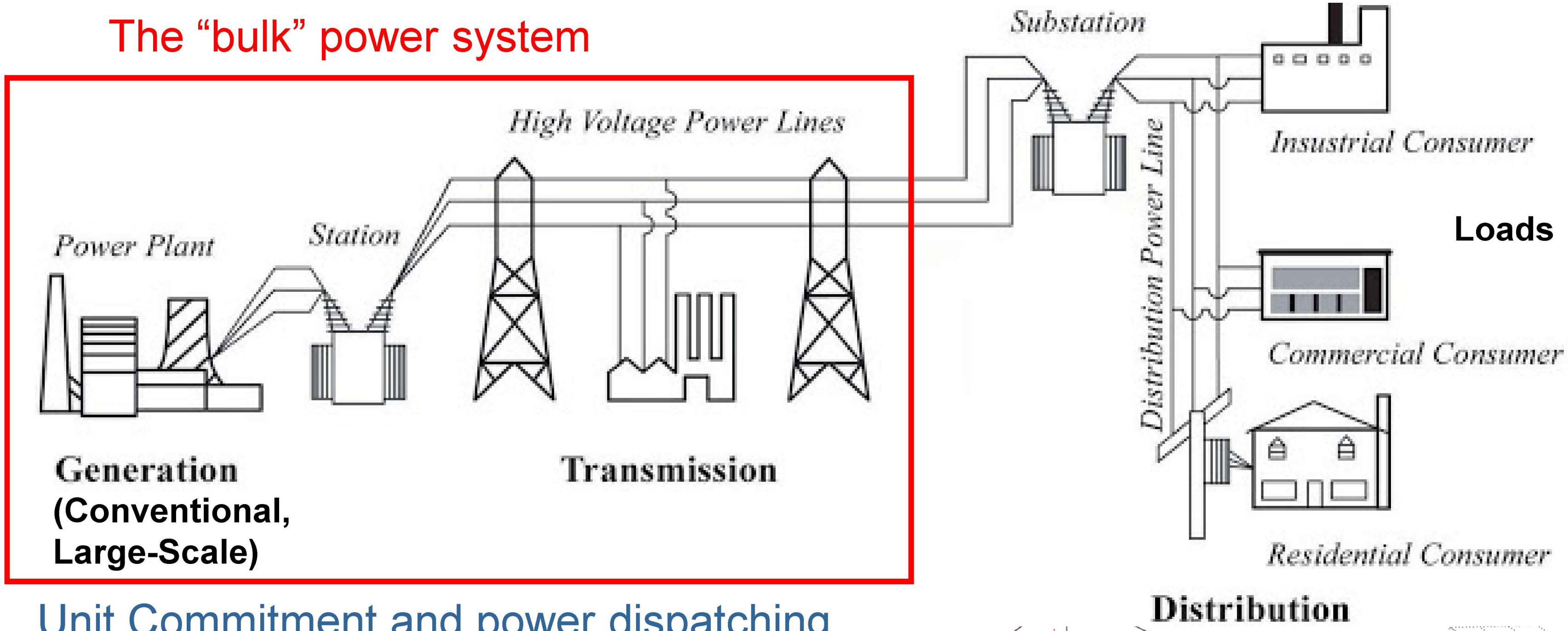
Gauss-Seidel

Stott FDLF

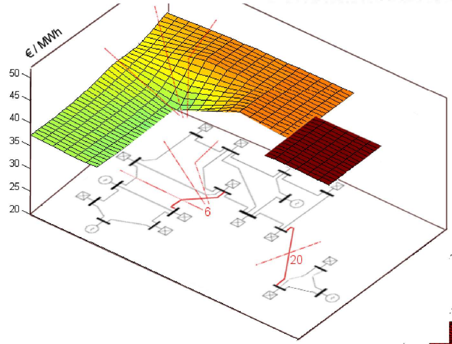


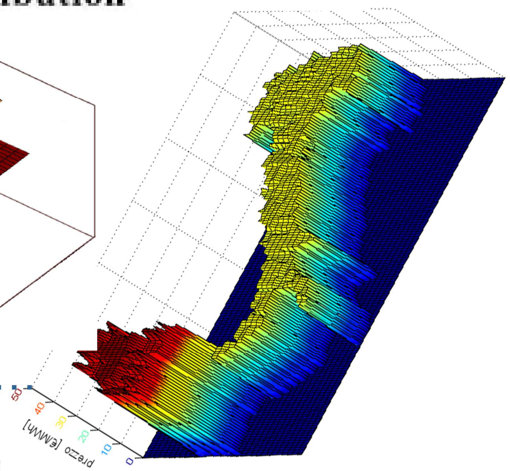


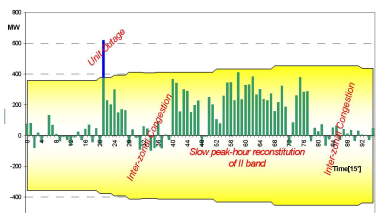
The “bulk” power system

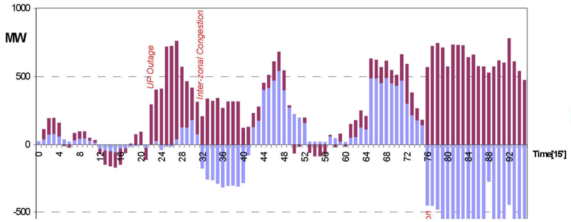


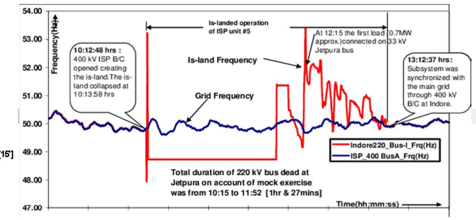
- Unit Commitment and power dispatching
  - Minimum (fuel) cost: vertically-integrated systems
  - *(Minimum transmission losses)*
  - Max social wellness (demand/supply): the market
- Electricity pricing (nodal, zonal, LMP, ..)
- Optimal size and use of generation reserve
- Simulation and tuning of emergency procedures, black-start, ...



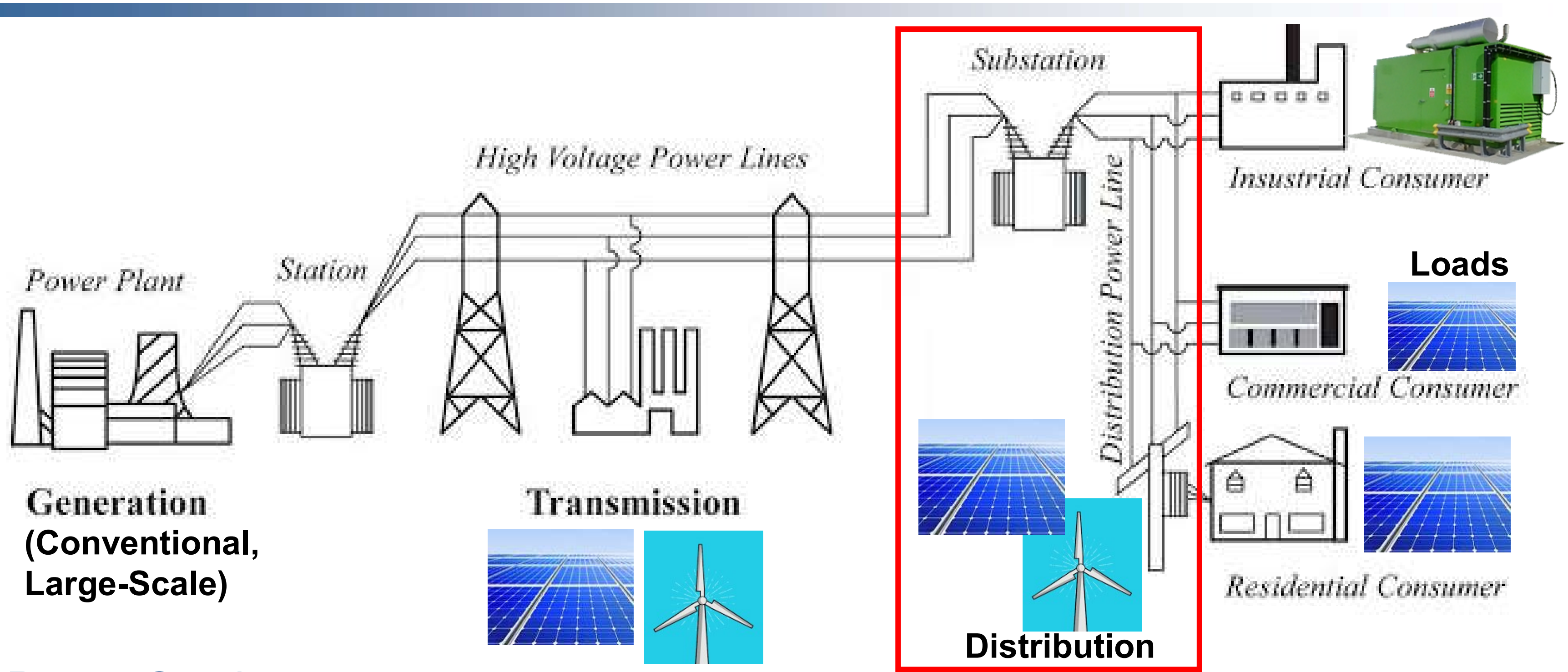






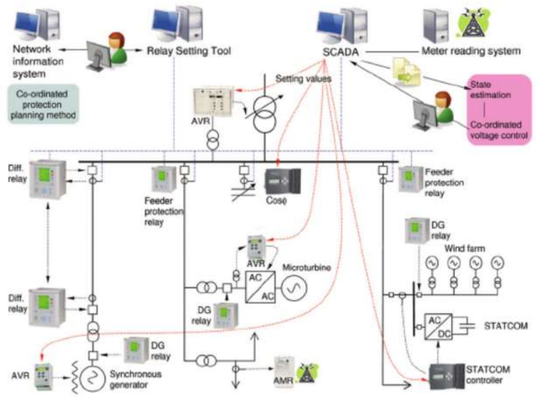


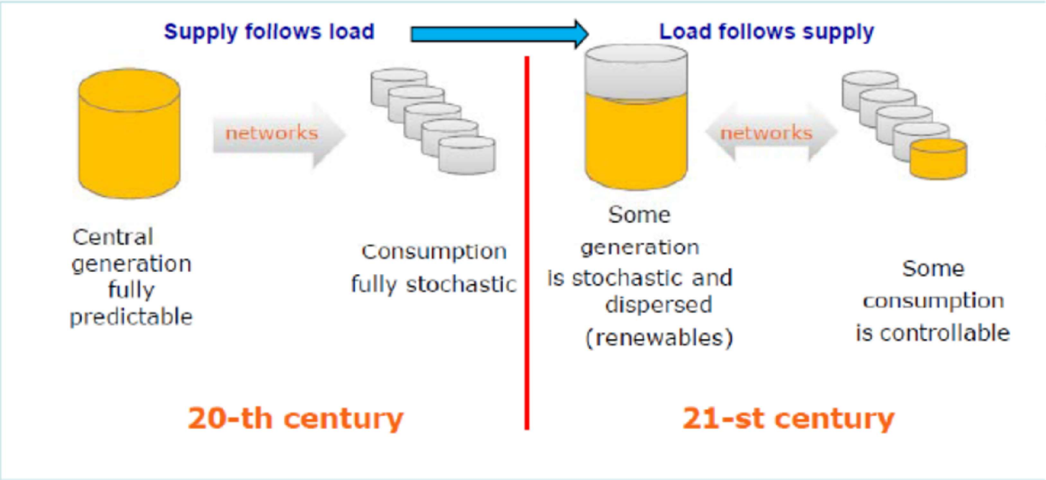
SummerSoC Service Oriented Computing

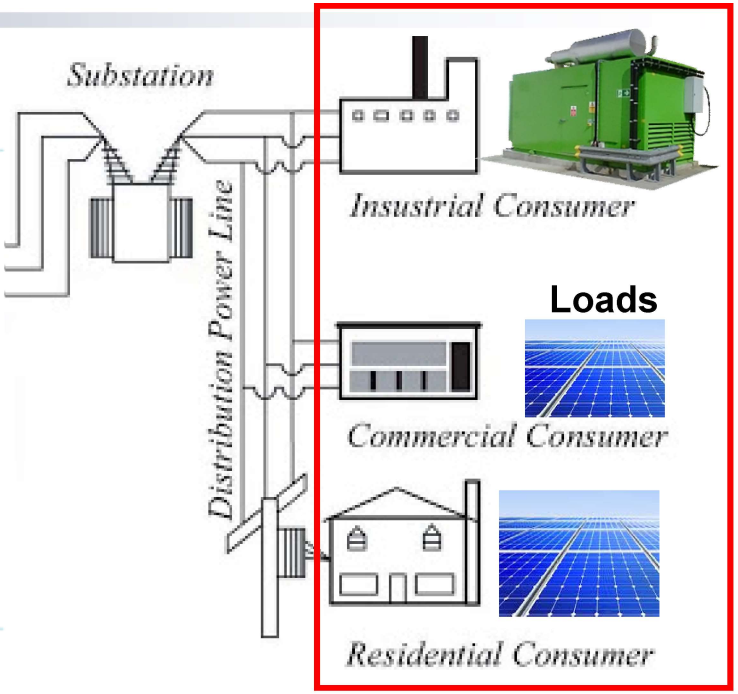


- Power Quality:
  - Continuity of supply
  - Voltage quality: |V|, symmetry, dips, swell, harmonics, …
- Meshed topologies; ICT → remote monitoring and control, ..
- <u>**Active distribution networks**</u> → from D.N.O. to D.S.O.
  - Distributed Generation (DG)
  - Renewable Energy Sources: Hosting Capacity, V and f control, …

    → **BULK power system** (large-scale RES, balancing, observability, dispatching, …)

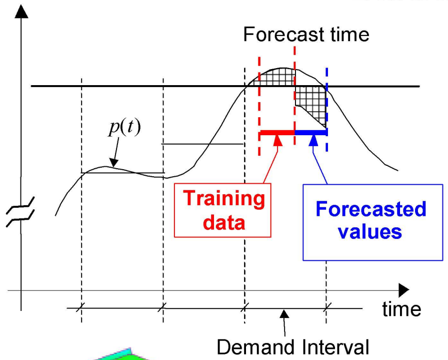


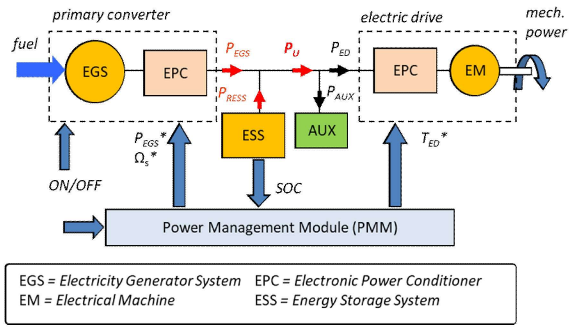


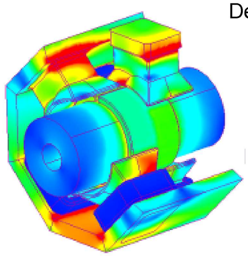


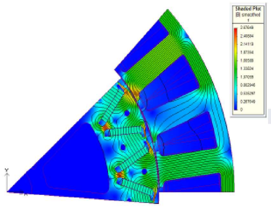
Distribution

- Forecasting techniques
- Demand Response and flexibilities
- Contribution to ancillary services
- Energy saving and novel machines
- New users: EVs, heat pumps
- Optimal operation of prosumers
- Tariff schemes, …

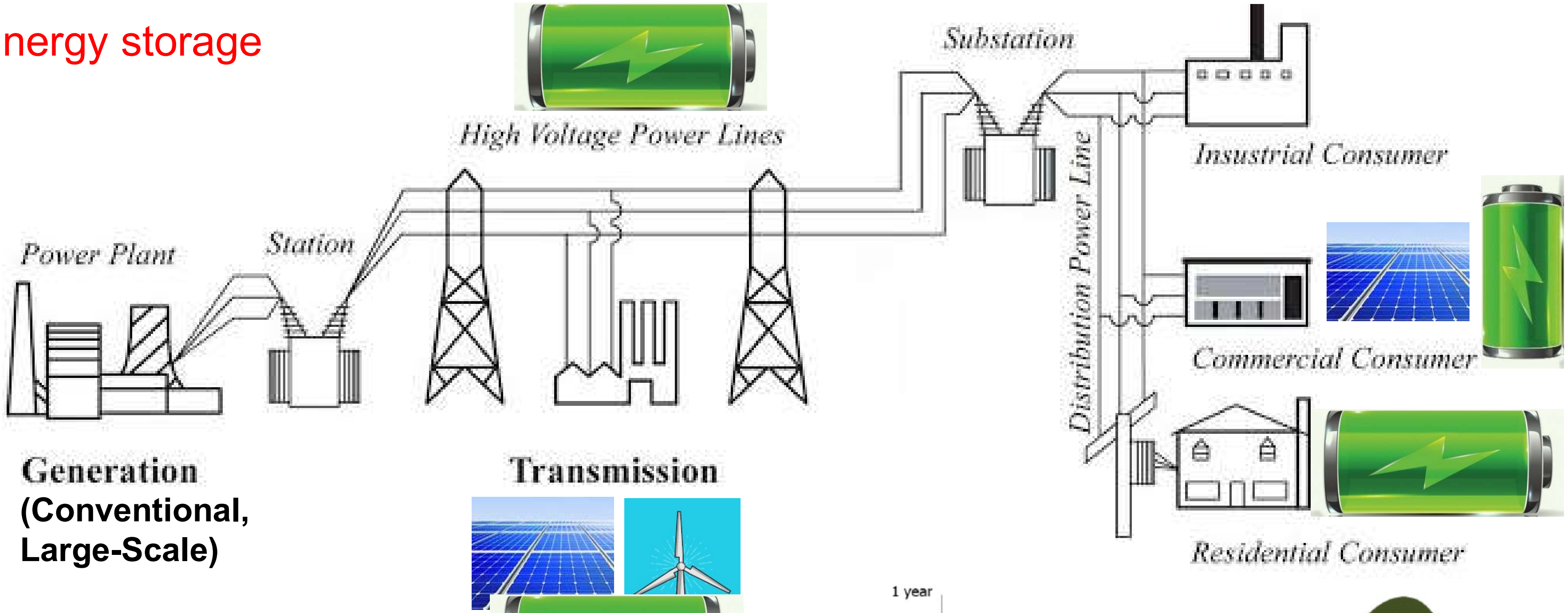




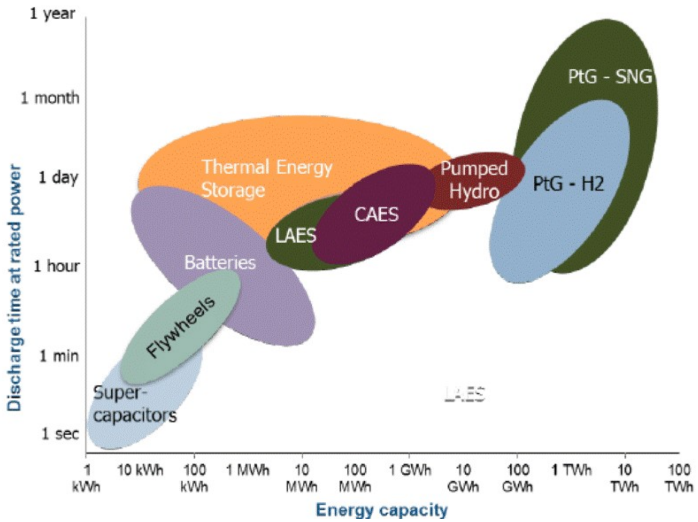


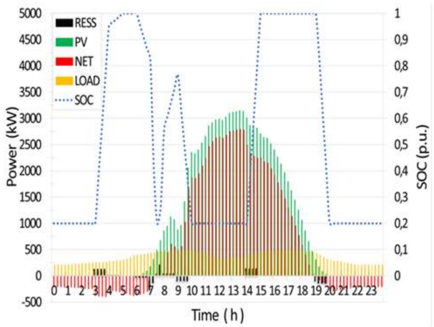


Energy storage



- Functions (predictability, congestions, flexibility) ↔ position
- Optimal technology (E/P) for each function
- Optimal sizing and siting
- Optimal operation





A short bibliography suggested to approach some of these topics:

V.Telukunta, J. Pradhan, A. Agrawal, M. Singh, S. Garudachar Srivani, "Protection Challenges Under Bulk Penetration of Renewable Energy Resources in Power Systems: A Review", CSEE Journal of Power And Energy Systems, Vol. 3, No. 4, December 2017.

S. K. Khaitan, J. D. McCalley, "Cyber physical system approach for design of power grids: A survey", 2013 IEEE Power & Energy Society General Meeting, 21-25 July 2013, Vancouver.

C. Sun, Z. Mi, H. Ren, J. Lu, Q. Chen, D. Watts, L. Zhang, "Sustainability evaluation in power system related applications — A review", 2016 IEEE International Conference on Power System Technology (POWERCON), 28 Sept.-1 Oct. 2016, Wollongong, NSW, Australia.

G. Bedi, G. K. Venayagamoorthy, R. Singh, R. R. Brooks, "Review of Internet of Things (IoT) in Electric Power and Energy Systems", IEEE Internet of Things Journal, Vol. 5, No. 2, April 2018.

A. Keane, L.F. Ochoa, C. L. T. Borges, G. W. Ault, A. D. Alarcon-Rodriguez, "State-of-the-Art Techniques and Challenges Ahead for Distributed Generation Planning and Optimization", IEEE Transactions on Power Systems, Vol. 28, Issue 2, May 2013.

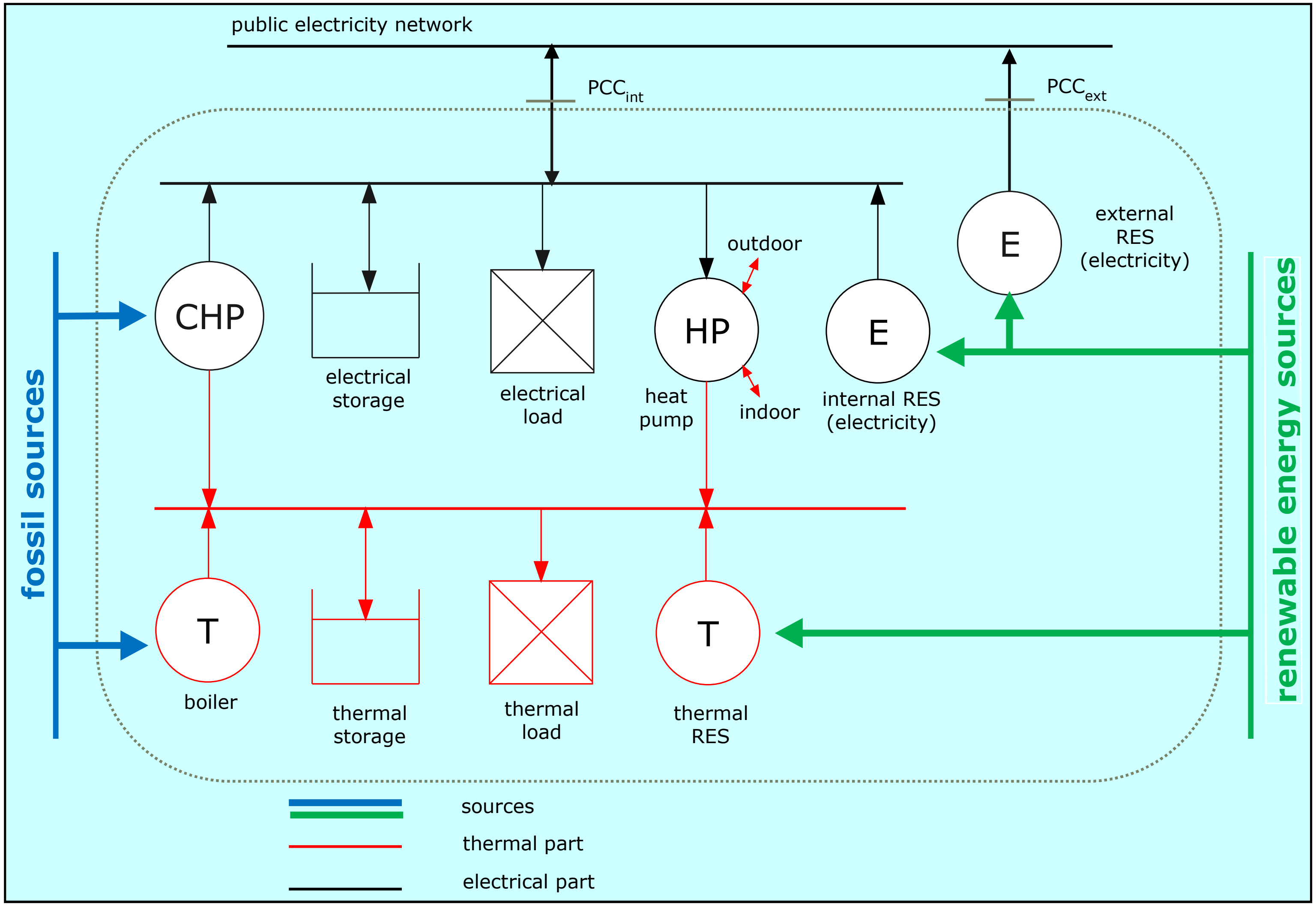
J. H. Kehler, M. Hu, "View All Authors Planning and operational considerations for power system flexibility", 2011 IEEE Power and Energy Society General Meeting, 24-29 July 2011, San Diego, USA.

P. Chen, Z. Chen, B. Bak-Jensen, "Probabilistic load flow: A review", 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 6-9 April 2008, Nanjing, China.

(BOOK) Siddhartha Kumar Khaitan, Anshul Gupta, "**High Performance Computing in Power and Energy Systems**", Springer, 2013, ISBN 978-3-642-32683-7.

More on https://ieeexplore.ieee.org/Xplore/home.jsp

Optimization of complex hybrid prosumers (or Virtual Power Plants)



Optimal operation

"Optimal" use of available *energy storage devices* and of *dispatchable resources*.

Technical and **economical** perspective:

- technical constraints (capab. of components; *expected* RES(t) and load(t))
- economical targets (objective function: min costs or max revenues)

a.Real-time priority rules: load following, battery charging, electrical following, thermal following…

b.Optimal scheduling (hours before; day-ahead+infra-daily corrections)
Unit Commitment + Dispatching

?

Mixed-Integer Linear Programming
(only with piecewise linear efficiency curves, non-quadratic power terms)

Non-linear models (ex. power losses RI^2 or variable round-trip efficiences)

Multi-objective functions? (+Reliability, +CO_2, +RES/ICE, …)

?

Optimization under **uncertainties** (load(t), RES(t), outages)

?

Deterministic + sensitivity
Analytical probabilistic methods (combinatorics, convolutions, …)
Monte Carlo simulations (need of PDF)
(cycles of scheduling/real-time)
Stochastic optimization, …

Which time horizon?
Load-RES periodicity is year, season, week, day? typical-day approach? (but edge effects on SoC)

Grid-connected (free power exchange or committed p(t)) or off-grid?

???

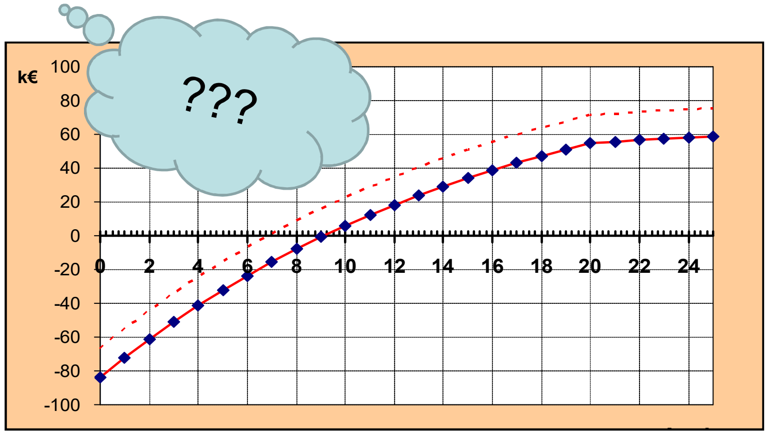
Which **software**? In-house software? General-purpose optimization packages?
Commercial specific software for prosumers? (e.g. Homer)

Optimal design

Optimal sizing of components ($P_{PV/WIND}$, $P_{DIESEL\text{-}GEN}$, P & E of storage, …): usually approached as an **external loop** w.r.t. the optimal operation.

Several **possible sizing scenarios** are taken under consideration. For each one, the *yearly* operation is optimized. The scenario with the best long-term objective function (CAPEX+OPEX+RISK) is the best size of components.

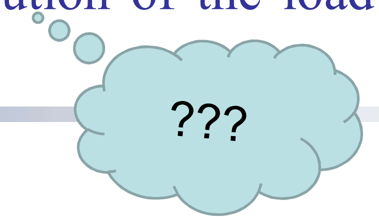
The choice of scenarios is typically **heuristic**, possibly driven by Particle Swarm Optimization or similar.



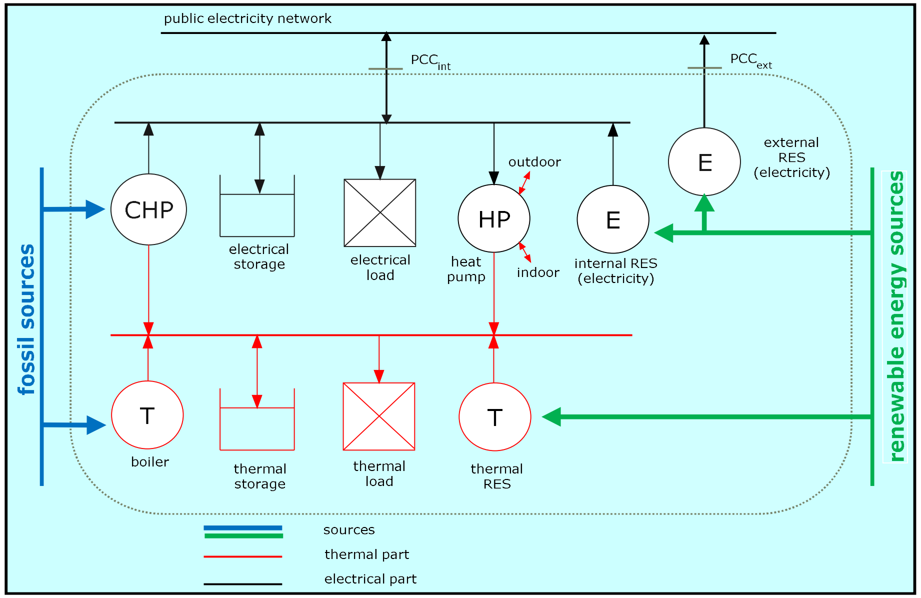
Which long-term objective function?

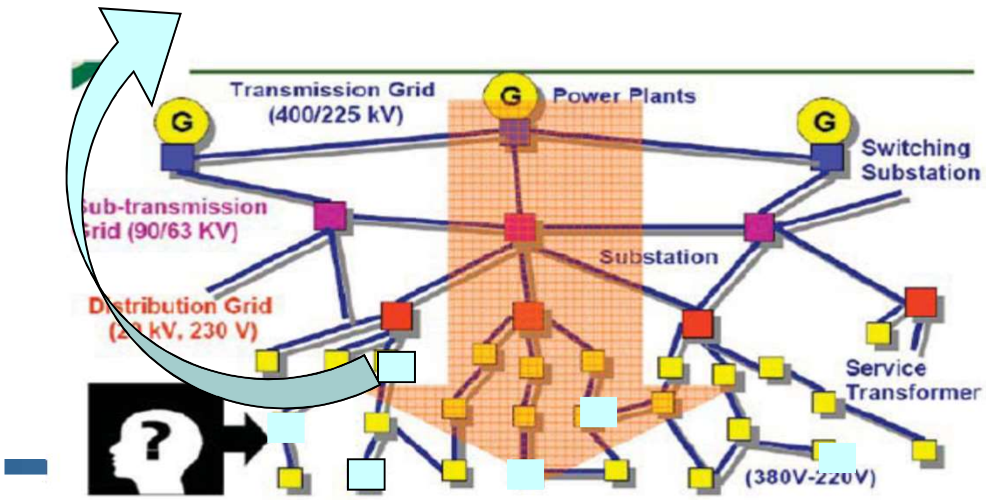
- Net Present Cost/Value
- Payback time
- LCOE, ….

"Multi-year" approaches: long-term evolution of the load → different values of the objective function at each year.



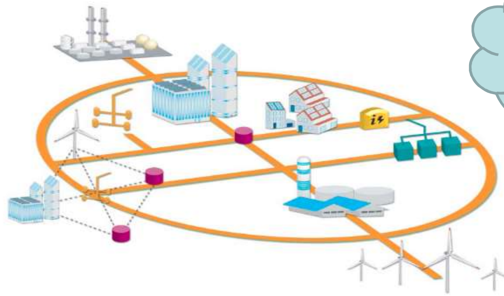
Prosumers and Smart Grid





From Virtual Power Plant to
a **Large Scale** VPP:
<u>network constraints are included</u>
to manage clusters of VPP.
From competion to sinergy.

Towards Local Energy Markets...
Blockchain?

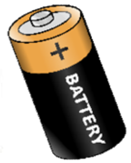


D.Poli, M.Giuntoli, “Optimized thermal and electrical scheduling of a Large Scale Virtual Power Plant in the presence of energy storages”, *IEEE Transactions on Smart Grid*, Vol.4 (2), 2013.

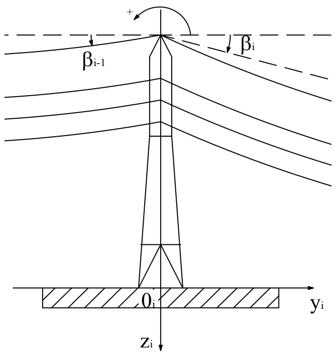
To be continued:

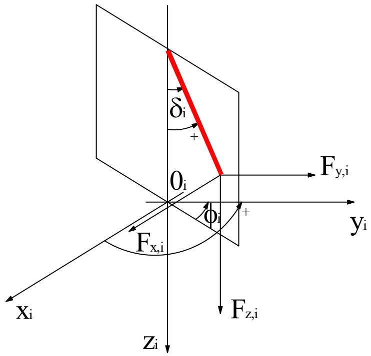
- Optimal sizing and operation of use of **renewable *isolated* minigrids**:

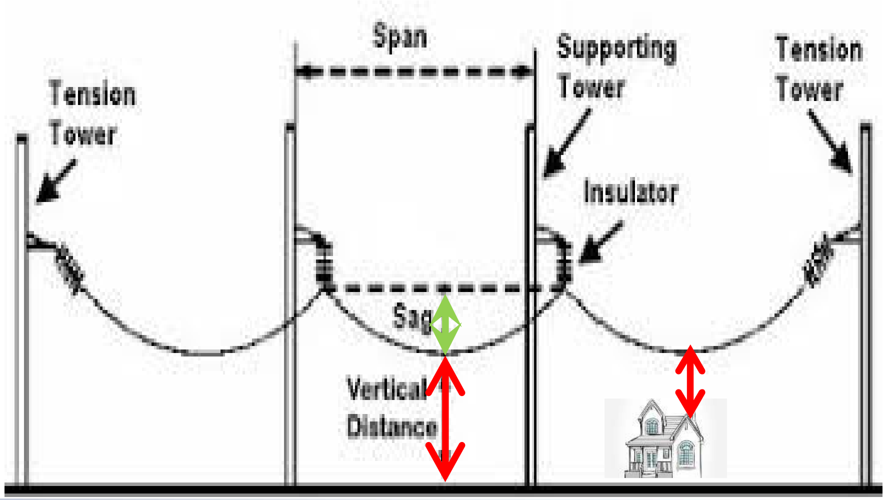
  - PSO → size scenarios
  - MonteCarlo → uncertainties
  - MILP to optimize each deterministic scenario



- Thermal and mechanical problems related to **Dynamic Thermal Rating** of multi-span overhead power lines







For more details or collaborations:

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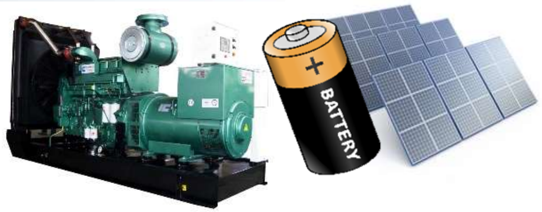
- **Assessment of system issues in the presence of uncertainty or unbundling:**
- Power system planning and operation
- Asset management
- Massive integration of renewable energy resources
- Distributed storage systems
- Power system economics, energy markets, and regulation
- Power system reliability and security
- Uncertainty and risk management methods
- **Analysis of power system performance and control**
- Blackout prevention, system resilience, and restoration
- Control centre technologies and advanced operator tools
- Wide-area monitoring and control
- Power system dynamics
- Power system protection
- Power systems as part of multi-energy systems
- Power systems and electro-mobility
- Distribution system monitoring, operation, and control
- Aggregation of distributed energy resources
- Flexible demand
- Power electronics and HVDC as part of a power system
- Electro-magnetic transients on a system
- Power quality
- **Integrated modelling and operation of information and communication technologies (ICT) in power systems**
- Cyber security in power systems operation and control
- ICT-driven intelligent and autonomous controls
- Modelling of cyber-physical energy and communication systems
- **Data analysis and computation applied to power systems**
- Data-driven modelling techniques
- Machine learning, statistics, and computational intelligence
- Management and utilisation of big data• Mathematical and computational issues in modelling and simulation
- Forecasting methods

https://pscc2020.pt/

Optimal sizing and operation of hybrid minigrids for developing countries

- Power and energy systems are facing a huge challenge: enabling the electricity access to the **1.2 billion people** currently living without electricity in rural areas of developing countries
- This must be **clean**, **efficient**, **reliable**, **affordable, scalable**
- Minigrids (MGs) are promising power configurations, able to bypass the **expensive** and **slow** connection to the national TX/DX grid: isolated minigrids → clusters → interconnection
- IEA estimates that raising the electricity access up to the 85% of world population by 2040 requires hundreds of billion dollars and **100-200k minigrids** : colossal **technical challenge** and huge **market**
- Almost the totality of current minigrids are **diesel-based** and only 2-3% are **hybrid** (RES, fossil sources and batteries)
- Hybrid minigrids have low environmental impact and OPEX, with a trend of CAPEX reduction: **combining RES and storages, the fossil source can be downgraded to simple backup power!**

Computational issues in hybrid mini-grids

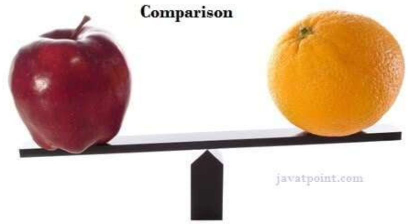


- MGs are sized by **simulating a typical yearly operation in different size scenarios,** assuming a given load profile and wind/solar availability
- Probabilistic approaches can be adopted to cope with **load and RES uncertainties** (e.g. Monte Carlo techniques or Stochastic Optimization)

- In priority-list strategies (e.g. Load-Following and Cycle-Charging), the operation of the mini-grid is based on **simple real-time priority rules (merit order lists),** without any periodic optimization
- In predictive approaches, the scheduling of conventional generators and storage devices is *optimized* some hours in advance, based on the *forecasting* of load/RES power profiles for the hours to come

?

Operating strategies



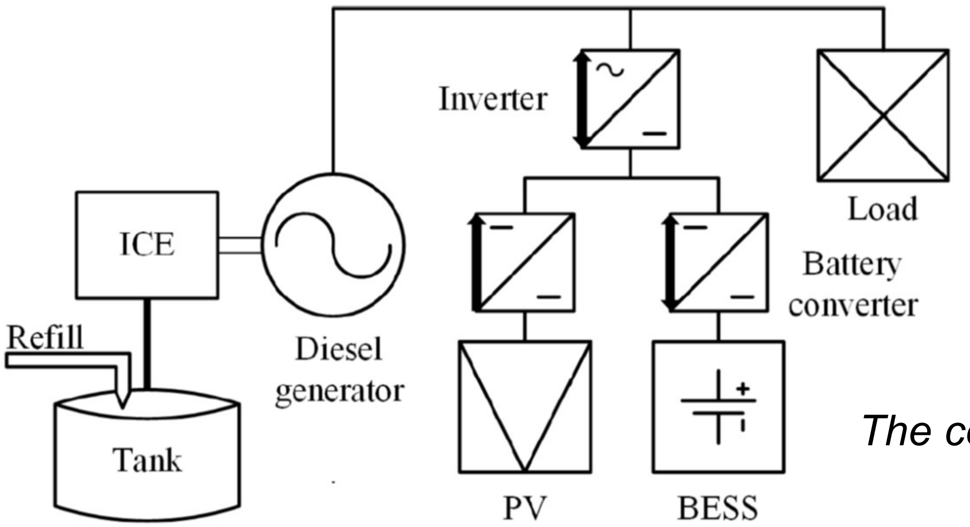
1. In priority-list strategies, a real-time controller dispatches first the renewable sources, then the energy storage devices, and finally the conventional fuel-fired generator.
   The fuel generators are turned on only when the batteries reach their minimum SOC or their maximum power.

   → in Load-Following Strategies (**LFS**) the fuel-fired generators only supply the load without recharging the battery

   → in Cycle-Charging Strategies (**CCS**) the conventional generators recharge the batteries up to a fixed threshold

2. Recent predictive approaches are **rolling-horizon** optimization cycles of dispatchable resources (e.g. every 6h, horizon of 12h), combined with fast real-time priority rules to cope with forecasting errors.
   Rolling-Horizon Strategies (**RHS**) are a good candidate not only for simulation/design purposes, but also for the actual operation of the minigrid.

Sizing purposes



The considered mini-grid

The mini-grid is sized by **searching the set of components, whose operation (LFS, CCS, or RHS) during the mini-grid lifetime is expected to be the cheapest one**, accounting for:

- investment costs
- operational (fuel) costs
- the cost of risk (economic value of load curtailment)

$$NPC = \sum_{y=0}^{N_{LT}} \frac{CAPEX_y + OPEX_y}{(1+i)^y}$$

The algorithm: 3 loops

1) An external Particle Swarm Optimization (PSO) procedure properly selects the size scenarios
    2) A year of operation is simulated S times according to a Sequential Monte Carlo (MC) procedure
        3) No load/PV forecasting is carried out
            - At each time step, the MC procedure draws the current load and PV power; batteries balance the system; when they are at the min. SOC, the diesel generator is switched on to meet the load (load following) and recharge batteries up to a fixed target (cycle charging)

Load Following or Cycle Charging

        3) The operational costs of the current year are evaluated
    2) The Net Present Cost (NPC) of the current size scenario is assessed, based on obtained CAPEX and OPEX (=average of S OPEX values)
1) When PSO convergency is reached, the size scenario with the lowest NPC is chosen as the best design of the mini-grid

The algorithm: 3 loops

1) An external Particle Swarm Optimization (PSO) procedure properly selects the size scenarios
    2) A year of operation is simulated S times according to a Sequential Monte Carlo (MC) procedure

Rolling horizon optimal dispatching

        3) Every 6 hours, the load and PV power profiles expected for the following 24 hours are used by a MILP procedure that optimizes the use of resources
            - At each time step, the MC procedure draws possible real-time **deviations** from expected load/PV patterns; priority rules correct the real time dispatching
        3) The operational costs of the current year are evaluated
    2) The Net Present Cost (NPC) of the current size scenario is assessed, based on obtained CAPEX and OPEX (=average of S OPEX values)
1) When PSO convergency is reached, the size scenario with the lowest NPC is chosen as the best design of the mini-grid

- With respect to LFS and CCS, RHS enables predictive strategies, like **recharging in advance** the batteries by anticipating the diesel start-up, based on expected load and irradiation

- The MILP procedure of RHS calculates the **optimal dispatching of batteries and diesel generator** for the following 24 hours, in order to minimize:
  – the cost of fuel and load curtailment
  – the cost of battery overuse (a penalization is added when the final SOC set by the MILP is below its initial value)

- The **stochastic approach** is applied to:
  - the load and irradiation patterns (Gaussian deviations, with STD increasing with time distance between forecasting and real time)
  - in case, the actual time required for fuel delivery (Weibull)

One-Shot (OS) algorithm

- Fourth class of algorithms aimed to set a **benchmark** → the lowest NPC achievable
- Able to optimize at the same time both the sizing and the operation of the mini-grid, **assuming the perfect forecasting of load and RES profiles**
- The size of each component and the power provided by the generator and batteries for each hour of a reference year is optimized using a **single MILP procedure**

$$\min CAPEX_0 + \sum_{y=1}^{N_T} \frac{\frac{1}{N_s}\sum_{s=1}^{N_s} OPEX_{s,t}}{(1+d)^y}$$

$$CAPEX_0 = C_{PV}\left(P_{PV,c}\right) + C_B\left(P_{B,c}\right) + \\ +C_{DCDC}\left(P_{DCDC,c}\right) + C_I\left(P_{I,c}\right) + C_D\left(P_{D,c}\right)$$

$$C_x\left(P_{x,s}\right) = \text{piecewise linear function}$$

$$OPEX_{s,t} = \sum_{t=1}^{N_T=8760} C_{D,O\&M,s,t} + C_{LC,s,t}$$

Results of a case study (Kenya)

Strategy	Exec. time (min)	NPC (k$)	Load curt. (%)	PV (kWp)	Battery (kWh)	Generator (kW)	DCDC Conv. (kW)	Inverter (kW)
LFS	1.5	183.3	0.31	743	2069	127	413	247
CCS	1.5	181.9	0.47	743	2044	134	419	241
RHS	274	178.0	0.07	726	2001	59	453	235
OS[1]	446	177.4	0.06	716	1990	75	391	236

In terms of NPC:

- the NPCs of the three other strategies are not far (+2÷3% for RHS and +3÷4% for LFS and CCS) from OS (theoretically the lowest bound achievable)

In terms of computational requirements:

- priority-list strategies are extremely quicker than predictive approaches
- RHS is less time-consuming than OS (-40%)

Load curtailment is lower in predictive approaches (RHS≈OS)

Concerning the optimal size of components:

- very similar, except for the generator in RHS and OS: a smaller generator can be used for recharging batteries, hours before than load request

- Predictive strategies (RHS, OS) enable a better coordination of components (savings of 2-4% in NPC), but with **higher computational requirements**
- LFS and CCS can be used for the preliminary design of the PV panel, of power electronics and batteries
- RHS is more suitable for refinement stages and for sizing of the generator

- Future improvements **and need for help**:

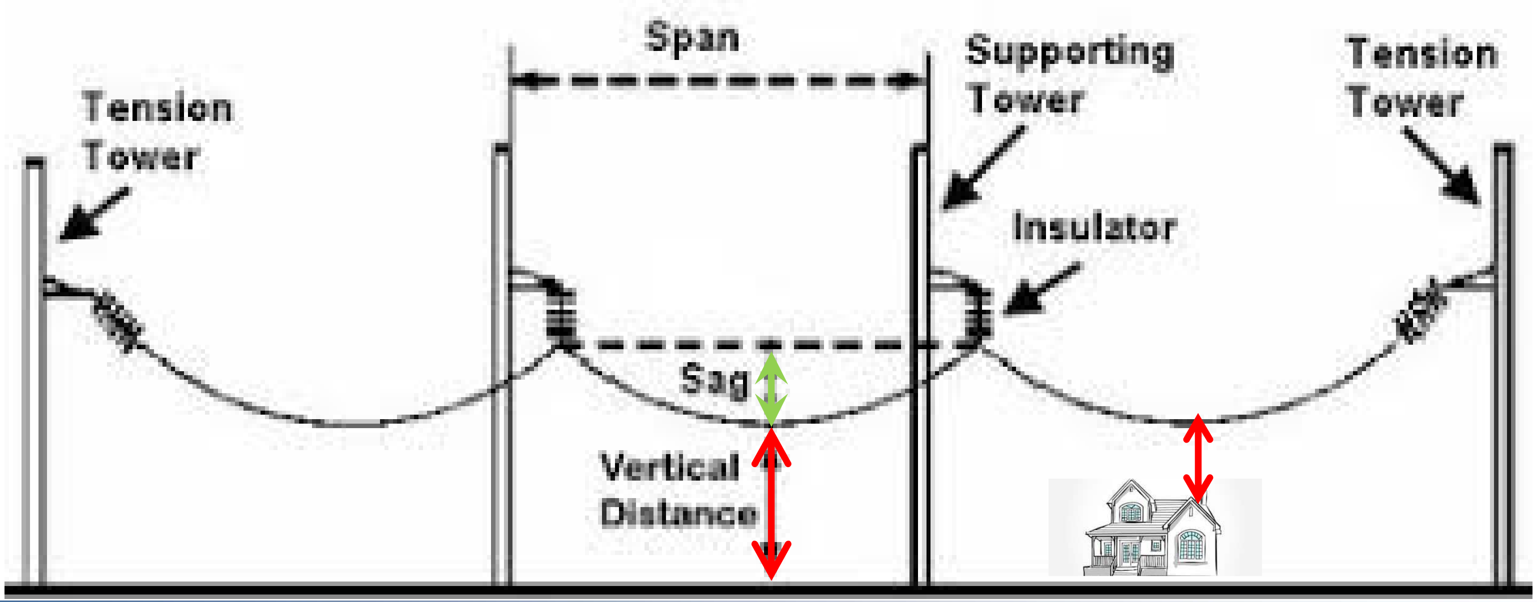
  - **other (heuristic?) approaches to suggest size scenarios**

  - **multi-year** analysis to capture the long-term evolution of the load

  - optimize the change of topology in progress
    (e.g. interconnection, year suggested by the PSO)

Smart transmission systems: Dynamic Thermal Rating

- "***Use better what you have!***"
- Load is increasing and transmission assets are also stressed by new RES
- The maximum power ("**rating**") that a power line can carry is limited by:
  - max temperature of the conductor (→ performance of the material)
  - max sag allowed at each span of the line (→ clearance to ground)



The rating of a power line

- The temperature of the conductor, his sag/clearance and consequently his maximum possible power are strictly dependent on **weather conditions**
- Traditional ("Static" or "steady-state") ratings are based on **worst weather conditions** → extremely low and precautionary!
- "Dynamic" Thermal Rating (DTR) of transmission lines represents a strong and recent improvement:

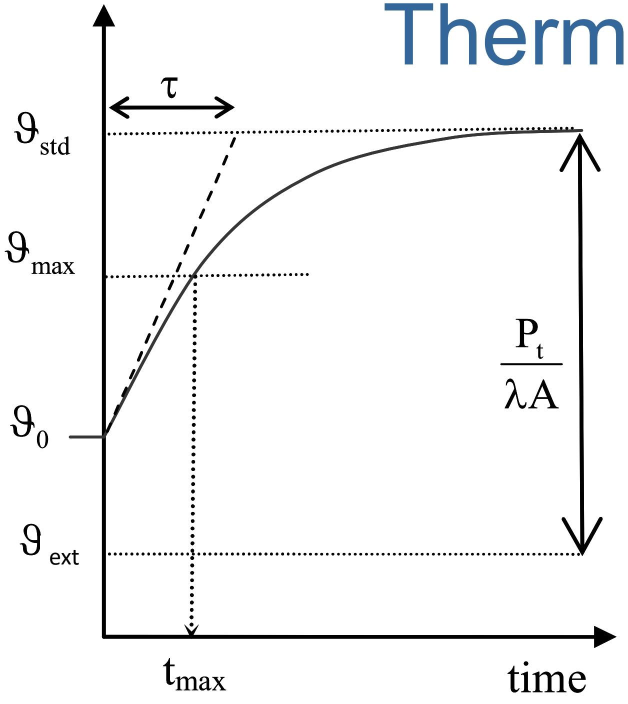
  1) the rating is strictly dependent on the **actual weather conditions**

  2) "current → temperature" is a **first-order system**

     - **thermal time constants:** τ = 15-30 minutes
     - the maximum current allowed for a transitory period is **significantly higher than the steady-state thermal limit**

- DTR allows TSOs exploiting the dynamic performances of conductors during transient contingencies, thus **reducing re-dispatching costs of generation plants** and minimizing the curtailment of RES.

Thermal (dynamical) aspects



Heating curve of the conductor.
Max allowed duration t_{max} of the overloading condition (CIGRE dynamic model)

$$P_t = C_t \frac{d\vartheta^{\Delta}}{dt} + \lambda A \vartheta^{\Delta}$$

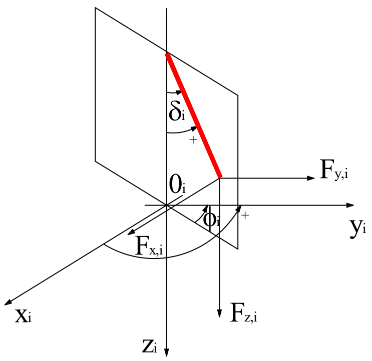
(first-order transient)

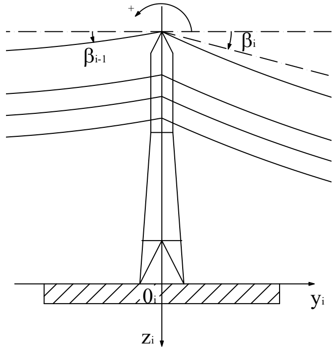
P_t	thermal power applied to the conductor (Joule losses, solar radiation, magnetic losses and corona);
C_t	heat capacity of conductor;
ϑ^{Δ}	$=\vartheta-\vartheta_{ext}$: temperature w.r.t. the ambient;
λ	heat transfer tot. coefficient;
A	heat exchange surface;
ϑ_0	initial temp. of the conductor
ϑ_{std}	steady-state temperature
$\tau =$	R_tC_t : thermal time constant
R_t	$=1/(\lambda A)$: thermal resistance

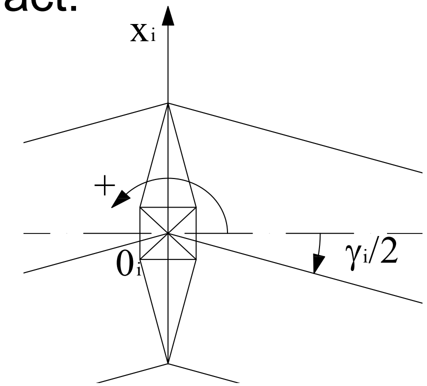
- Heat transfer and conductor cooling are driven by thermo-fluid dynamics (Reynolds, Nusselt, Grashof, Prandtl numbers…) → λ and τ
- Current, solar radiation, speed/direction of wind and ambient temperature are assumed to vary at steps of 5 minutes, separately span by span
- Sample-and-hold procedure: the **dynamic** time trend of conductor's temperature is calculated, separately span by span, as a **series of first-order step responses**

The mechanical (algebraic) problem

At each time step, the temperatures at each span of the line are known.
3D angles of each **insulator string** and stress/elongation of conductors are unknown.
All spans between two dead-end towers mechanically interact:







$$F_{x,i} + (n_{i-1}\cdot s_{i-1} + n_i \cdot s_i)\cdot \mathrm{sen}\frac{\gamma_i}{2} = 0$$

$$F_{y,i} + (-n_{i-1}\cdot s_{i-1} + n_i \cdot s_i)\cdot \cos\frac{\gamma_i}{2} = 0$$

$$F_{z,i} + (n_{i-1}\cdot s_{i-1}\cdot \tan\beta_{i-1} + n_i \cdot s_i \cdot \tan\beta_i) = 0$$

$$[(F_{x,i}\cdot \mathrm{sen}\phi_i + F_{z,i}\cdot\cos\phi_i)\cdot \mathrm{sen}\delta_i - F_{y,i}\cdot\cos\delta_i]\cdot L_i = 0$$

$$[(F_{y,i}\cdot \mathrm{sen}\delta_i + F_{z,i}\cdot\cos\delta_i)\cdot \mathrm{sen}\phi_i - F_{x,i}\cdot\cos\phi_i]\cdot L_i = 0$$

$$s_1^3 - s_1^2\cdot\left[s_0 - E\left(\frac{\Delta l}{d} + \alpha(\vartheta_1 - \vartheta_0) + \frac{q_0^2 d^2}{24\cdot s_0^2}\right)\right] - \frac{q_1^2 d^2 E}{24} = 0$$

5 non-linear equations (translational and rotational equilibria of strings) + “eq. of change of state” of conductors, per span

Clamp displacements Δl can be expressed as a function of the angles of insulator strings ?

Results (with *multivariate Netwon-Raphson method*) are angles, stress, elongation, **sag, clearance to ground** of each span/time_step.

Non-linear “High-Temperature Low-Sag” Conductors

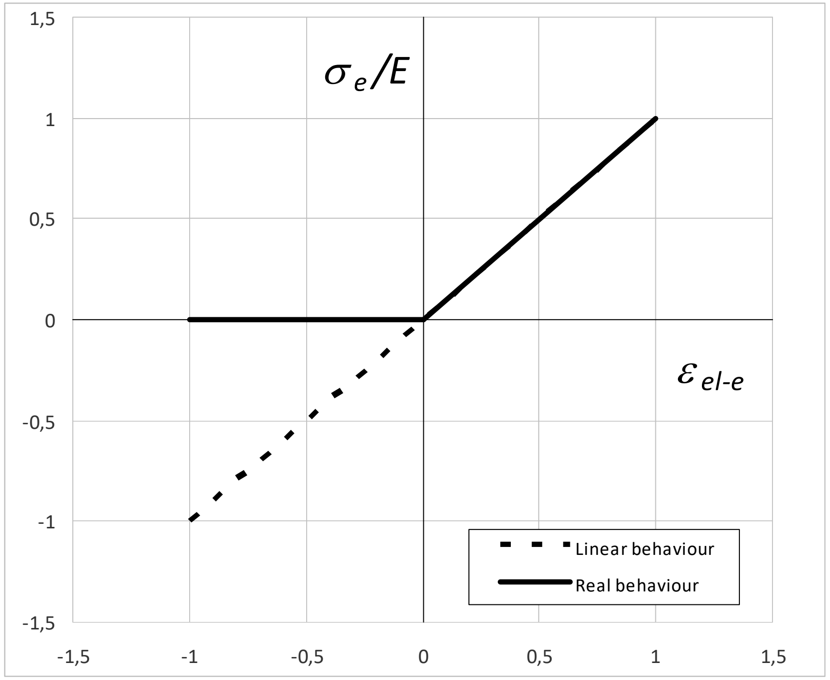
- Over the “knee-point” temperature, the stress of the ext. strand is zero (compressed, stranded, it swells up!) → non-linearity in elasticity equation
- 5 more equations per span:

$$\sigma_i = \frac{T_i}{A_i} = E_i \cdot \left[\varepsilon_i - \alpha_i \cdot (\vartheta - \vartheta_0)\right]$$

$$\sigma_e = \frac{T_e}{A_e} = \frac{E_e}{2} \cdot [\varepsilon_e - \alpha_e \cdot (\vartheta - \vartheta_0) + \sqrt{(\varepsilon_e - \alpha_e \cdot (\vartheta - \vartheta_0))^2 + \xi}\,]$$

$$\varepsilon_i = \varepsilon_e \qquad T = T_i + T_e$$

$$\frac{(p \cdot d)^2}{24} \cdot \left(\frac{1}{T^2} - \frac{1}{T_0^2}\right) - \frac{(T_i - T_{i,0})}{E_i \cdot A_i} - \alpha_i \cdot (\vartheta - \vartheta_0) + \varepsilon_{\Delta l} = 0$$



Stress VS elastic elongation: ext strand

Possible uses of DTR calculations

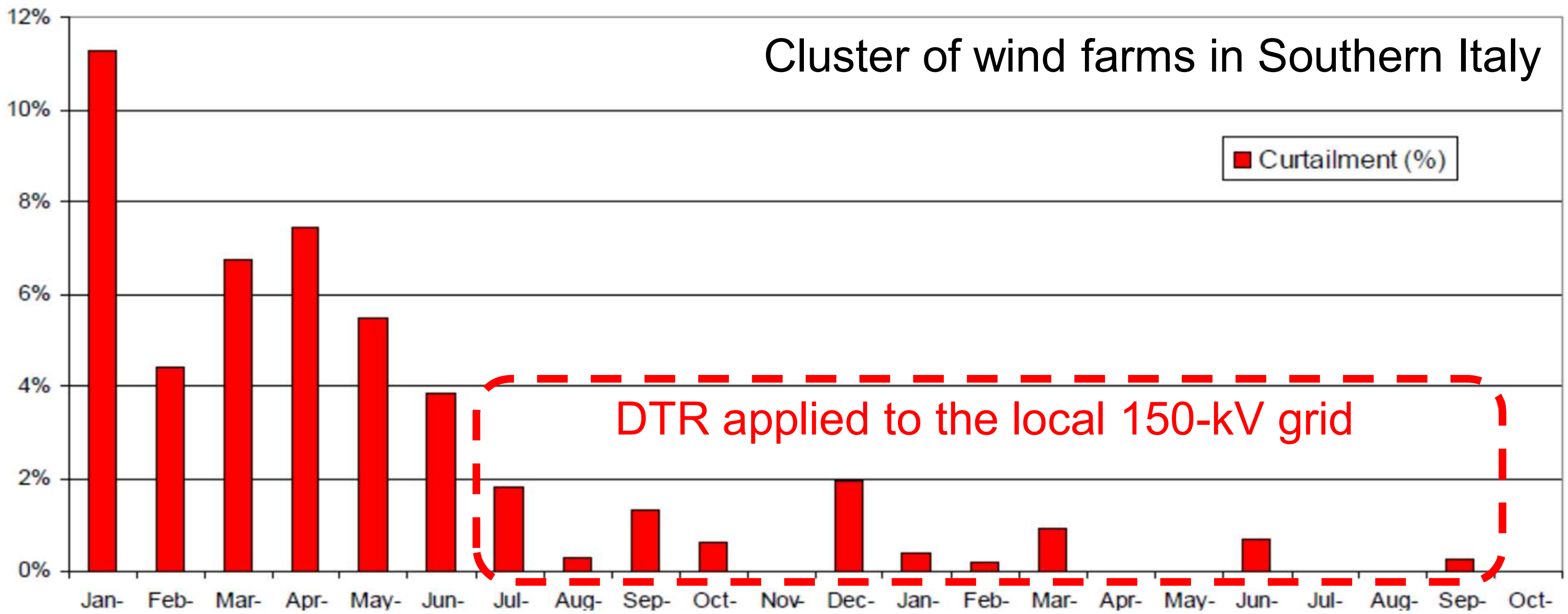
- Forecast of future trend of temperatures and sags (2h)→ **TSO decision support**

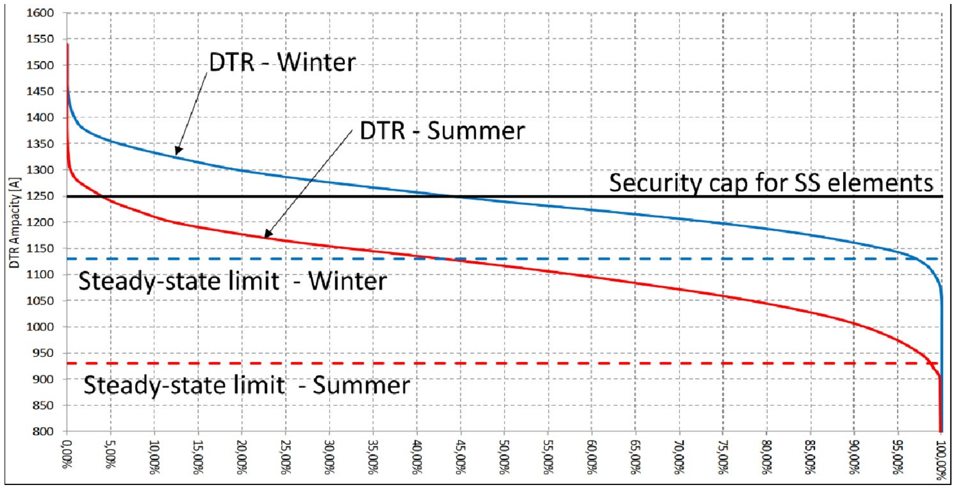
  - expected temperatures, sags and clearances at each span and t-step (1 min)
  - the TSO can stress the line for a transient period, **without redispatching generators to modify the power flow**
  - Currently in use at TERNA control room, Rome
  - Computational times of a 60-spans line: 30sec, common PC

- Dichotomic calculation of **max current step allowed for ex. for 30 minutes ("30-min DTR")** while respecting all temperature and sag constraints

- **Full exploitation of wind farms**, well beyond steady-state limits of the lines:

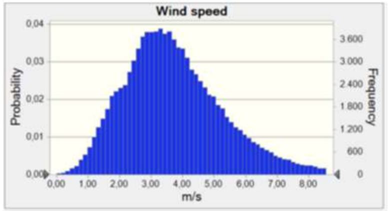
  the higher wind speed, the higher power flows and congestion issues,
  but also the higher cooling of the conductor → DTR shows that temperatures remain low and **wind farms are not curtailed**.

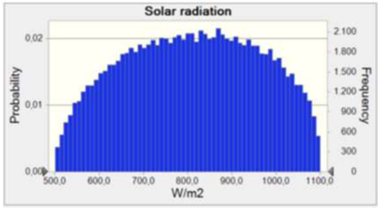


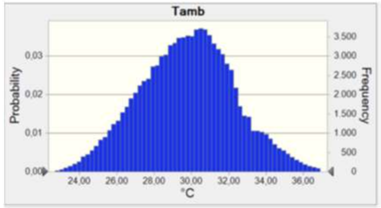


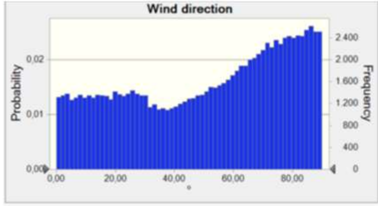
DTR ex-post duration curve [A] of a real 150-kV Over Head Line

Probabilistic approaches: weather is uncertain!









PDF of weather parameters