Reconciling reliability and sustainability:

Some thermodynamic insights dedicated to the integration of renewables in the Power System

Motivation

- Drastically reduce DoF to manage macroscopic and relevant information on a system

- Provide rich- and simple-enough lumped insights on operation to long term technico-economic planning exercise
  - Space: from µm to grid scale
  - Time: from ms to 50-100 years

- Existence of « constant(s) of motion » for any steady-state dynamic system
  - Energy-based theoretically expected from time-uniformity
  - ➔ 2nd principle of thermodynamics
  - ➔ Space aggregation and time reconciliation

- Power system is Schneider Electric' playground:
  - Intimacy of control and power flow
  - Indiscernability of mechanical and electromagnetic powers
  - ➔ Two energy-based constants of motion

1	Thermodynamic of power system
2	Multi-scale analysis
3	French case study
4	Conclusion

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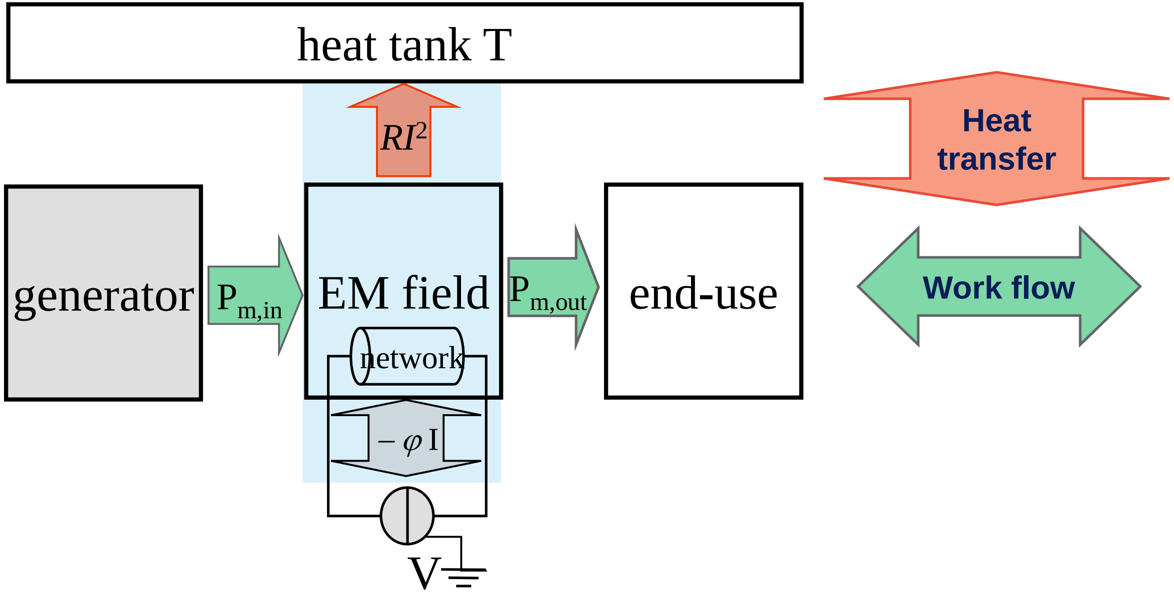
Electromagnetism: from steady-state to transient regimes



Couplings:

- magnetic free currents I
- Electric earth potential V
- heat tank Joule losses

The utility acts on:

- the mechanical power P_m
- the excitation of the rotor I

Modeling issue:

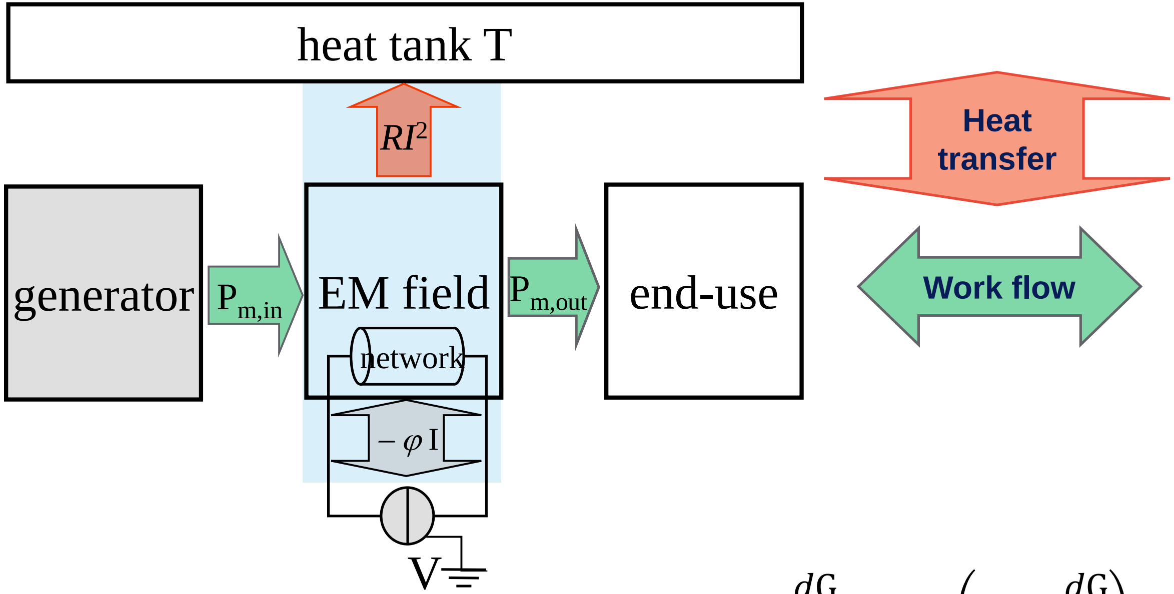
➔ Decouple control and power flow

V. Mazauric, "From thermostatistics to Maxwell's equations: A variational approach of electromagnetism," *IEEE Transactions on Magnetics,* vol. 40, pp. 945-948, 2004.
X. Li, N. Maïzi, and V. Mazauric, "A lattice-based representation of power systems dedicated to synchronism analysis," *International Journal in Applied Electromagnetics and Mechanics,* vol. 59, pp. 1049-1056, 2019.

Relevant perimeter for energy assessment (1st principle) : $G(T,I,V,\mathbf{X})$

2nd principle of thermodynamics: $$P_m - \frac{dG}{dt} \geq 0$$

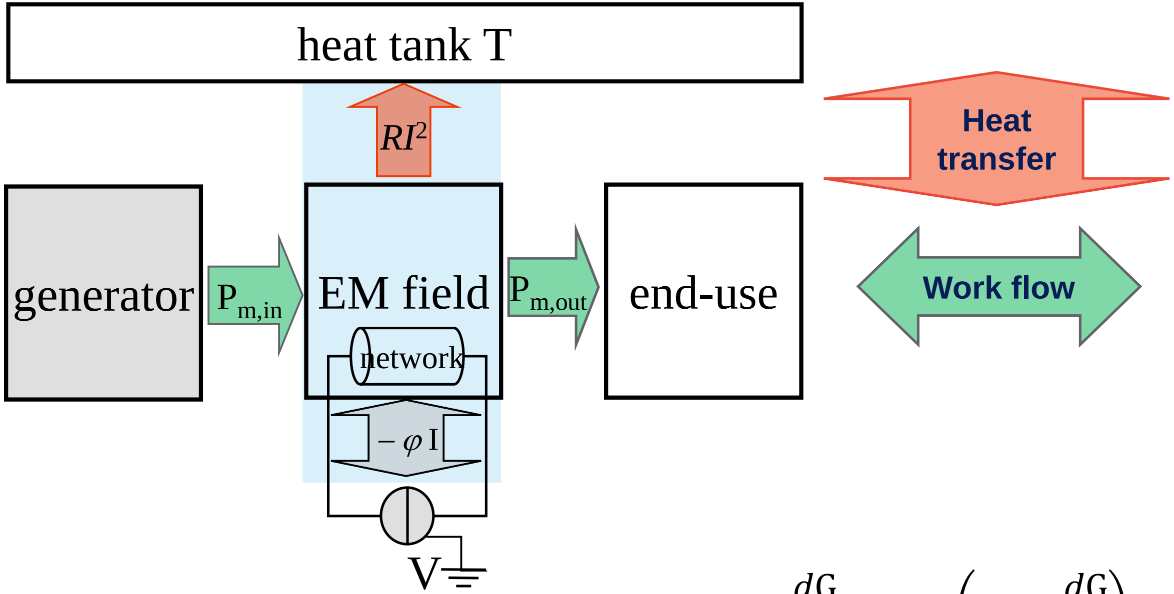
Electromagnetism: A natural trend towards reversibility



Weak reversibility : $$P_m - \frac{dG}{dt} = \min\left(P_m - \frac{dG}{dt}\right) \geq 0$$

2nd principle of thermodynamics: $$P_m - \frac{dG}{dt} \geq 0$$

Electromagnetism: A natural trend towards reversibility



Weak reversibility :

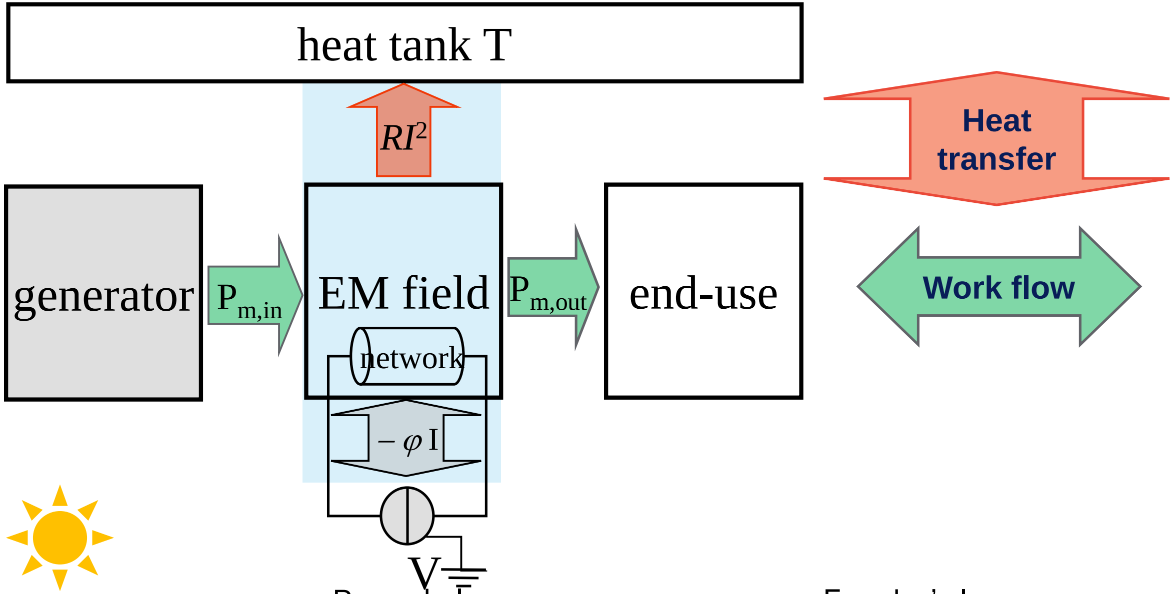
$$P_m - \frac{dG}{dt} = \min\left(P_m - \frac{dG}{dt}\right) \geq 0$$

Energy conservation:

$$P_m - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d(\varphi I + QV)}{dt}\right) \geq 0$$

Lenz law

Electromagnetism: A natural trend towards reversibility



Power balance

Faraday's law

Radiation

Energy conservation

Inertia

$$P_{elec} + P_{m,ext} - \frac{dE_{kin}}{dt} \; P_m - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d(\varphi I + QV)}{dt}\right) \geq 0$$

Lenz law

Faraday's law is restored by assuming a reversible evolution:

- All the energy losses (conversion, distribution, end-use) are attainable
- Multi-scale framework with successful issues (material law,…, CAD tools,...)

Energy-based «constants of motion»:

➔existence justified by time-uniformity:

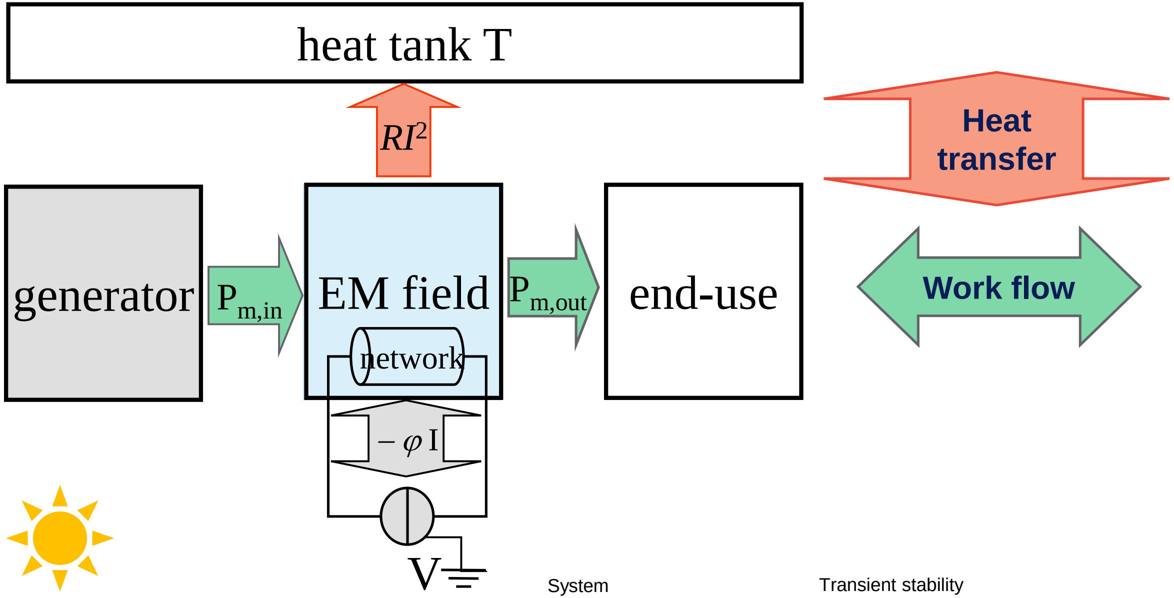
- Electromagnetic energy w/ coupling G
- Kinetic energy E_{kin}

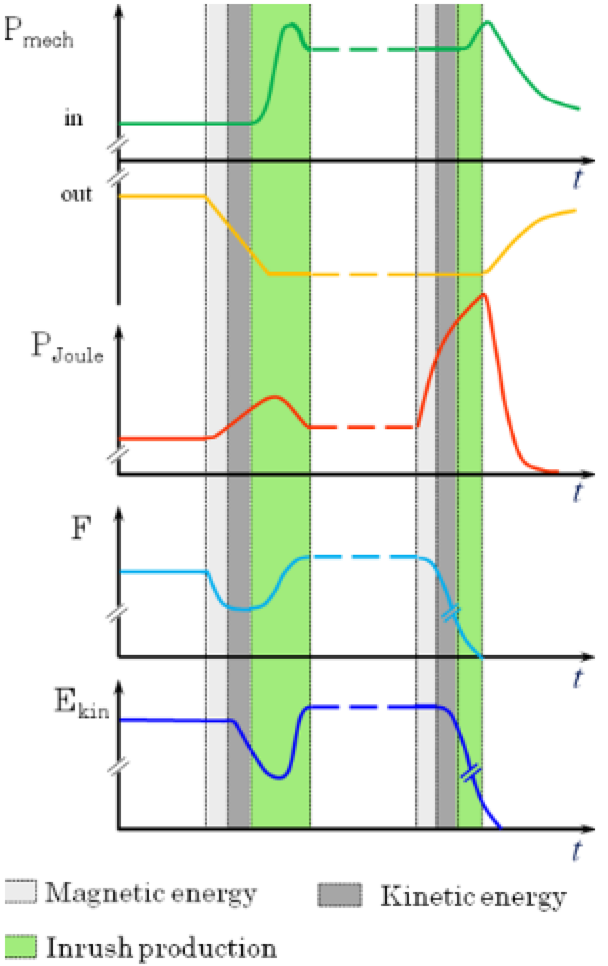
➔Conversely, provide insights for:

- time-reconciliation, and
- space-analysis

Power management: Basics

Focus at the higher aggregated scale





System adequacy — Transient stability (ancillary services)

Poynting equation: $$P_{elec} + P_{m,ext} = P_{Joule} + \frac{dE_{kin}}{dt} + \frac{dF}{dt}$$

fatal — min-hour fatal — seconds — ms

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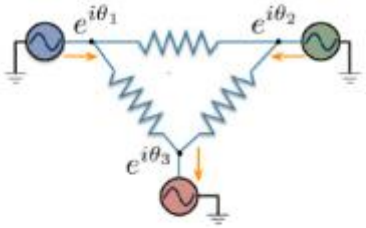
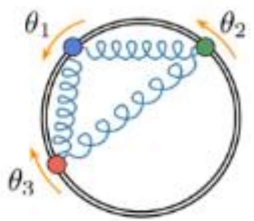
Power management: Leverage the highest kinetic energy

Before adequacy (primary/secondary/tertiary reserve)

$E_{kin}(\Omega) \leq E_{kin} \leq \sum_{\Omega} E_{kin}(\Omega)$?





Upper bound is enforced by synchronism

➔ Capture the critical behavior thanks to a dedicated lattice model:

derived (virtual works) from the Gibbs free-energy

- Coherence of fully-correlated oscillator population:

$$\ddot{\theta}_i + d_i \dot{\theta}_i = \omega_i - \sum_{<ij>} \frac{K_{ij}}{N} \sin(\theta_i - \theta_j)$$

- Synchronism is ensured for tight enough binding (admittance matrix):

$$\lambda_2(G) \geq \left\| B^T P_{\text{mech}} \right\|_\infty = \max_{\langle i,j \rangle \in G} \left| P_{\text{mech},i} - P_{\text{mech},j} \right|$$

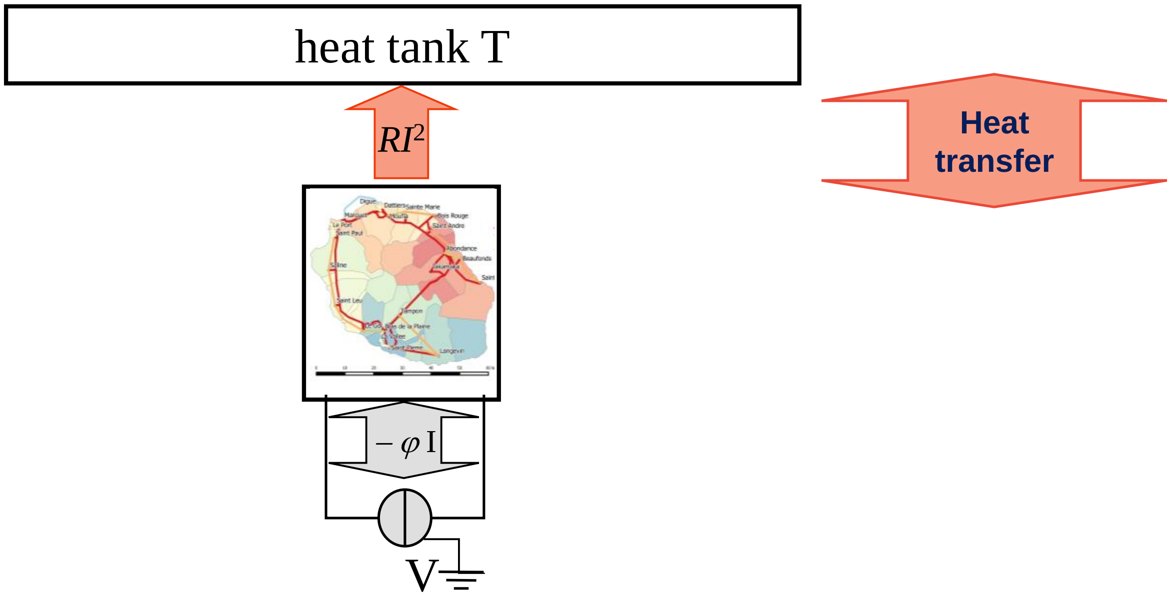
Y. Kuramoto, "Self-entrainment of a population of coupled non-linear oscillators," in International Symposium on Mathematical Problems in Theoretical Physics, ser. Lecture Notes in Physics, H. Araki, Ed. Springer Berlin Heidelberg, vol. 39, pp. 420–422, 1975.
F. Dörfler and F. Bullo, "Synchronization in complex networks of phase oscillators: A survey", Automatica 50 (2014), 1539–1564.

- Disordering factors:
  - N→∞ (long range disordering modes)
  - Intensive use of transmission lines
  - High frequency
- Ordering factors:
  - Lattice interaction and admittance
  - Locally balanced connection point
  - Low frequency

Synchronization is not inconditionnally stable!

J. M. Kosterlitz, "The critical properties of the two-dimensional xy model," *Journal of Physics C: Solid State Physics*, vol. 7, pp. 1046–1060, 1974.

Power management: Decoupling control and power flow

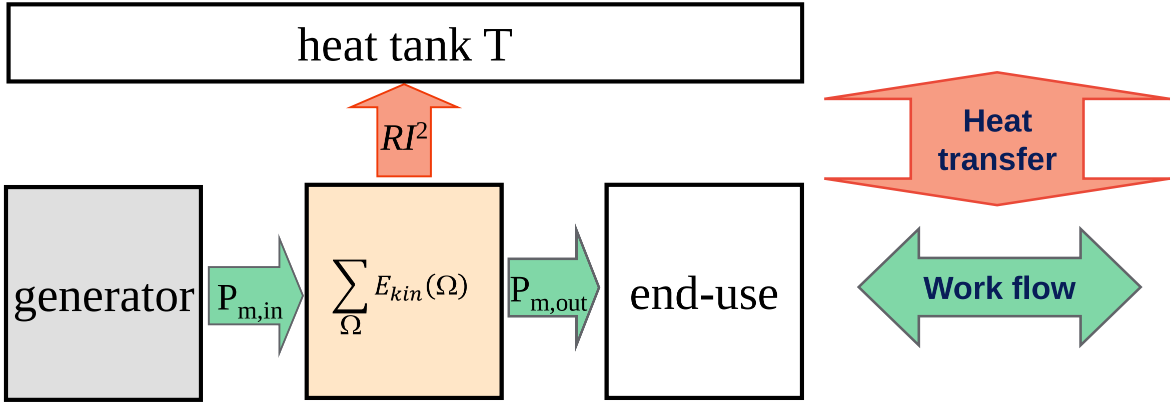


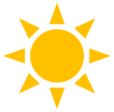
Synchronism:

- Voltage plan conditions Reactive Power and
- Gibbs free-energy G induces electrodynamic resistant torque
- « Rigidity » -induced synchronism:
  - ➔ Decrease congestion rate
  - ➔ Improve grid connectivity
  - ➔ Decrease frequency

$$H_{syn} = \frac{\lambda(G)}{\max\limits_{\langle ij \rangle}(P_i - P_j)}$$

Power management: Decoupling control and power flow



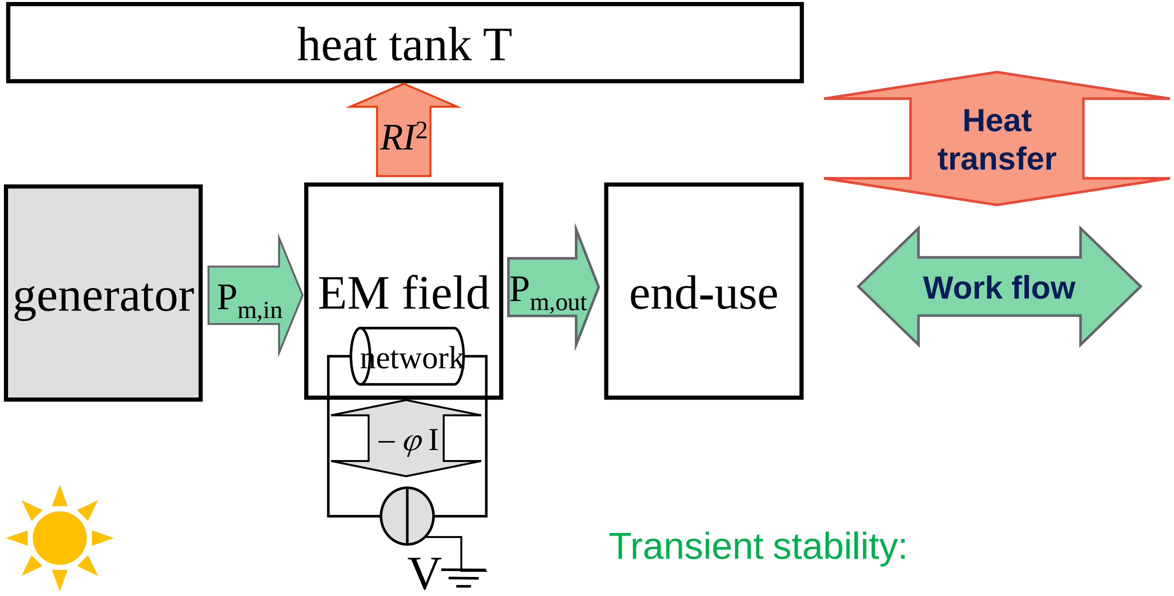


Transient stability:

- Frequency
- Kinetic energy E_{kin}
- Transient stability provides time-reconciliation:
  - ➔ Extend « copper plate » for aggregation
  - ➔ Favour huge moving mass
  - ➔ Increase the frequency

$$H_{kin} = \frac{\sum_{\Omega} E_{kin}(\Omega)}{S}$$

Power management: Decoupling control and power flow



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Active power flow exchanged throughout the grid

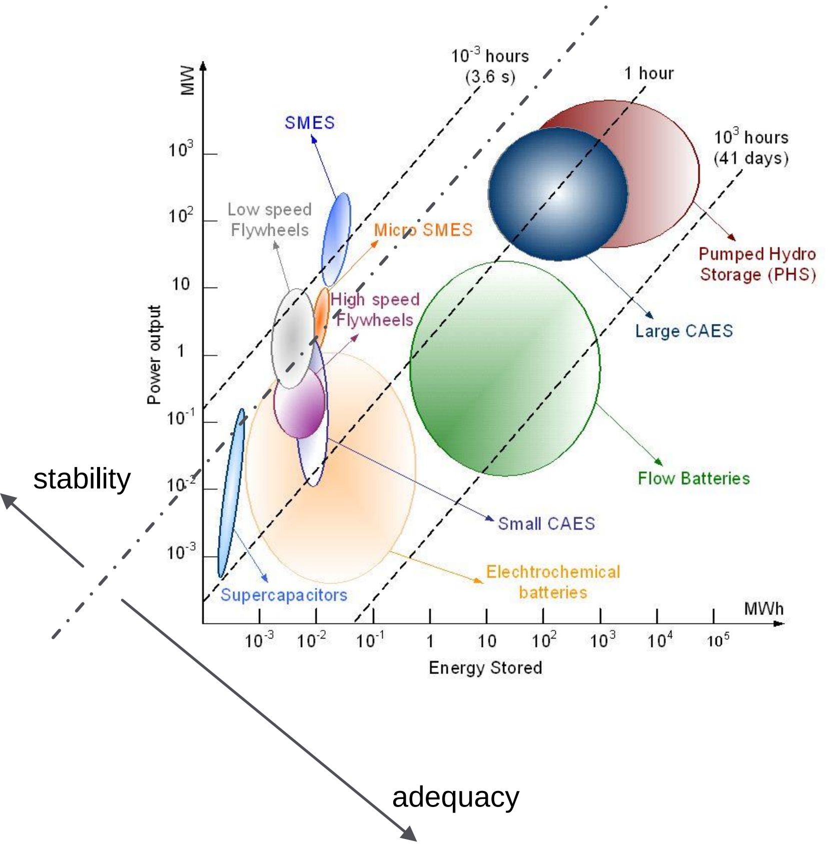
Power management: Forthcoming competitions

Naturally expressed within the second principle:

$$P_{elec} + P_{m,ext} - \frac{dE_{kin}}{dt} - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d(\varphi I + QV)}{dt}\right) \geq 0$$

Dedication	flexibility	adequacy	stability inertia	synchronism		coupling
Trends under SDG	↑ Migration	↓ Decommissioning of conv. power plants	↓	?	↑ Agility & Control	?
Sources	hν wind storage DSM		hydro (dam) conv. power plant			
Hardware Interfaces	grid-tie (support-, follow-ing) inverters			grid-forming inverters		
Functional materials	Si(C) Ga Dy, Nd Li		kg	Fe Si(C) Ga		Cu, Ag, Al

Stability vs. Flexibility issues



Energy-based «constants of motion»:

- ➔ Existence justified by time-uniformity:
  - – Electromagnetic energy w/ coupling G
  - – Kinetic energy E_{kin}
- ➔ Field-type energies dedicated to **stability**

Dedicating flexibilities to adequacy is limited by:

- ➔ IT energy footprint to manage:
  - Space complexity
  - Time agility
- ➔ Stability issue (« real-time » never exists!)

X. Li, N. Maïzi, and V. Mazauric, "A lattice-based representation of power systems dedicated to synchronism analysis," *International Journal in Applied Electromagnetics and Mechanics*, vol. 59, pp. 1049-1056, 2019.

The French case study

CMA (MINES ParisTech) partnership:

- G. Seck
- R. Cluet
- and many others before

Long term planning exercise:

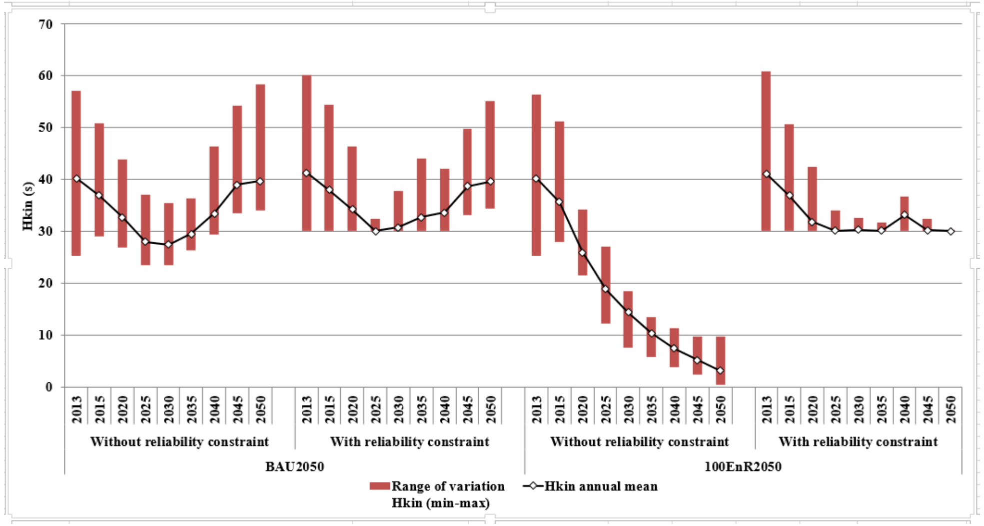
- Technical linear optimization model, demand-driven, achieving a technico-economic optimum
- TIMES-FR

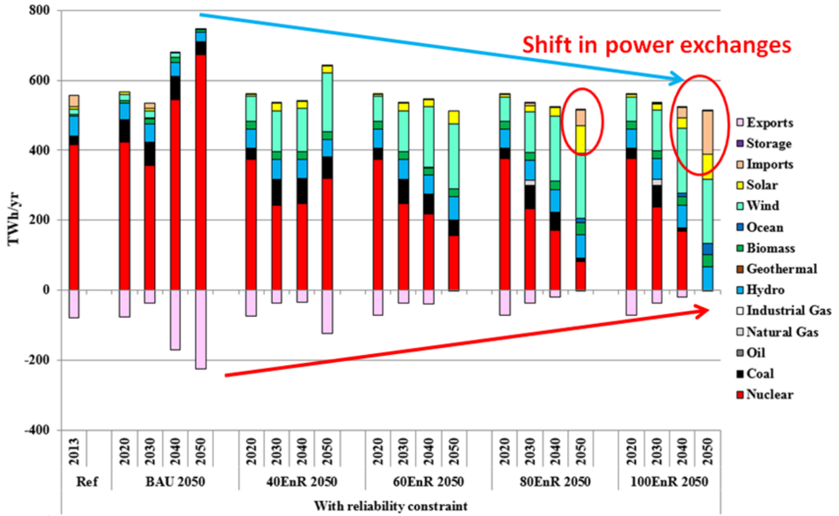
Reduction of the transmission grid:

- Over the 13 administrative regions
- Keeping the synchronism indicator constant

Cost-effectiveness fulfillment of generation potentials

Yearly generation under reliability constraint





G.-S. Sokhna, V. Krakowski, E. Assoumou, N. Maïzi, and V. Mazauric, "Embedding power system's reliability within a long-term Energy System Optimization Model: Linking high renewable energy integration and future grid stability for France by 2050," *Applied Energy,* vol. 257, p. 114037, 2020.

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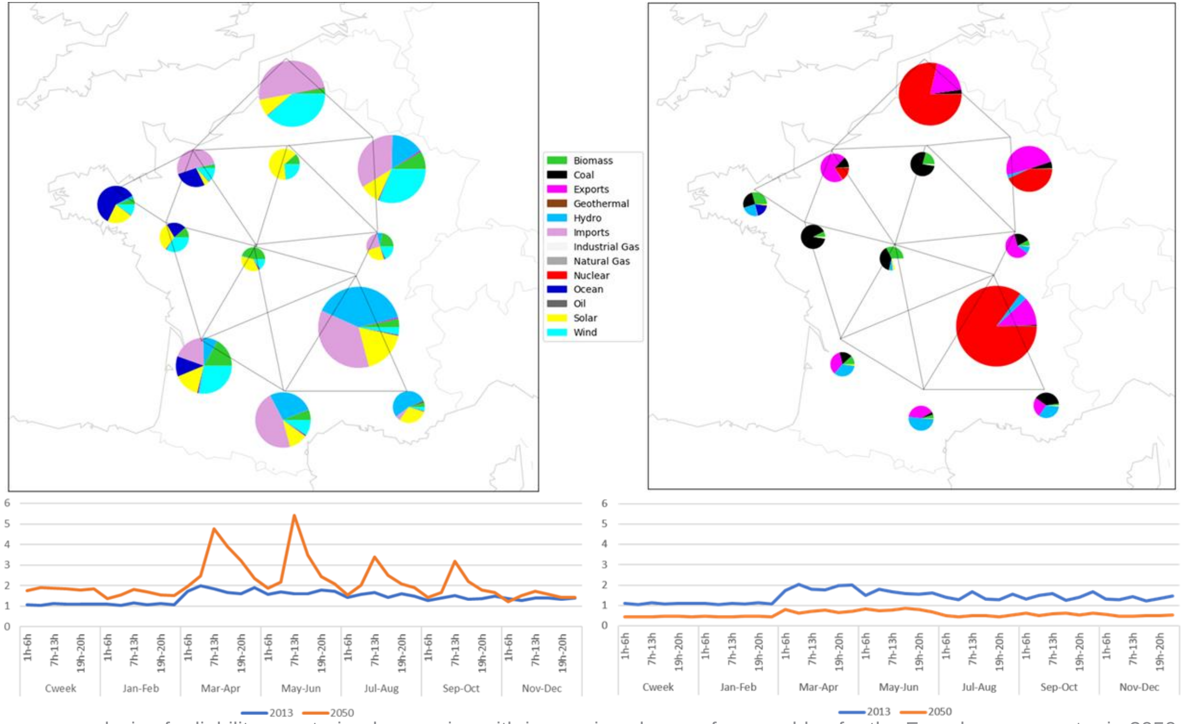
Regional mix under reliability constraints

100% REN generation

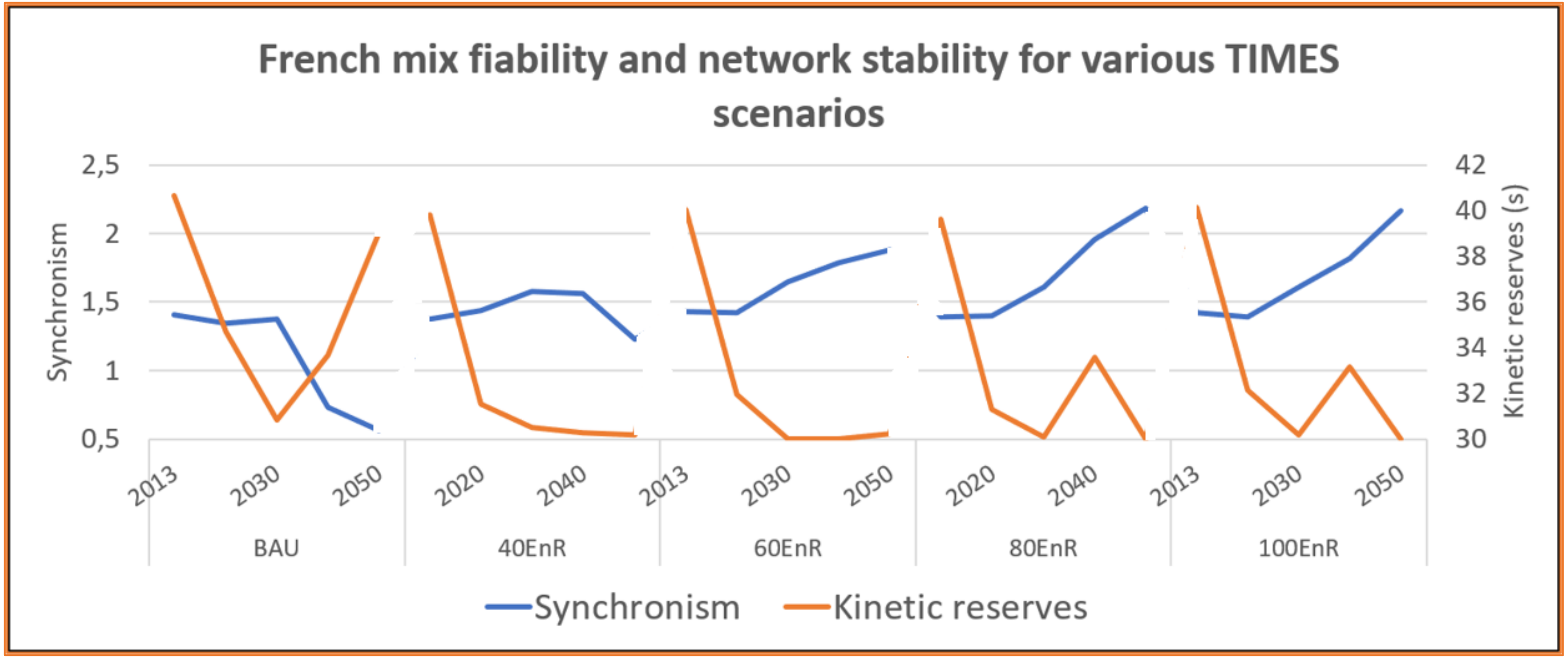
BAU generation



R. Cluet, N. Maïzi, V. Mazauric, space analysis of reliability-constrained scenarios with increasing shares of renewables for the French power sector in 2050, in proceedings of the International Conference on Applied Energy (Vasteras, Sweden) paper 1091, Aug. 12-15 2019.

R. Cluet, N. Maïzi, and V. Mazauric, "From centralized to decentralized power system: A space-analysis for France," *International Journal of Applied Electromagnetics and Mechanics*, vol. 64, pp. 73–78, 2020.

Transient stability *vs.* synchronism



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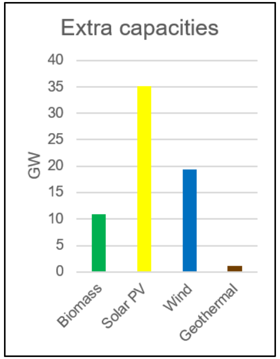
From “country” to “local” Renewable empowerment

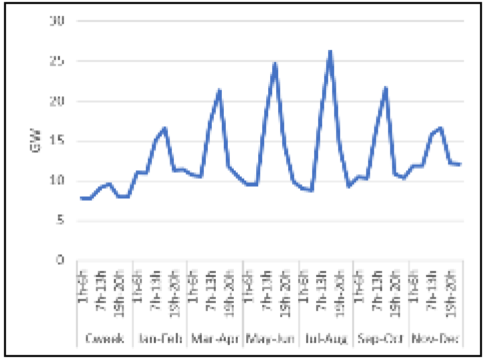
Realistic for balancing active energy (adequacy) for all regions except IdF (25 to 46%)

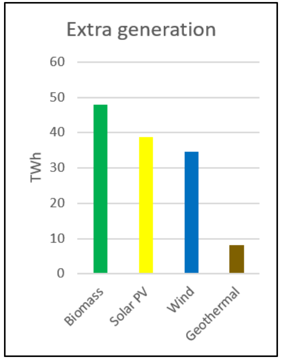
Low autonomy for ancillary services:

- Except RAA, HdF and Normandy
- High contribution of Biomass, Hydro and geothermy
- Implementation of 4GW storage (current STEP capacity)

Overgeneration of 124TWh







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Conclusion

Thermodynamics provides a natural and very efficient framework to derive an aggregated representation of dynamic systems

Grid synchronism is a critical issue to correctly aggregate kinetic energy and face to fluctuations:

- Centralized systems favors transient stability but needs grid reinforcement for the aggregation of kinetic energy; while
- Decentralized system favors synchronism but jeopardize transient stability by an intrinsic lack of kinetic energy. However, the constraint on synchronism is rejected on the distribution network (with lower voltage and extra losses) inducing investment at this scale;

➔ On-grid µ-grid concept consists in the first step of the grid transformation to host high share of renewables;

➔ Change the grid topology ("Russian dolls") to remain below the Kosterlitz transition… and achieve the power system decarbonation!

High variable renewable energy penetration seems technically feasible without jeopardizing the reliability, BUT:

- The necessity to use conventional flexible plants (biomass) which are functioning in extreme peak;
- The importance of power exchanges with neighboring countries;
- More implications of three options for flexibility to satisfy the reliability constraint: the Demand-Response, the storage technologies and the new interconnections (copper plate);

for which the environmental issue should be assessed!

Design should be performed at the largest scale :

- to ensure Cost-effectiveness;
- to size system adequacy AND ancillary services!
- To take externalities into account (scarcity of functional material and IT energy footprint)

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