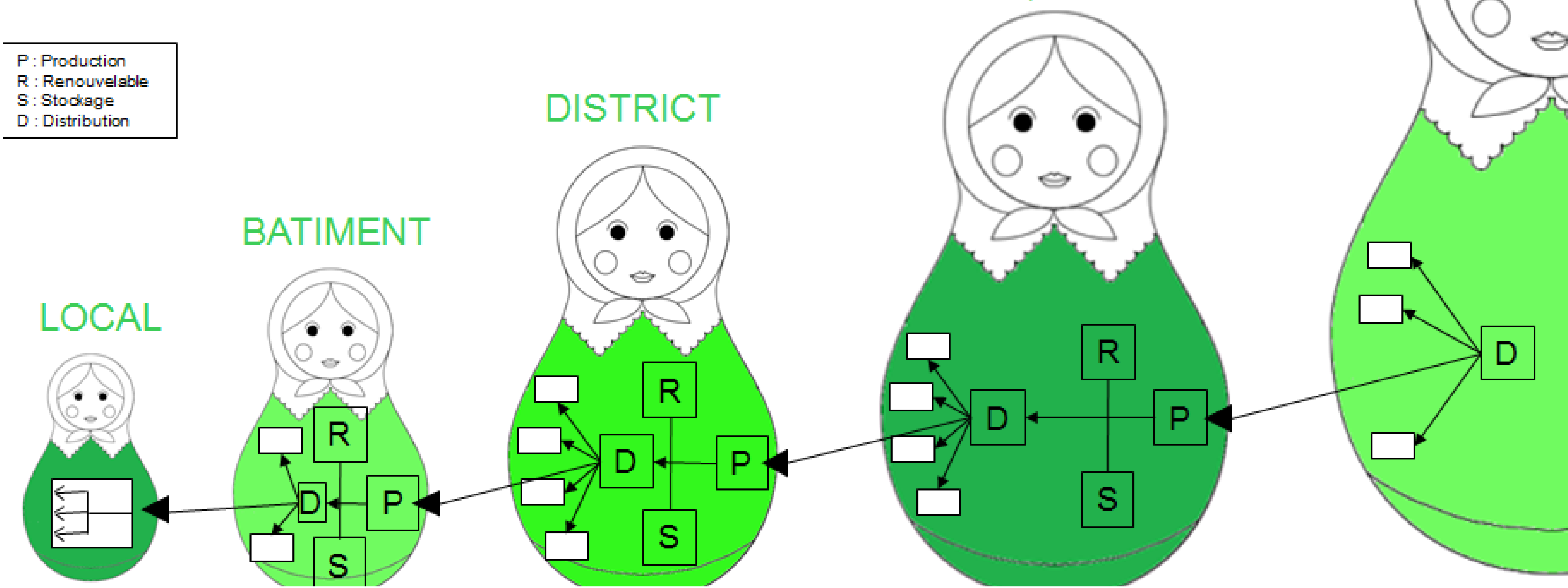

Proposition thermodynamique

pour une vision agrégée du système électrique

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Motivation

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

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

- Provide a suitable description of power flows:
    - Supply vs. Demand adequacy
    - Ancillary services

  to desintricate power management features

- 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

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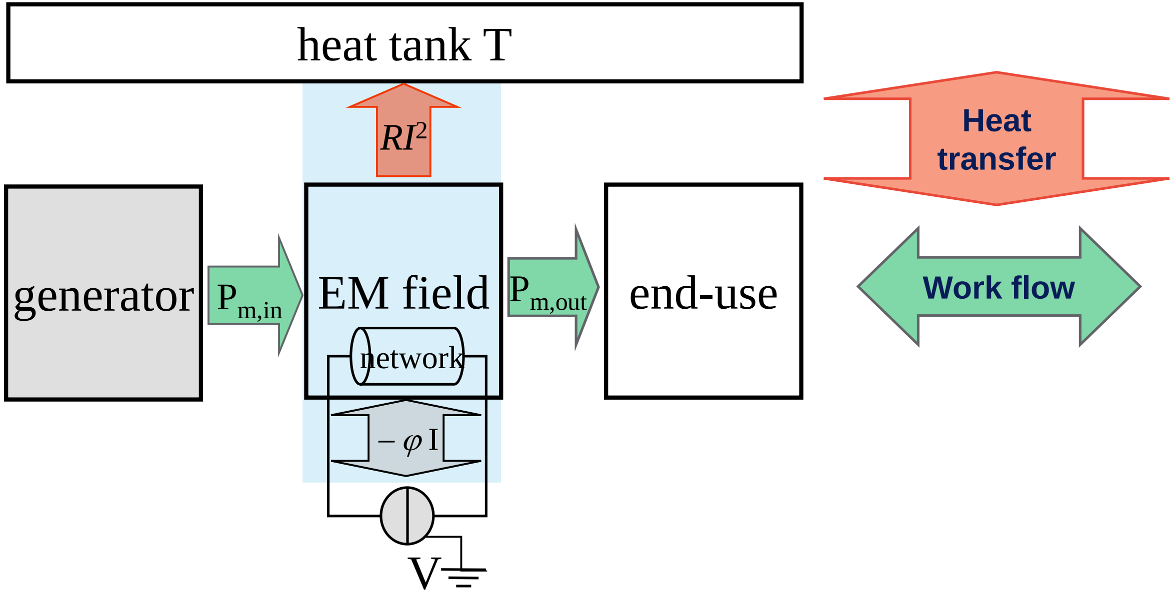
Electromagnetism: from steady-state to transient regimes



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:

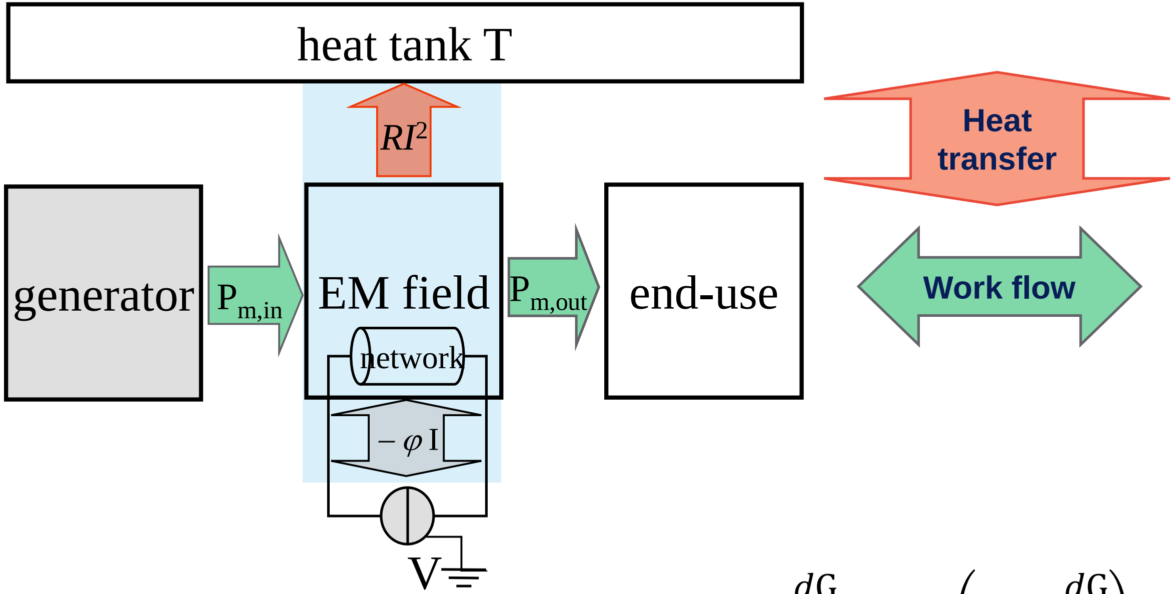
➔ Decouple control and power flow

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

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

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.

Electromagnetism: A natural trend towards reversibility



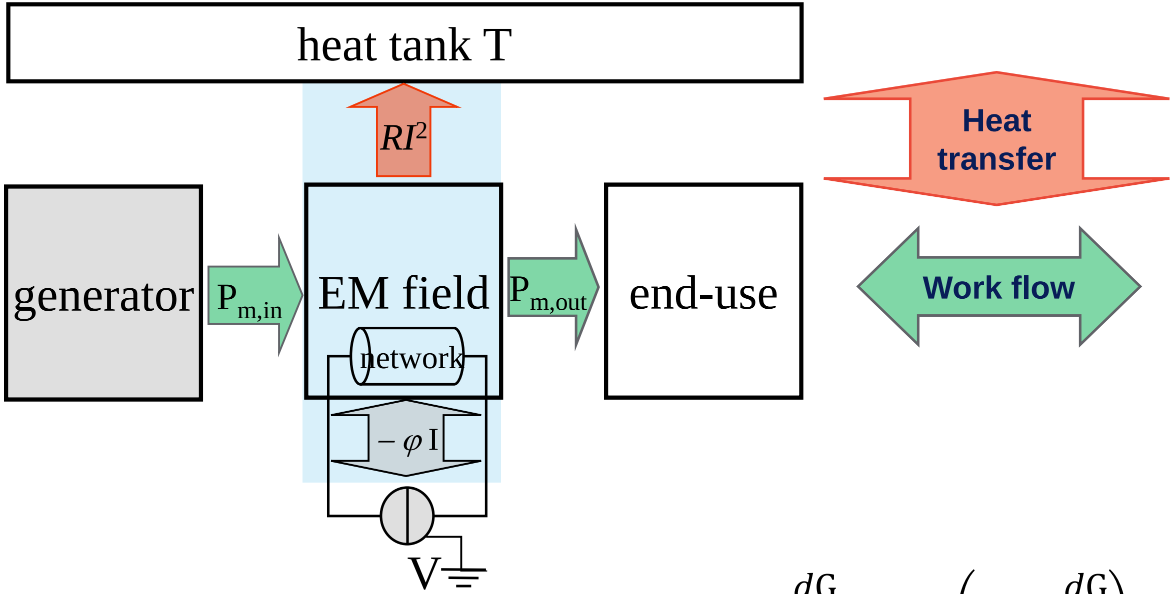
Weak reversibility :

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

2nd principle of thermodynamics:

$$P_m - \frac{dG}{dt} \geq 0$$

Electromagnetism: A natural trend towards reversibility



Weak reversibility :

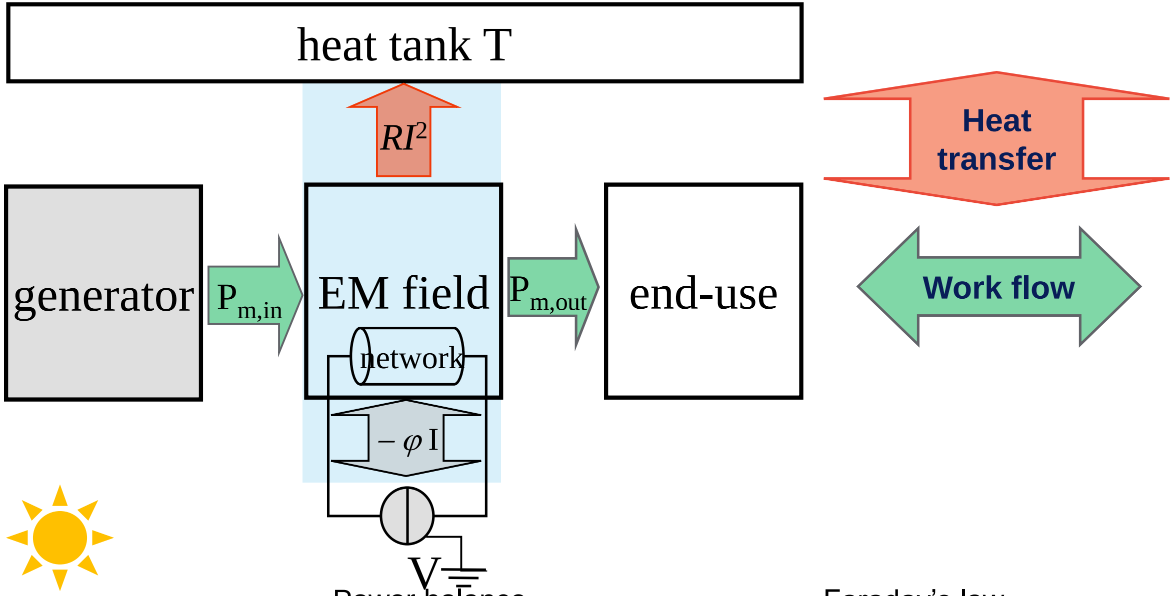
$$P_m - \frac{dG}{dt} = \min\left(P_m - \frac{dG}{dt}\right) \geq 0$$

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:

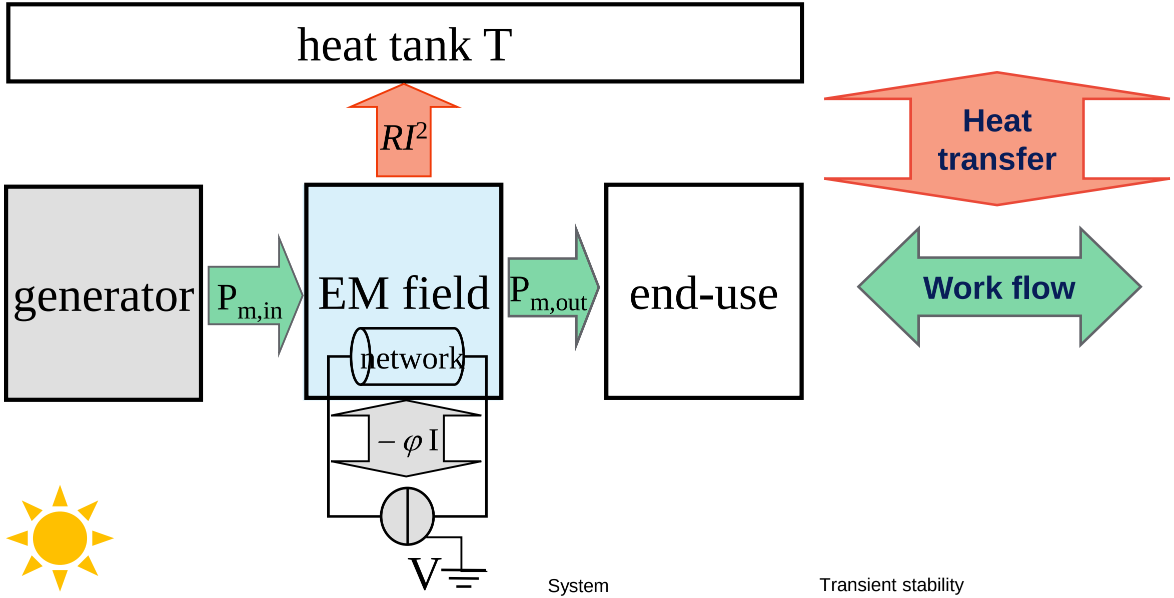
- Electromagnetic energy w/ coupling G
- Kinetic energy E_{kin}

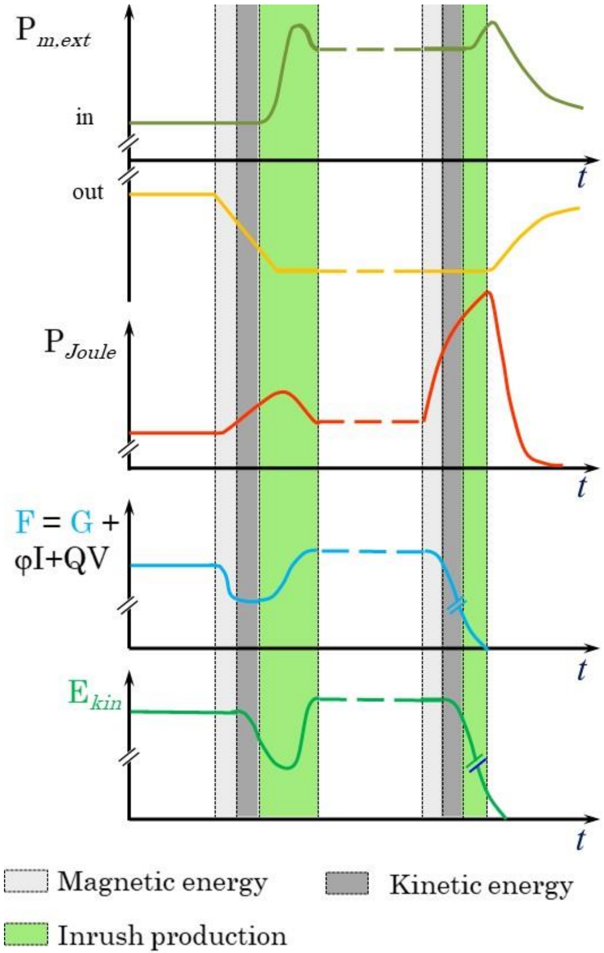
➔ Conversely, provide means for:

- time-reconciliation, and
- space-analysis

Power management: Basics

Focus at the higher aggregated scale



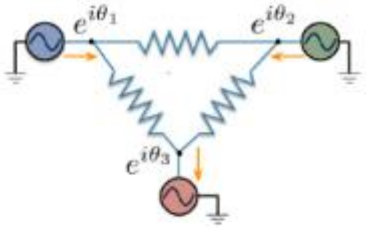


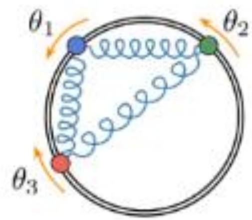
Poynting equation: $$\underbrace{P_{elec}}_{\text{fatal}} + \overbrace{\underbrace{P_{m,ext}}_{\text{min-hour fatal}}}^{\text{System adequacy}} = P_{Joule} + \overbrace{\underbrace{\frac{dE_{kin}}{dt}}_{\text{seconds}} + \underbrace{\frac{dF}{dt}}_{\text{ms}}}^{\text{Transient stability (ancillary services)}}$$

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:

- Coherence of fully-correlated oscillator population:
- Synchronism is ensured for tight enough binding (admittance matrix):

derived (virtual works) from the Gibbs free-energy G

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

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

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.

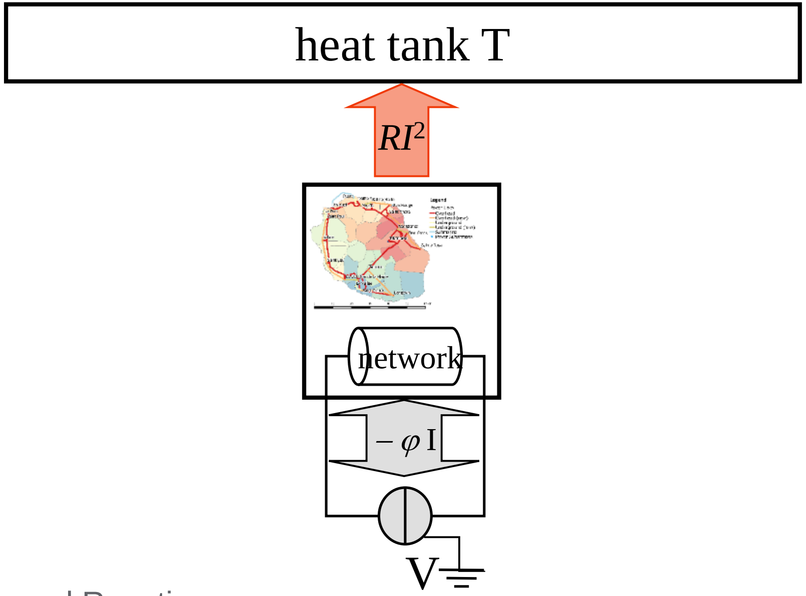
- Disordering factors:
  - N→∞ (long range disordering modes)
  - Intensive use of transmission lines
  - High frequency

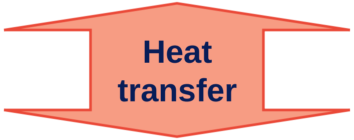
- Ordering factors:
  - Lattice interaction and admittance
  - Locally balanced connection point
  - Low frequency

Synchronism 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



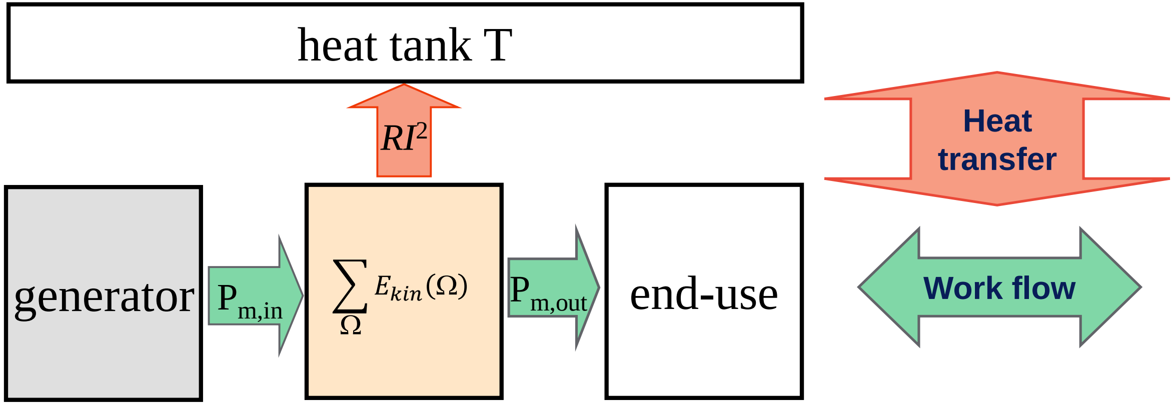


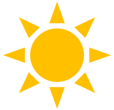
Synchronism:

- Voltage plan conditions and Reactive power
- Gibbs free-energy G induces electrodynamic resistant torque
- « Rigidity »-induced synchronism and space-aggregation:
  - ➔ 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



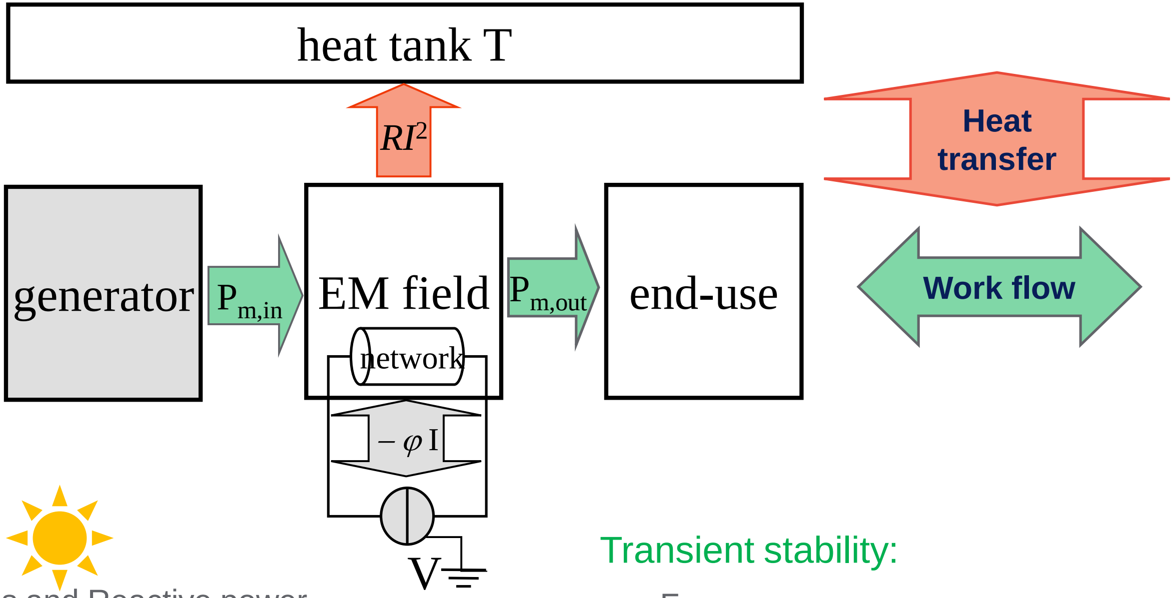


Transient stability:

- 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

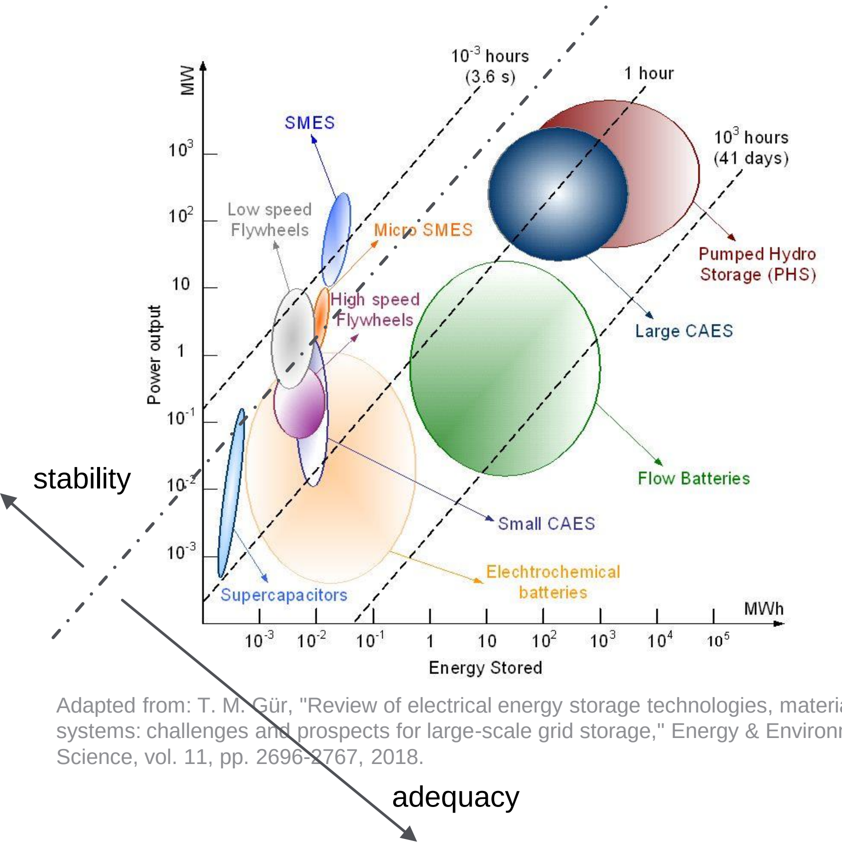
Power management: Forthcoming competitions

Naturally expressed within the second principle:

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

	flexibility	adequacy	stability		coupling
Sources	hν wind storage DSM		hydro (dam) conv. power plant		
Interfaces	grid-tie inverters			grid-forming inverters	
Functional materials	Si(C) Ga Dy, Nd Li		kg	Fe Si(C) Ga	Cu, Ag, Al

Stability vs. Adequacy issues



Adapted from: T. M. Gür, "Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage," Energy & Environmental Science, vol. 11, pp. 2696-2767, 2018.

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

Adequacy leverages flexibilities but is limited by:

- ➔ IT energy for dispersed asset management
- ➔ Tension on functional materials
- ➔ Stability issue

Mixed line is derived from: 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.

Conclusion

Thermodynamics provides a natural and very efficient framework to derive an aggregated representation of power system dynamics.

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.

For an expected level of reliability, forthcoming power mixes will result from trade-offs between:

➔ Variable installed capacity and storage-induced inertia with subsequent tension (circularity/extraction) on functional materials for “clean” power management; and

➔ Inertia and control of flexibilities with subsequent extra-energy for dedicated ICT to enforce adequacy.

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