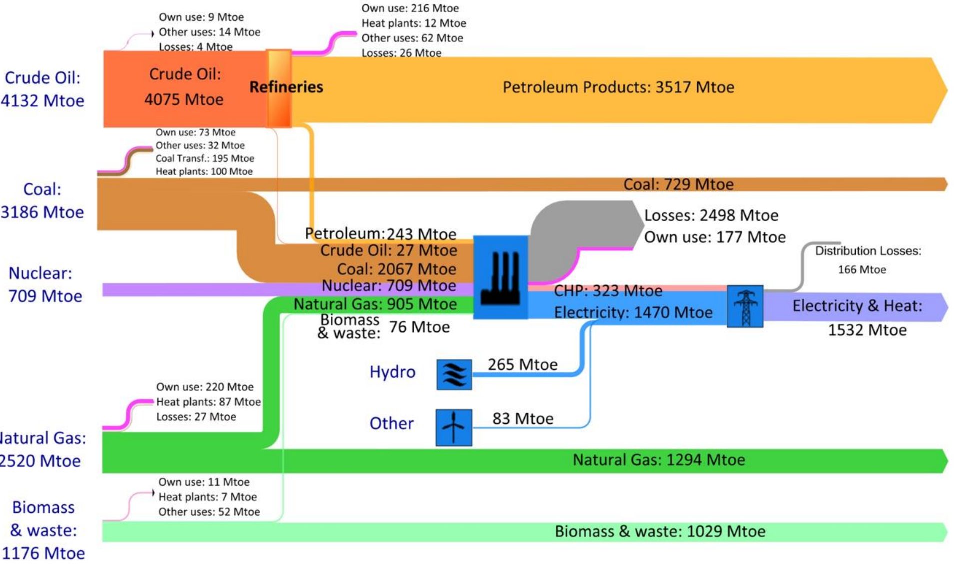
Entanglement of Energy, Material, and Informational Challenges for Attaining a Sustainable Global Future

Vincent Mazauric, Schneider Digital
vincent.mazauric*se.com

Life Is On | Schneider Electric

Energy supply Chain



From IEA 2007
otherwise: https://www.iea.org/Sankey/

Life Is On | Schneider Electric

A tight equation towards sustainability

The energy dilemma is here to stay

Demography:

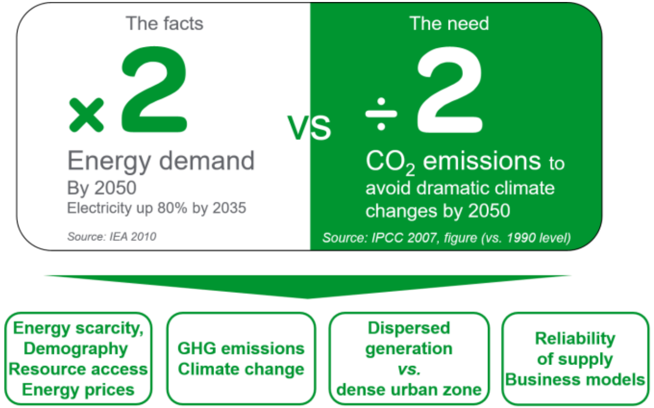
- Rise of energy systems in developing countries
- Refurbishment of existing capabilities in developed countries
- Urban population, from 50% today to 80% in 2100, claims for high-density power grids

The Earth: An isolated chemical system

- Fossil (and fissil) fuels depletion:
  - Conventional peak oil around 2020
  - Peak gas around 2030 (excluding shale gas)
  - Around two centuries for coal or Uranium (GIII)
- Climate change:
  - Whole electrical generation provides 45% of CO2 emissions
  - Global efficiency of the whole electrical system is just 27% (37% for all fuels)
  - Despite a thermodynamic trend toward reversibility

The Earth: A fully open energy system

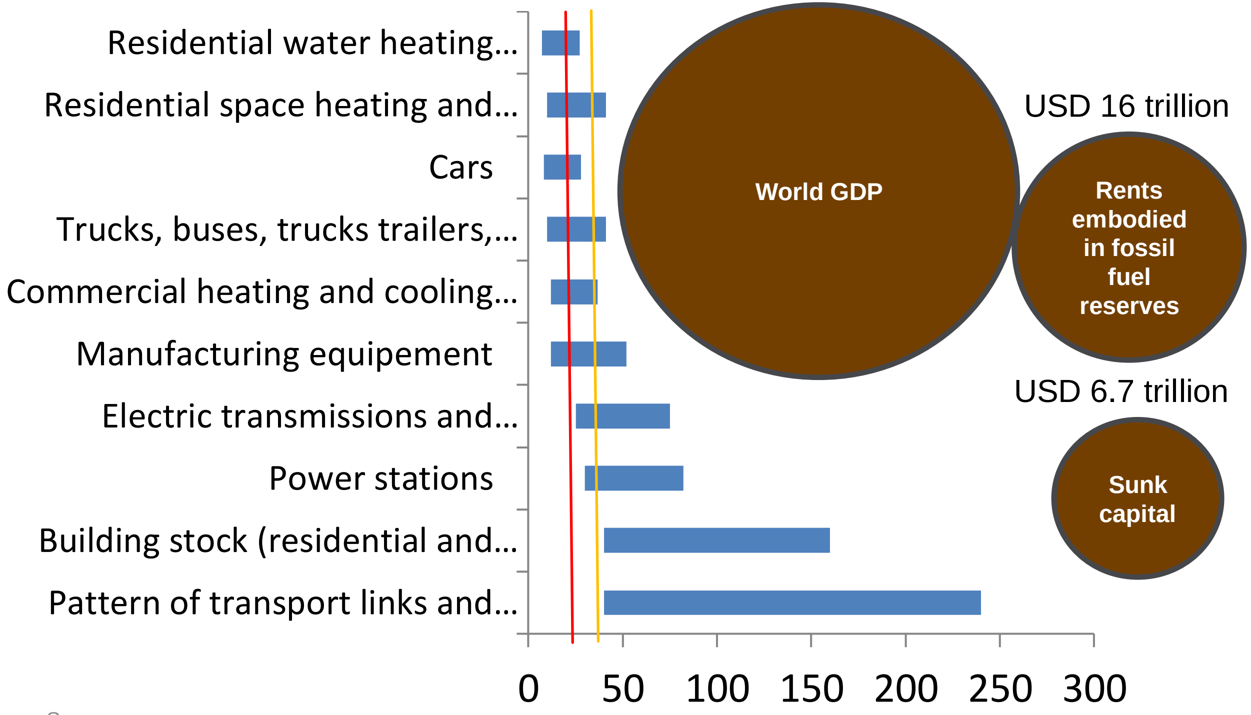
- Domestic energy is 10.000 times smaller than natural energy flows:
  Solar direct, wind, geothermy, waves and swell…
- But very diluted and intermittent



Life Is On | Schneider Electric

The "big picture" for changing

Overcome the inertia to walk to our future

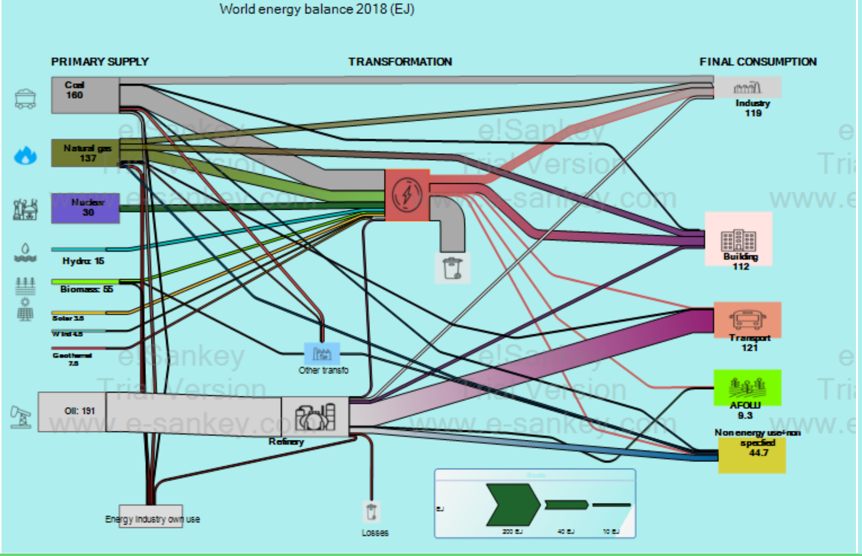


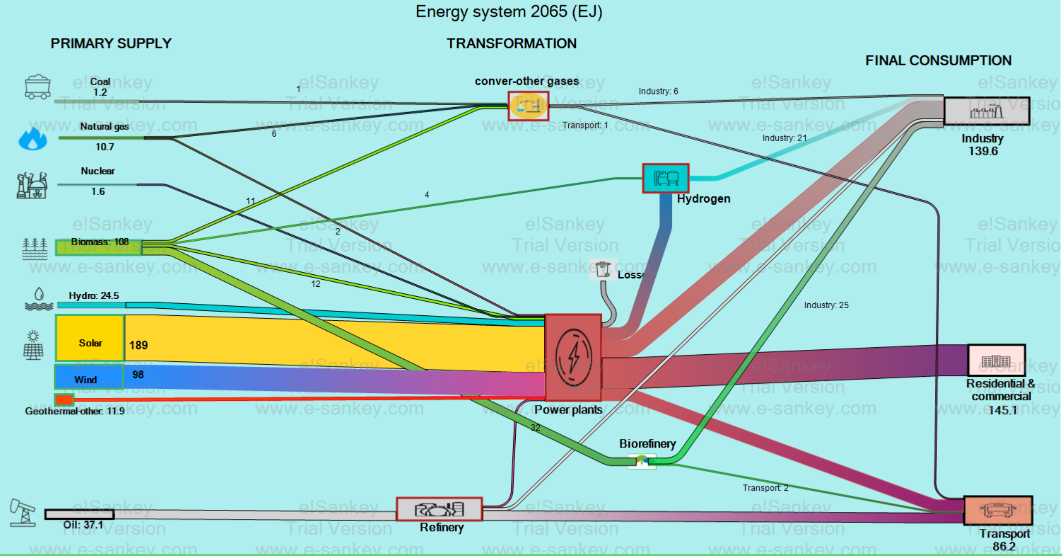
Global space and time duality:

- Geopolitics (space)
- Inertia (time) for:
  - design and
  - implementation
- Deadline for Carbon-free society:
  - 2°C
  - 1.5°C (Paris agreement)

Sources:

- OECD Green Growth Studies: Energy (2011); World Bank.
- https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf



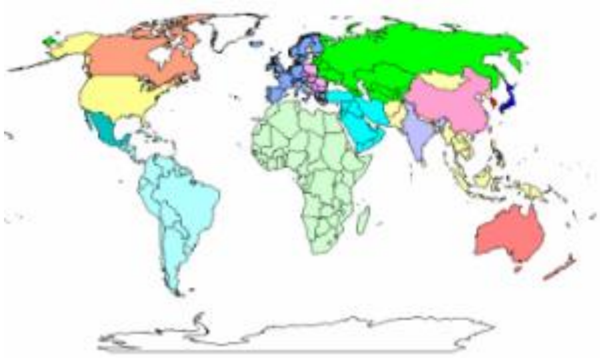


From IPCC 6th Assessment Report, Chapter 6, 2022

Why long-term planning?

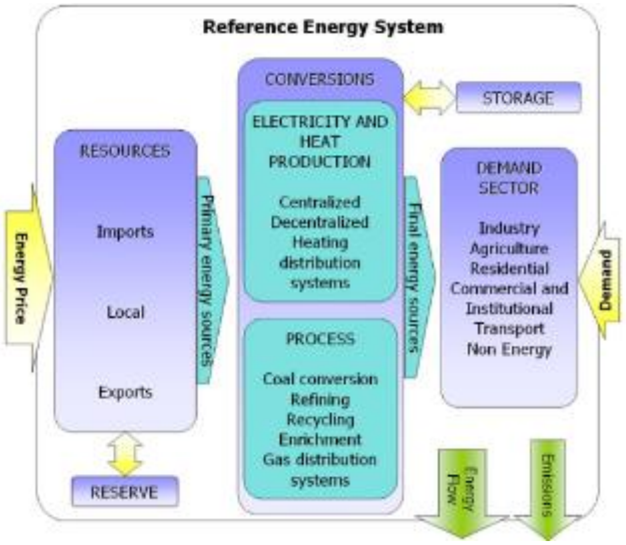
Necessity to Urge of planning tool

The TIAM-FR optimization model



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

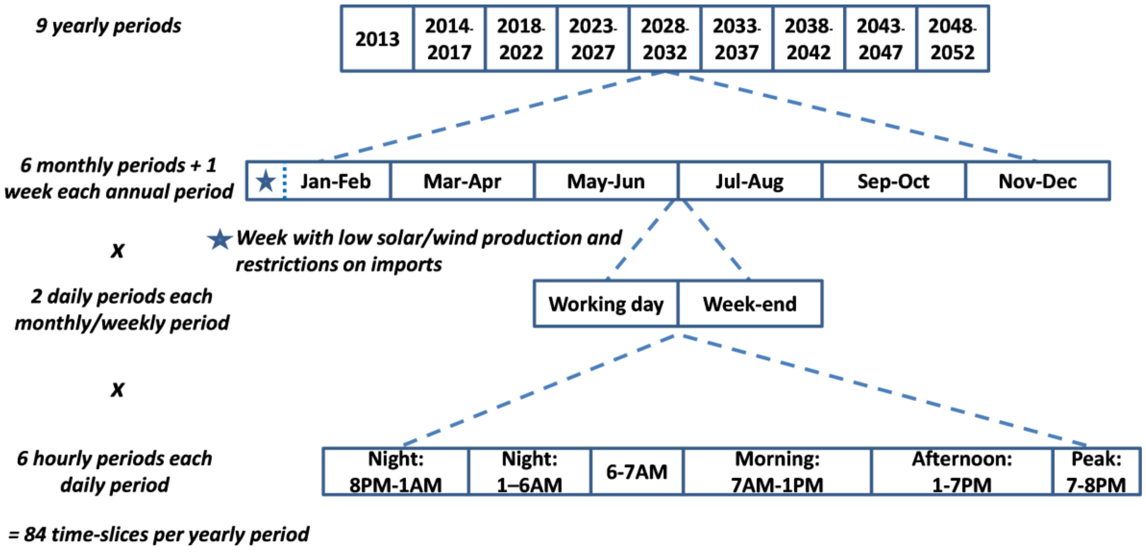
- for the reference energy system:
  - 3,000 technologies,
  - 500 commodities;
- subject to a set of relevant technical and environmental constraints:
  - CO_2 emissions
  - Nuclear phase-out
- over a definite horizon, typically long-term (50 years)
- 15 regional areas



www.modelisation-prospective.org

Life Is On Schneider Electric

Modeling features



R. Loulou, U. Remme, A. Kanudia, A. Lehtila, G. Goldstein: Documentation for TIMES model. Energy Technology Systems Analysis Programme (ETSAP), 2005.
R. Loulou, G. Goldstein, A. Kanudia, A. Lehtila, U. Remme. Documentation for the TIMES model. Energy Technology Systems Analysis Programme, 2016.
M. Gargiulo: Getting started with TIMES VEDA, Version 2.7, https://iea-etsap.org/index.php/documentation, 2009.
R. Loulou and M. Labriet, “ETSAP-TIAM: the TIMES integrated assessment model part i: Model structure,” Computational Management Science, vol. 5, no. 1-2, pp. 7–40, 2008.

Total discount cost:

$$NPV = \sum_{r\in R}\sum_{y\in Y}\left(1+\alpha(r)\right)^{y_{\text{ref}}-y} ANNCOST(r,y)$$

Constraints:

- commodity balance (in>out)
- Peak Reserve factor, ajusted to:
  - France 28%
  - La Reunion 69%
- Emissions, potentials, phase out, etc.

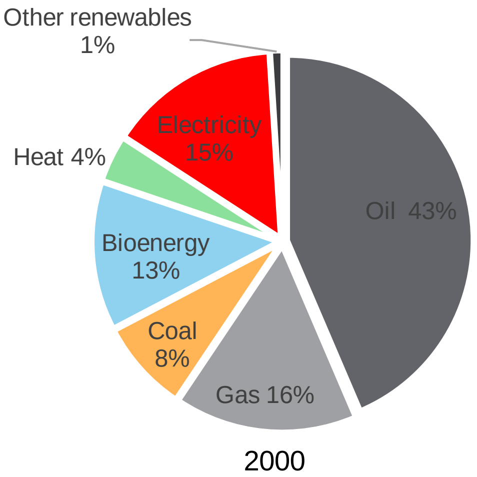
Database:

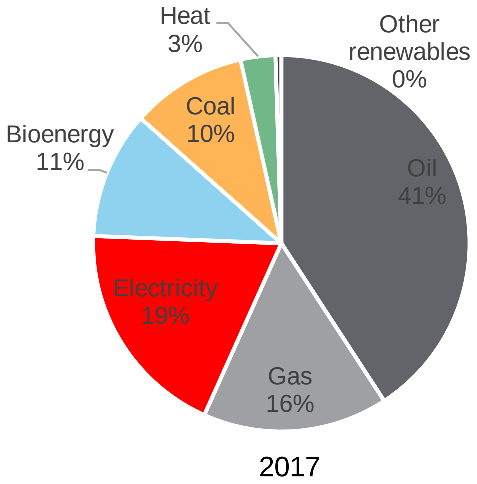
- Cost inventory on technologies (standard)
- Kinetic energy (specific for stability)

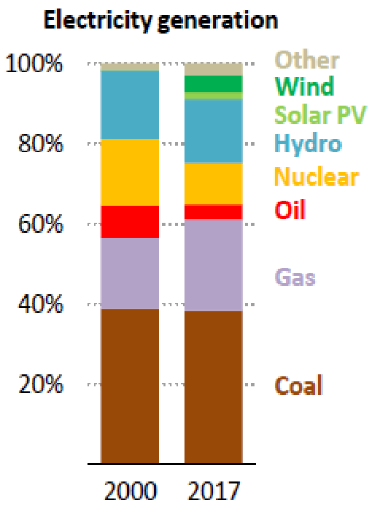
Optimization methods:

- Linear programming (adequacy only)
- Mixed Integer Linear Programming otherwise

Life Is On Schneider Electric



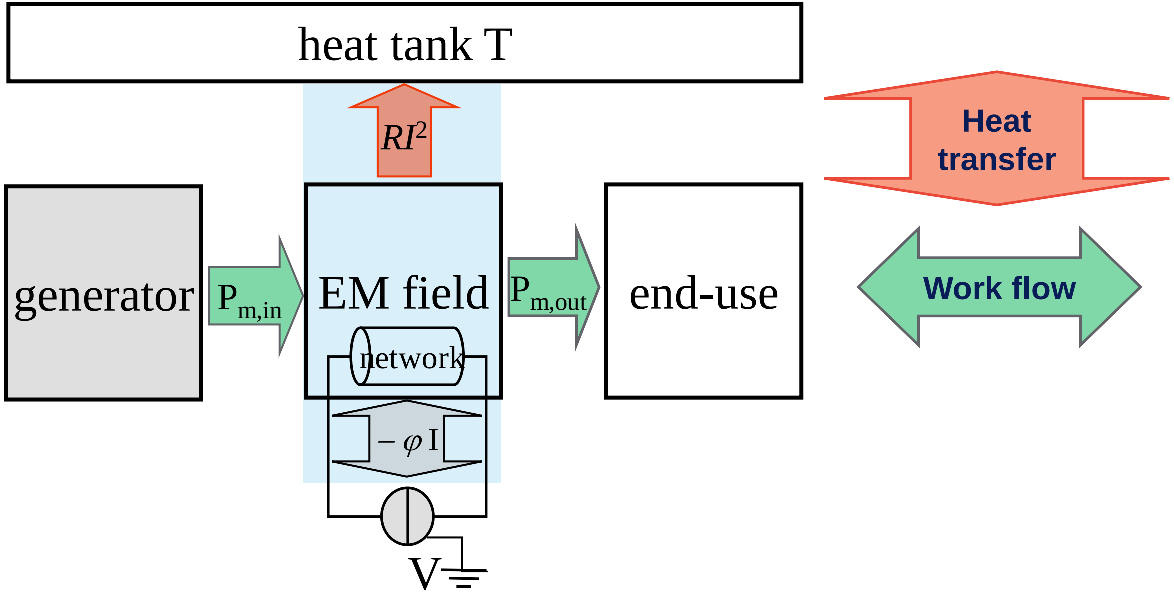




Total final energy (2000-2017) and electricity generation mix

Why electricity?

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:

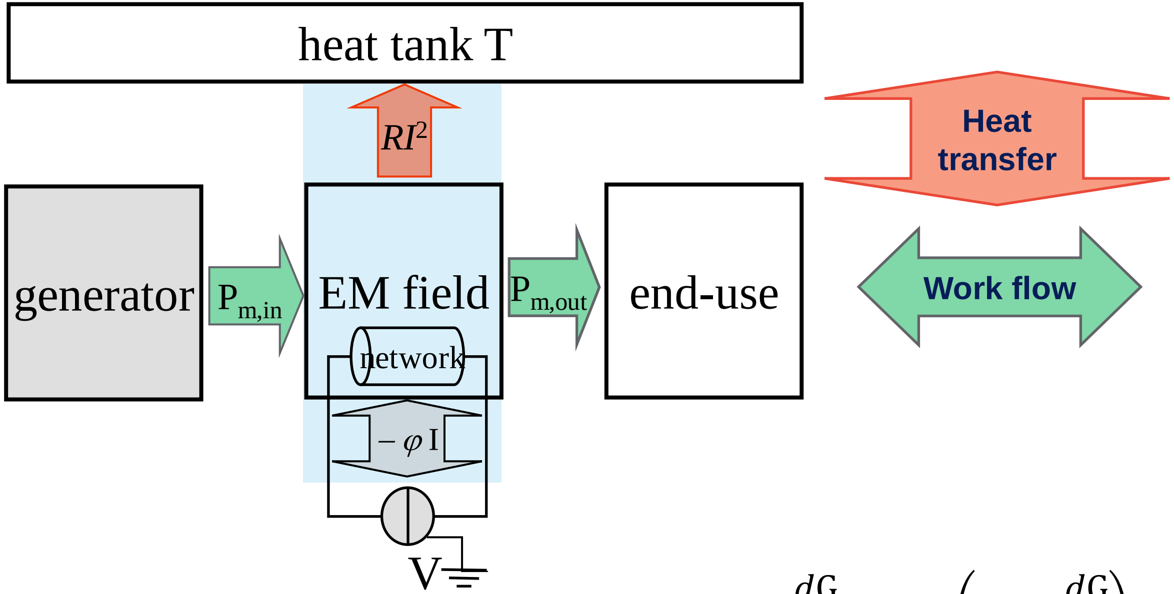
➔ Decouple control and power flow

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

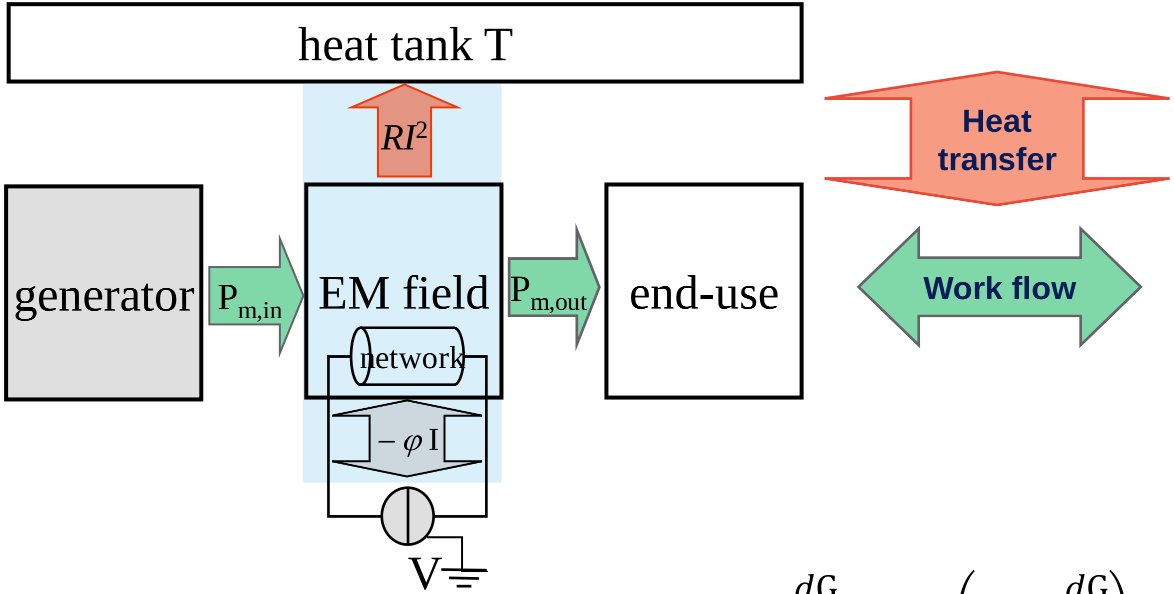
Electromagnetism: A natural trend towards reversibility



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

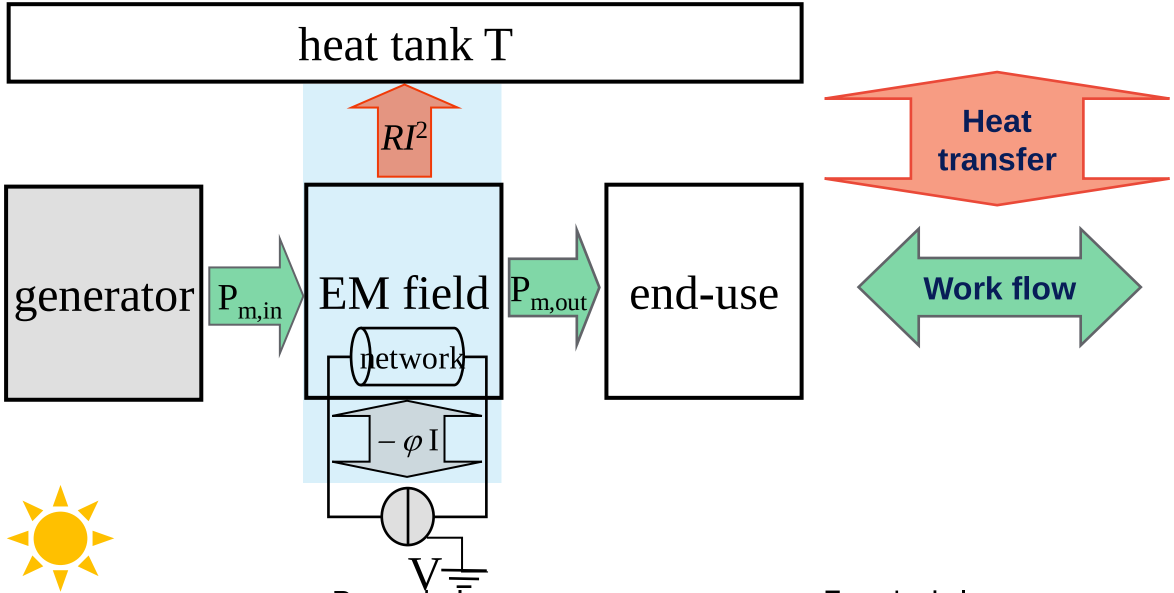


Weak reversibility : $$P_m - \frac{dG}{dt} = \min\left(P_m - \frac{dG}{dt}\right) \geq 0$$

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



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 balance — Faraday's law

Radiation

Inertia

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

Lenz law

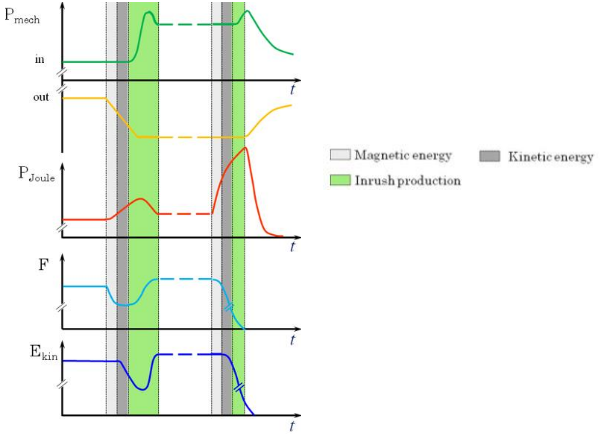
Classical electrodynamics revisited

	Axiomatic (1870)		Thermodynamics
Sources		$\operatorname{div}\mathbf{j}+\frac{\partial\rho}{\partial t}=0$	
Source fields		$\operatorname{div}\mathbf{D}=\rho$ $\mathbf{curl H}=\mathbf{j}+\frac{\partial\mathbf{D}}{\partial t}$	
Electromagnetic fields	$\mathbf{curl\ E}=-\frac{\partial\mathbf{B}}{\partial t}$ $\operatorname{div}\mathbf{B}=0$		Weak-reversibility 1st principle
Behavior laws	$\mathbf{B}(\mathbf{H}),\mathbf{D}(\mathbf{E}),\mathbf{J}(\mathbf{E})$		2nd principle
Mechanical coupling	$\mathbf{f}=q(\mathbf{E}+\mathbf{v}\times\mathbf{B})$		1st principle (virtual work)
Invariance			Joule losses/Galilean
Lack	Spoilt/Galilean		High frequency
	7 hypotheses		5 hypotheses (4 from energy)

Power management

Before adequacy and support from primary/secondary/tertiary reserves

1st insight: role of invariants



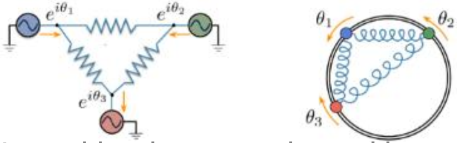
- Poynting equation

$$\underbrace{P_{elec}}_{\text{fatal}} + \overbrace{\underbrace{P_{m,ext}}_{\text{min}-\text{hour}}}^{\text{adequacy}} = P_{Joule} + \overbrace{\underbrace{\frac{dE_{kin}}{dt}}_{\text{seconds}} + \underbrace{\frac{dF}{dt}}_{\text{ms}}}^{\text{transient stabibilty}}$$

→ Leverage the highest kinetic energy

M. Drouineau, N. Maïzi, and V. Mazauric, "Impacts of intermittent sources on the quality of power supply: The key role of reliability indicators," Applied Energy, vol. 116, pp. 333-343, 2014.

2nd insight: role of synchronism



→ Upper kinetic energy bound is enforced by synchronism

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

- Coherence of fully-correlated oscillator population: to identify from virtual works

$$\ddot{\theta}_i + d_i\dot{\theta}_i = \omega_i - \overbrace{\sum_j k_{ij}\sin(\theta_i - \theta_j)}^{\text{to identify from virtual works}}$$

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

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

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.

3rd insight from phase transition

- Machines consist in X-Y magnets

- On a regular and infinite lattice:
  - Ising spin interaction provides long-range order for D≥2
  - No long-range order for D<3 for Heisenberg spins
  - → X-Y model in 2D is the marginal case for long range order inducing synchronism

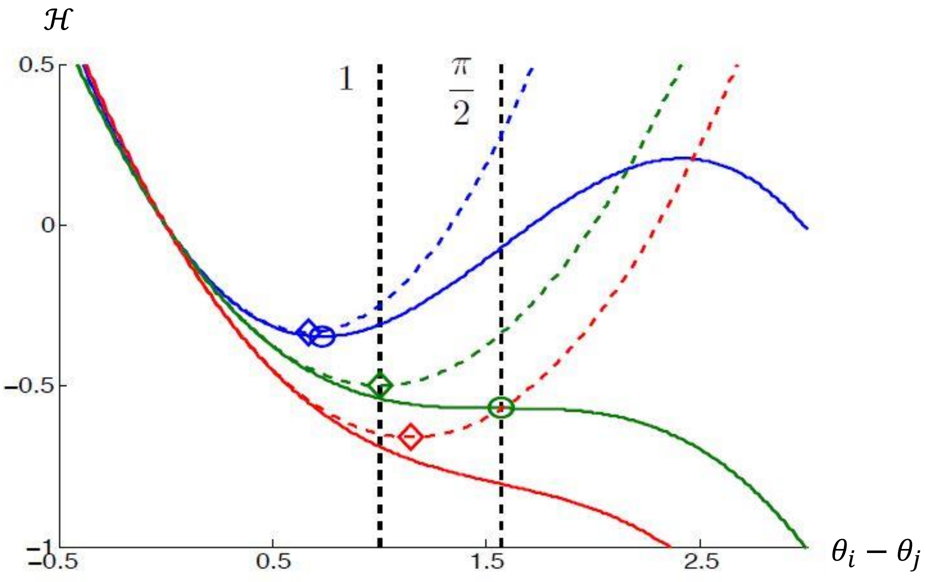
→ Synchronism is not unconditionally stable

→ Quantitatively reconcile phase transition with QS electromagnetics

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

Swing equations



Reduced 2nd order Kuramoto model:

$$\ddot{\theta}_i + d_i\dot{\theta}_i = \omega_i - \sum_j \mathrm{k}_{ij}\sin(\theta_i - \theta_j)$$

Stability is discussed:

- From the Hamiltonian/potential from which is derived the RHS of the swing equation

$$\mathcal{H} = \sum_{<ij>} \mathrm{k}_{ij} \underbrace{\left(1 - \cos(\theta_i - \theta_j)\right)}_{\text{spin alignement given by G}} - \sum_i \underbrace{\omega_i \cdot \theta_i}_{\text{external field}}$$

- within a linear development near the minimum (Hookean potential, dashed lines)

The higher the locally power supplied ω_i:

- the weaker the stability;
- The more critical the support from the grid

Fatal generation issue (*e.g.*, wind gust) requires "real-time" adaption of k_{ij}:

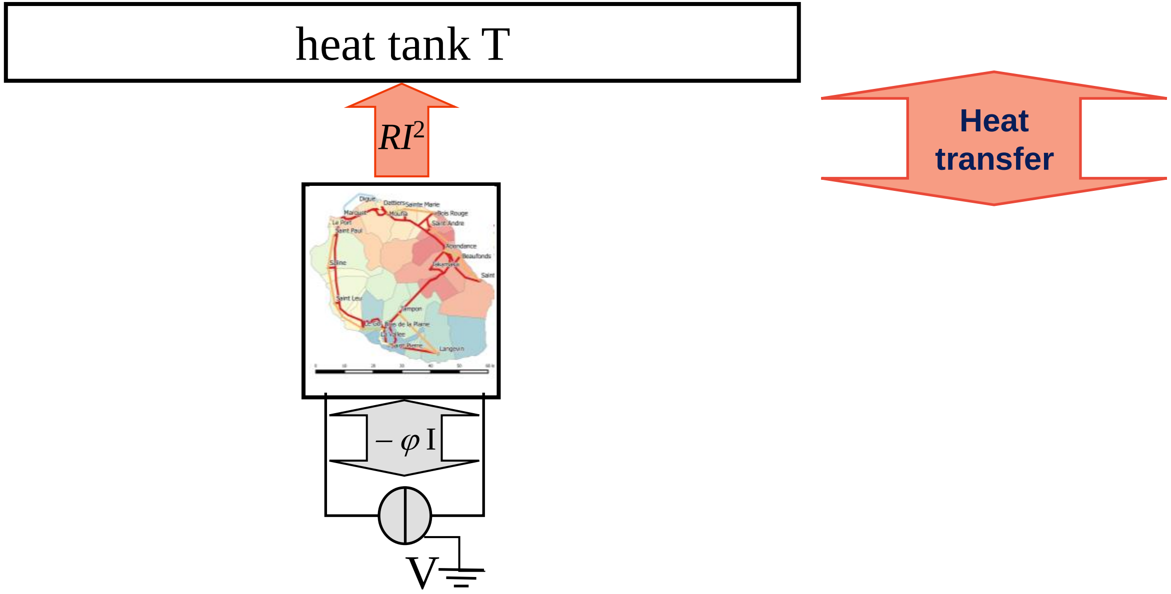
- to involve asset within stability issue

→ "Grid forming" inverters

Life Is On

Schneider Electric

Power management: Decoupling control and power flow

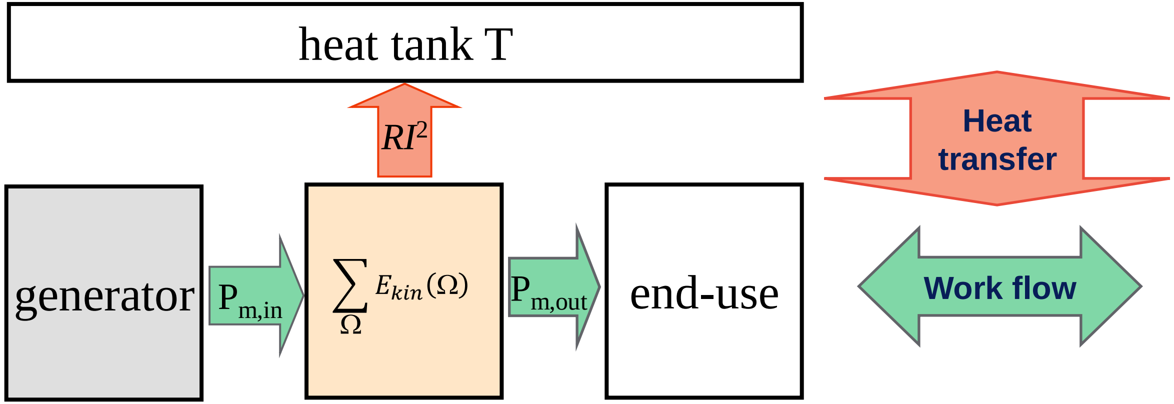


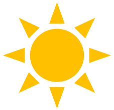
Synchronism:

- 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

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

Power management: Decoupling control and power flow





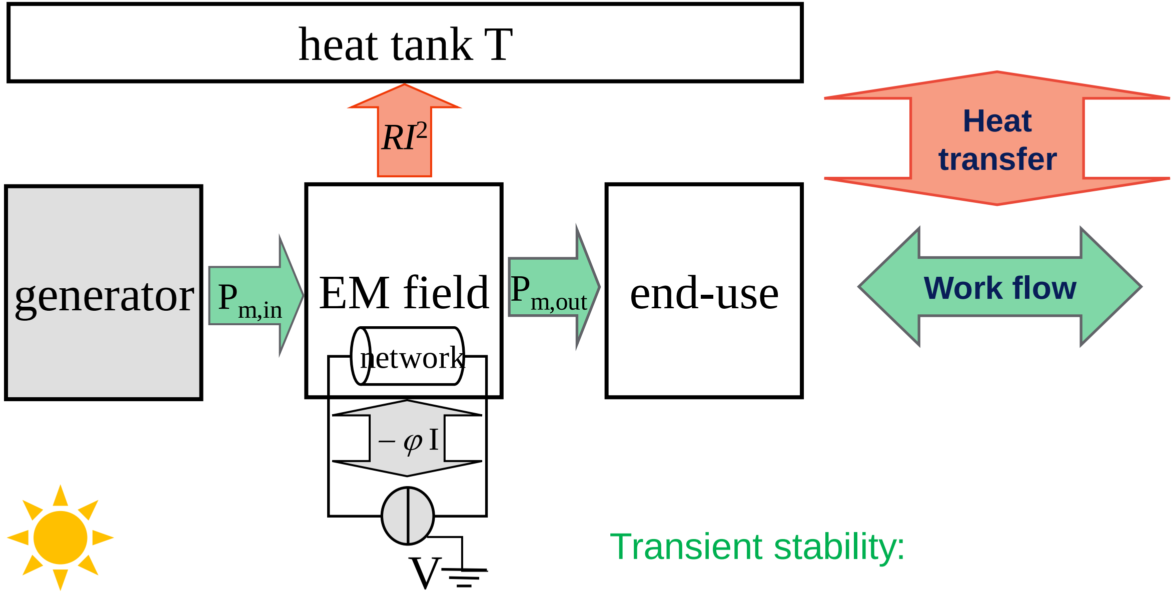
Transient stability:

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

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

Life Is On Schneider Electric

Power management: Decoupling control and power flow



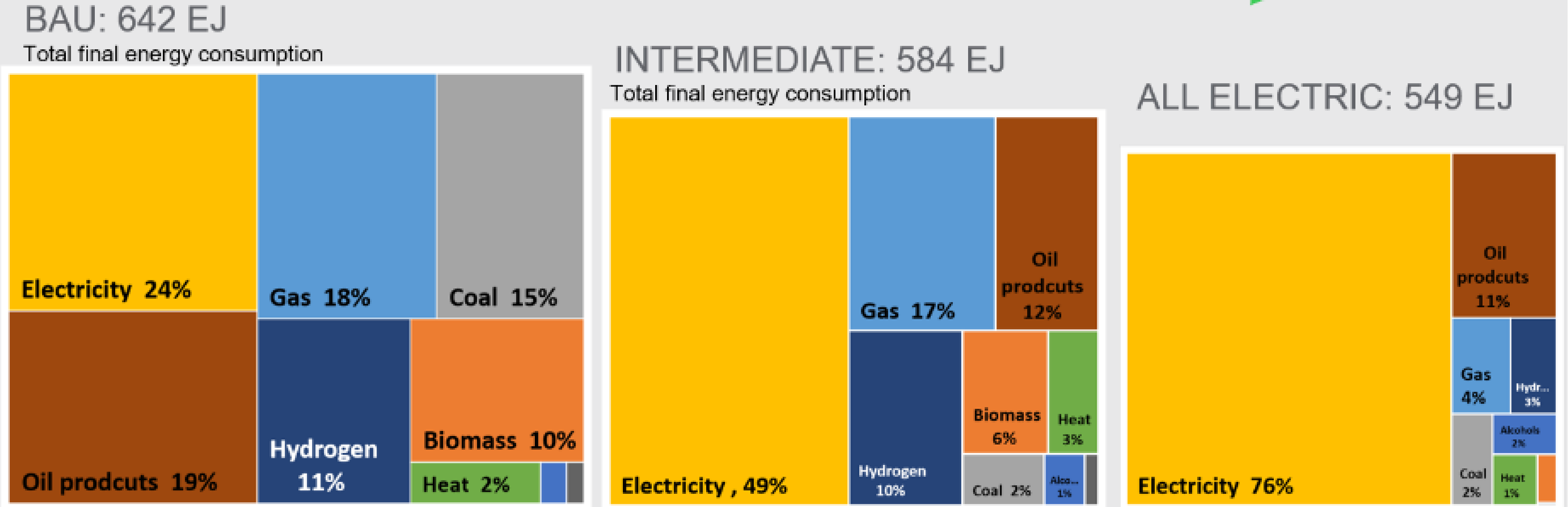
Synchronism:

- 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

Transient stability:

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

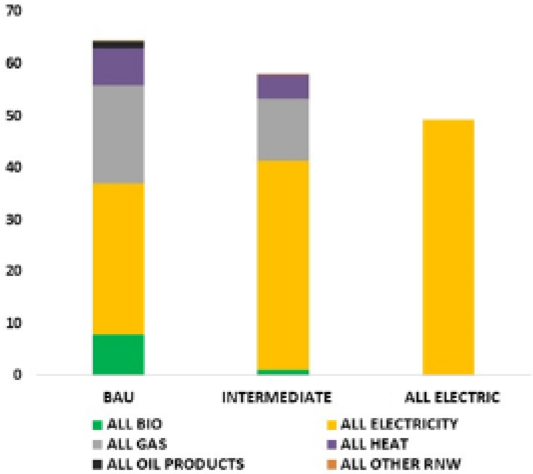
Active power flow exchanged throughout the grid



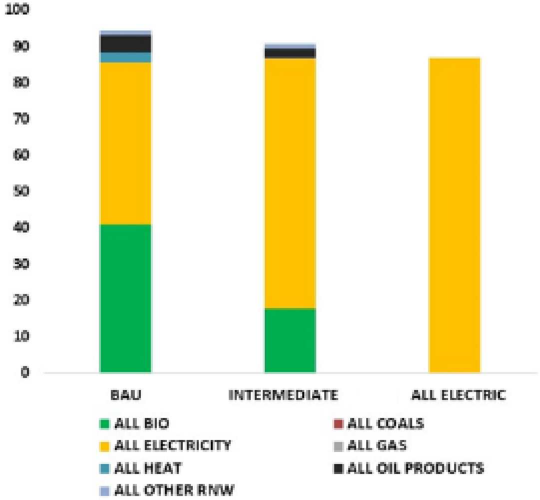
Total final energy consumption by 2050

Towards an all electric world?

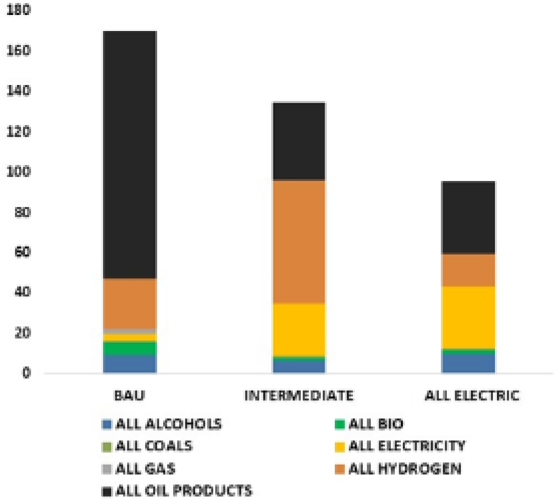
Commercial



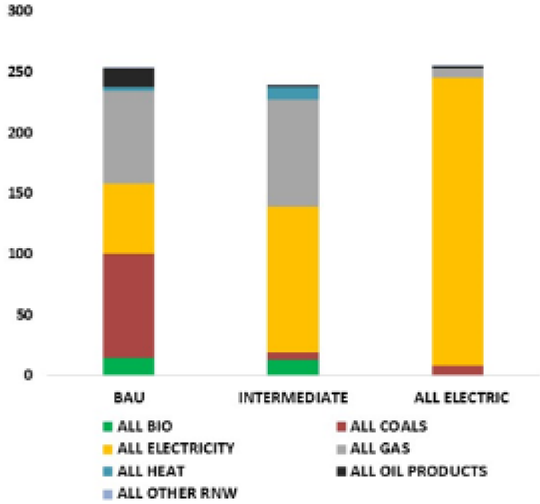
Residential



Transport

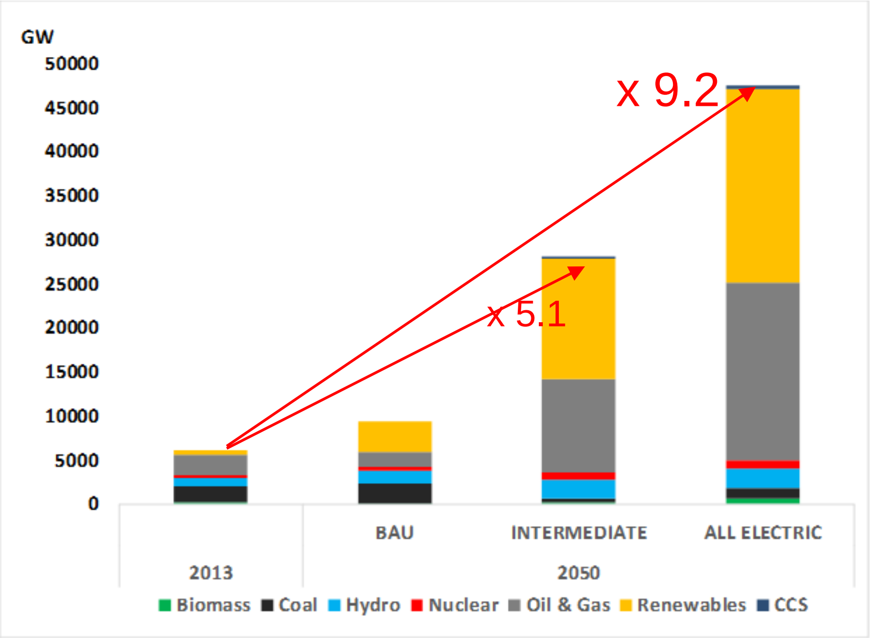


Industry

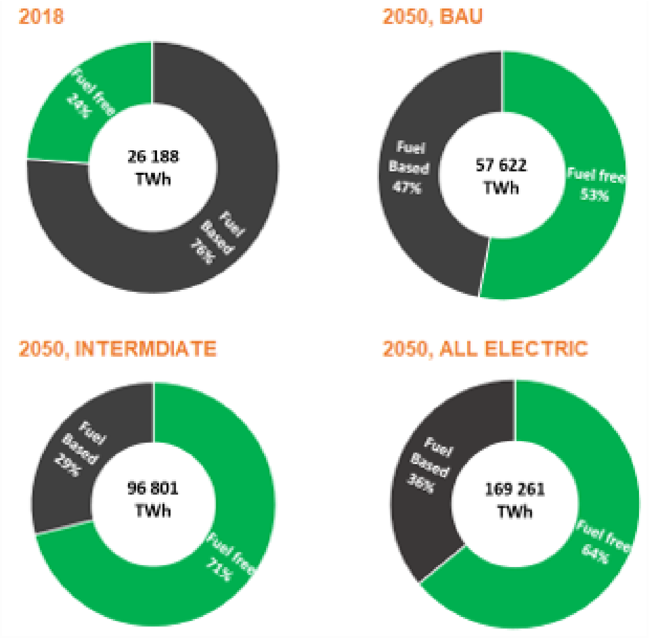


Power generation mix

Power supply requires massive investments in renewables supported by gas-based generation

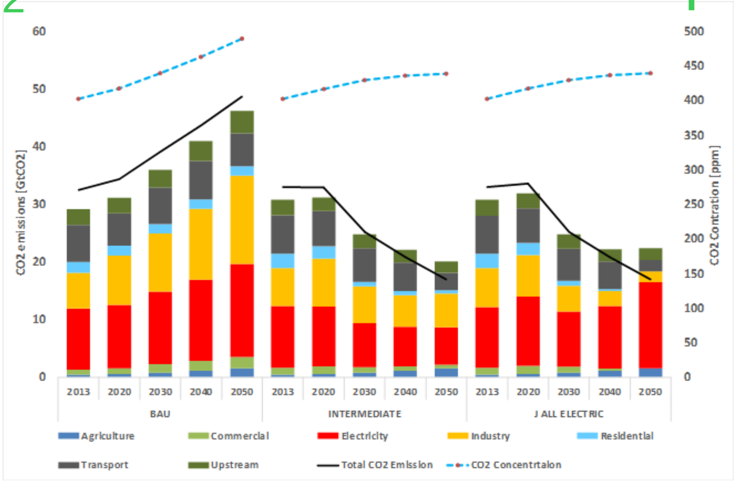


Installed capacity by 2050

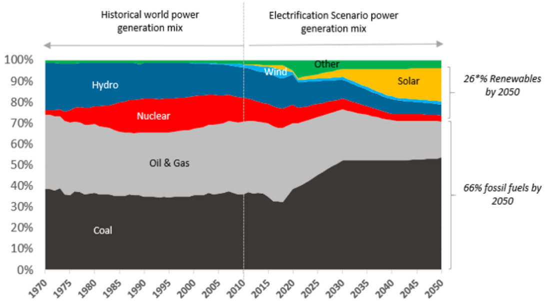


Power generation by 2050

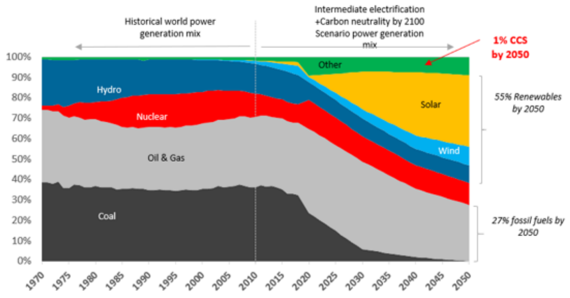
Global/sectoral CO_2 emissions and related power mixes



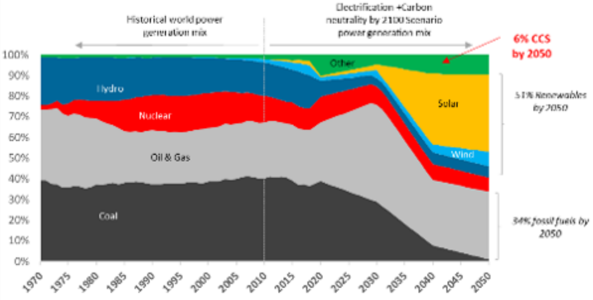
CO_2 emissions per sector



INTERMEDIATE Scenario NO climate constraint



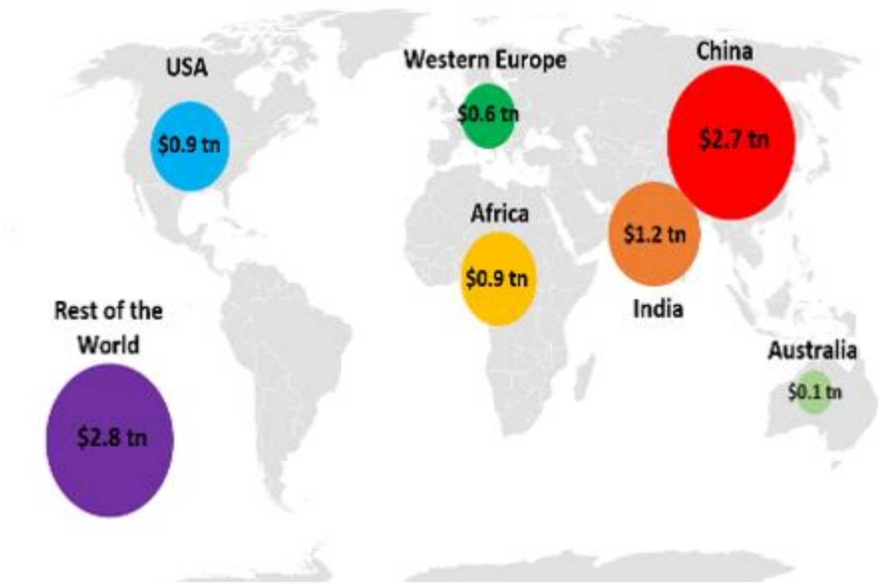
INTERMEDIATE Scenario with climate constraint



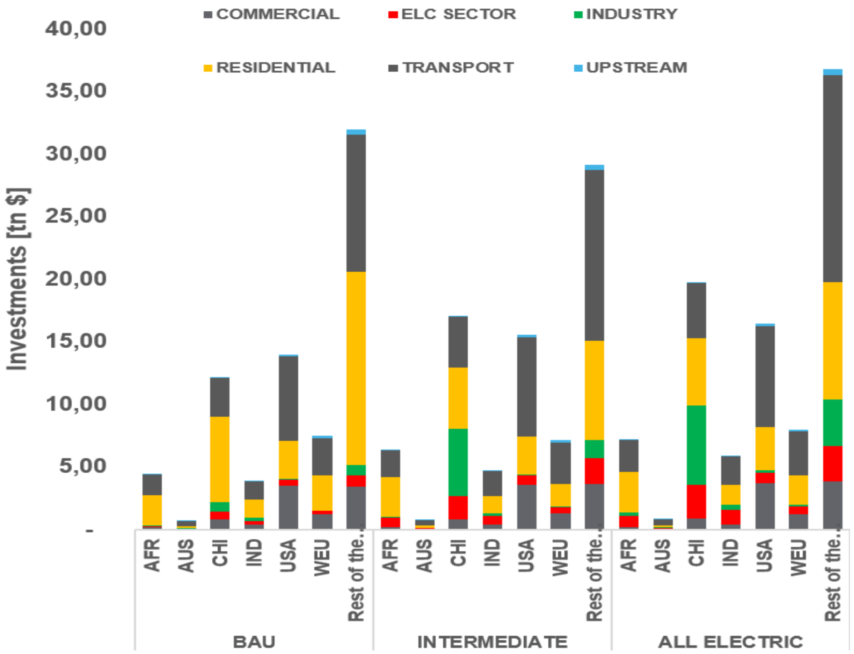
ALL ELECTRIC Scenario with climate constraint

Life Is On Schneider Electric

Investments per sector & geographies

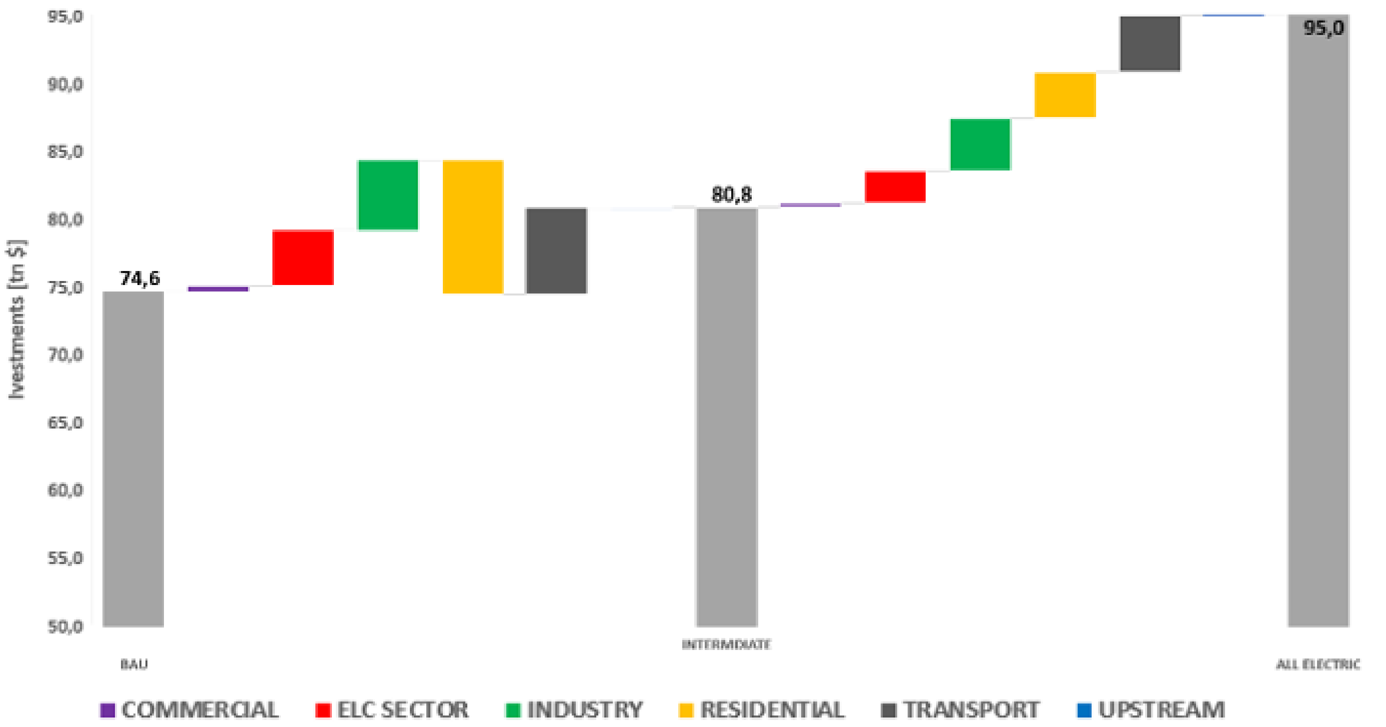


Investments in the power sector between 2020 & 2050 [$ tn]



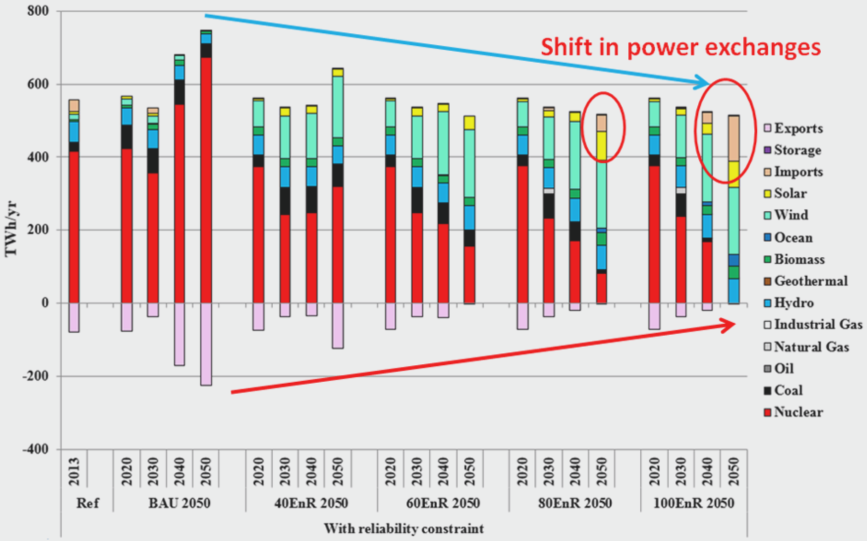
Investments between 2020 & 2050 per sector [$ tn]

Additional investments per scenario

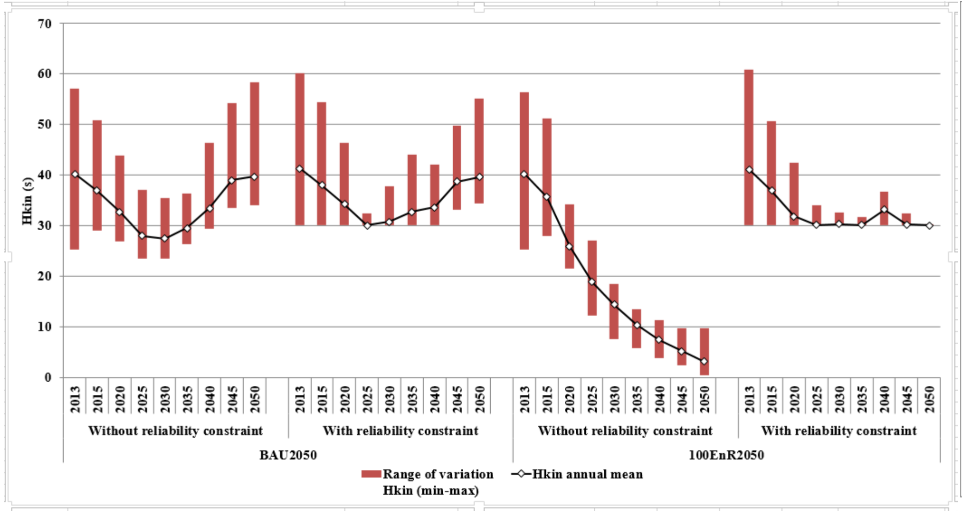


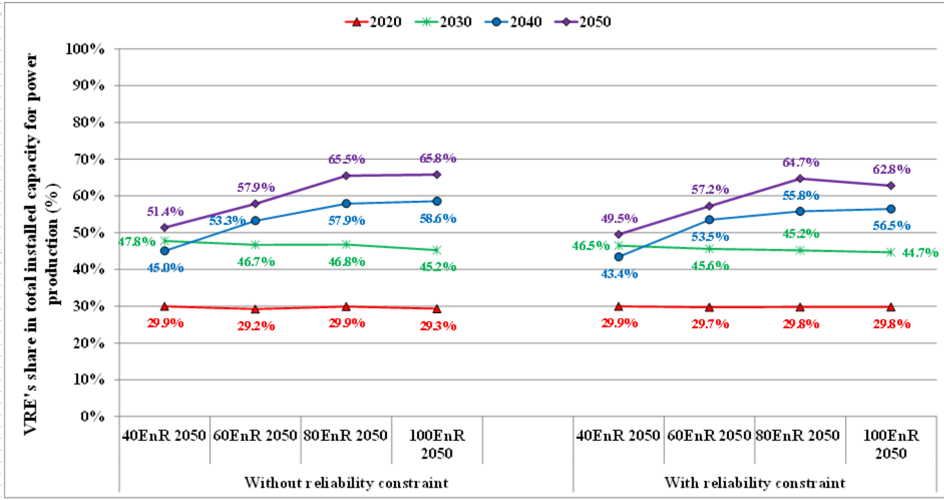
Lessons learnt from the French case study

Source : RTE



Yearly generation under reliability constraint

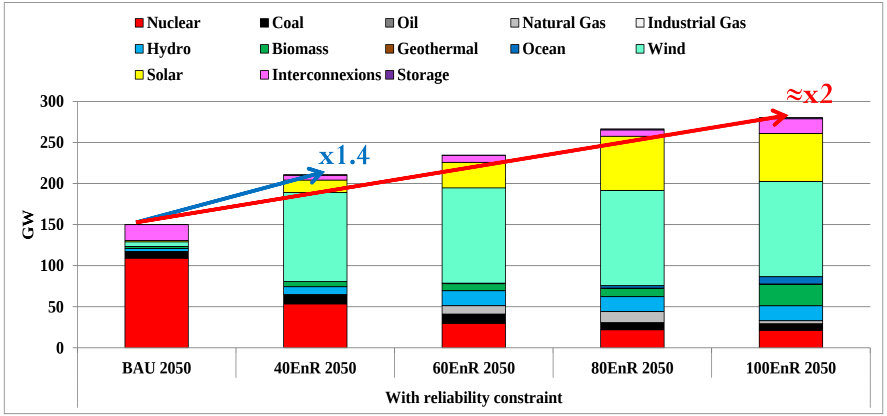


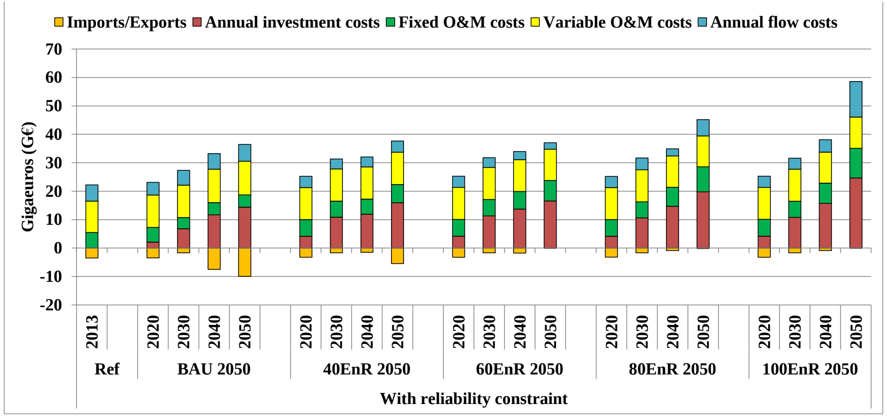


G.-S. Sokhna, V. Krakowski, E. Assoumou, N. Maïzi, and V. Mazauric, "Embedding power system’s reliability within a long-term Energy System Optimization Model: Linking high renewable energy integration and future grid stability for France by 2050," *Applied Energy*, vol. 257, p. 114037, 2020.

Life Is On Schneider Electric

Installed capacity vs. cost decomposition

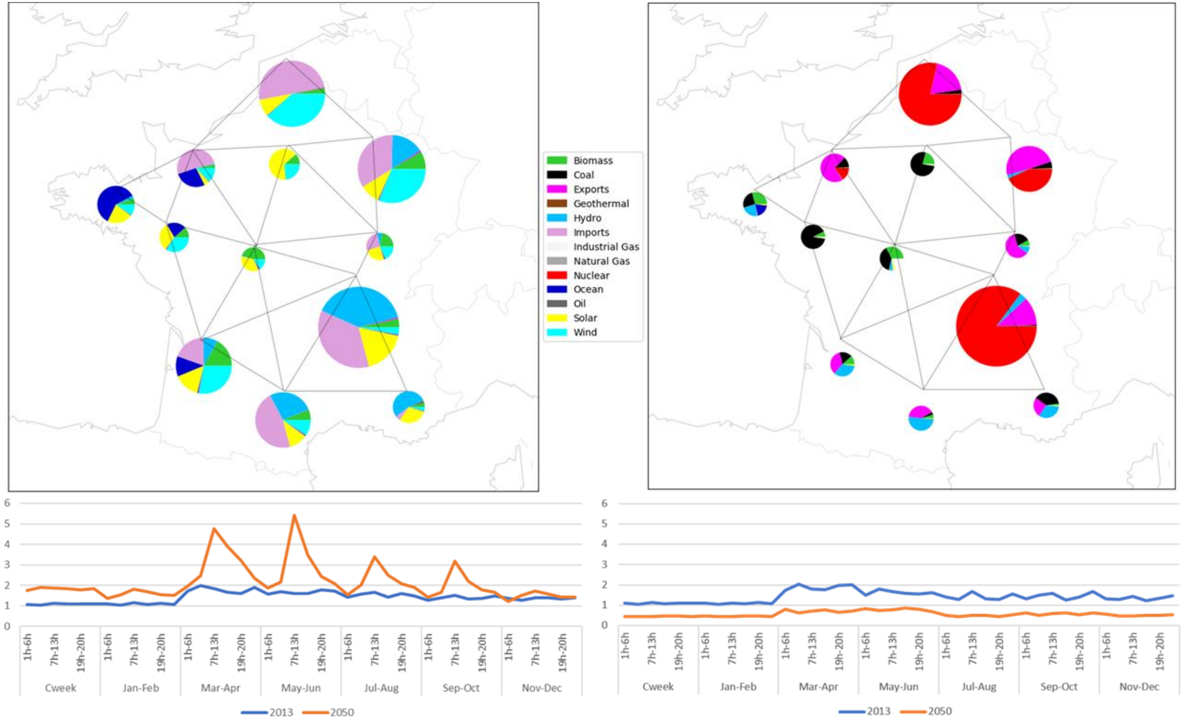




Life Is On Schneider Electric

Regional mix under reliability constraints

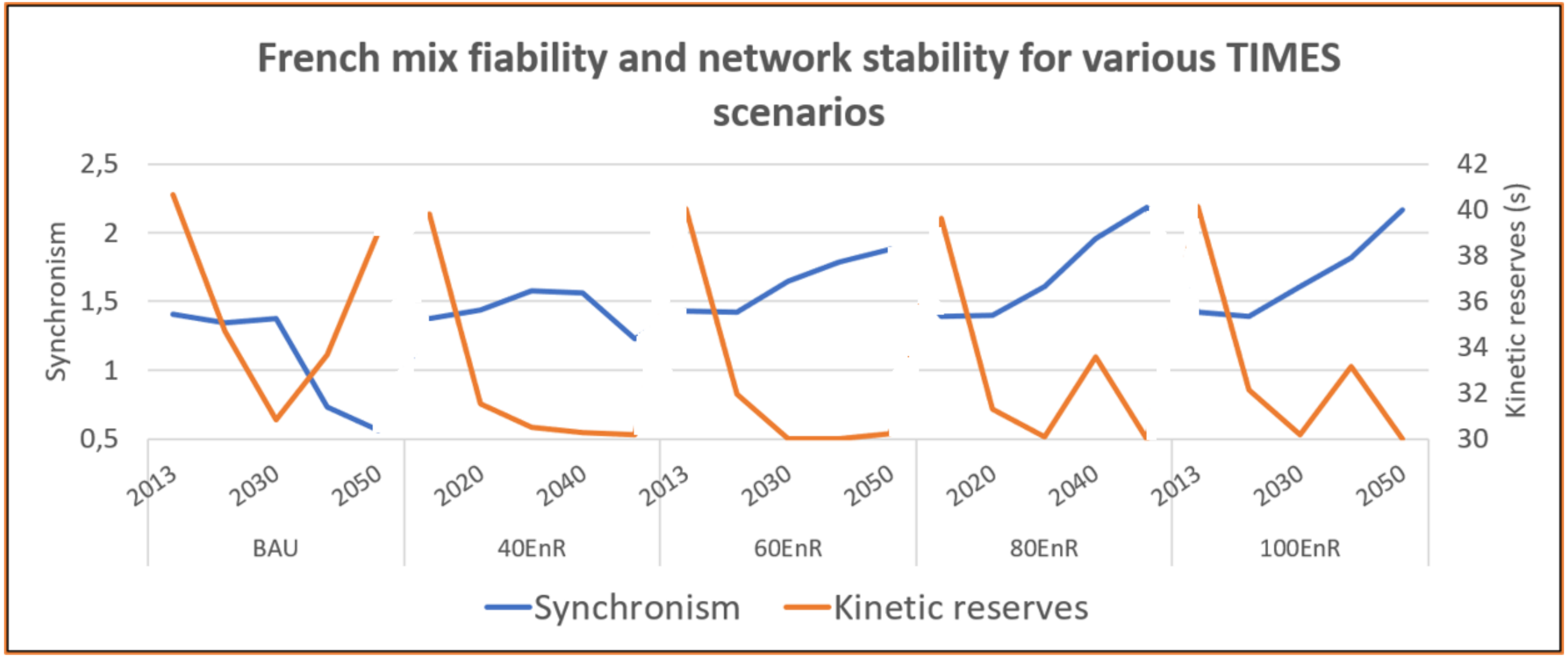
100% REN generation | BAU generation



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



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.

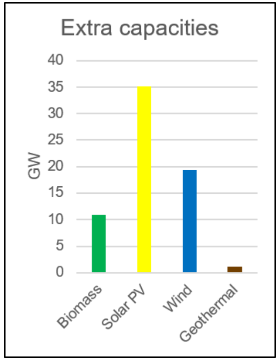
From “country” to “local” Renewable empowerment

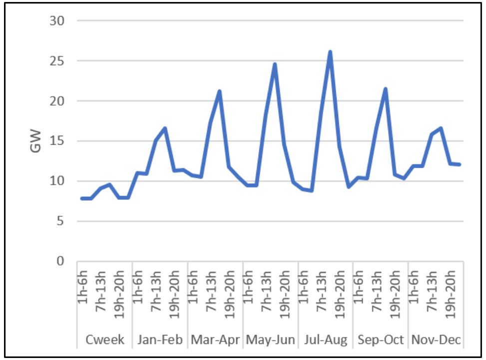
Realistic for balancing active energy (adequacy) for all regions except IdF (25 to 46%)

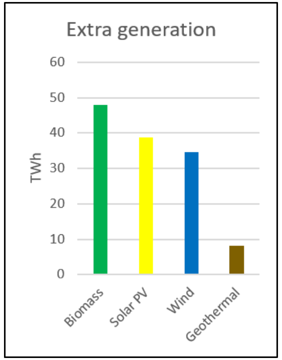
Low autonomy for ancillary services:

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

Overgeneration of 124TWh



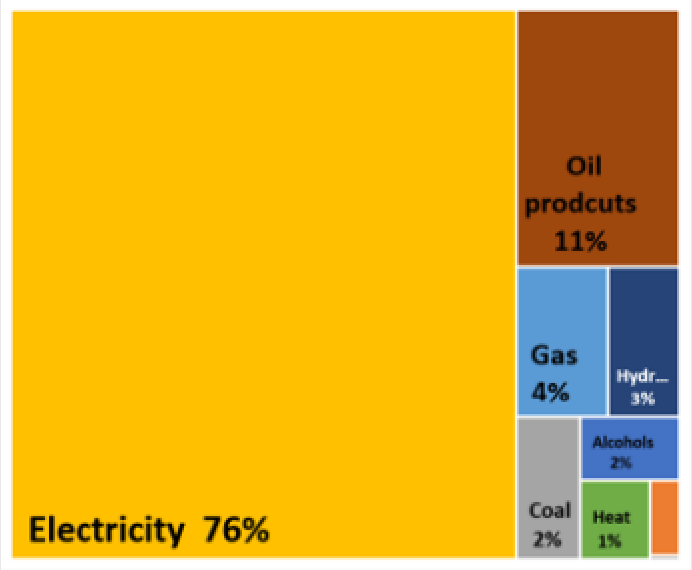


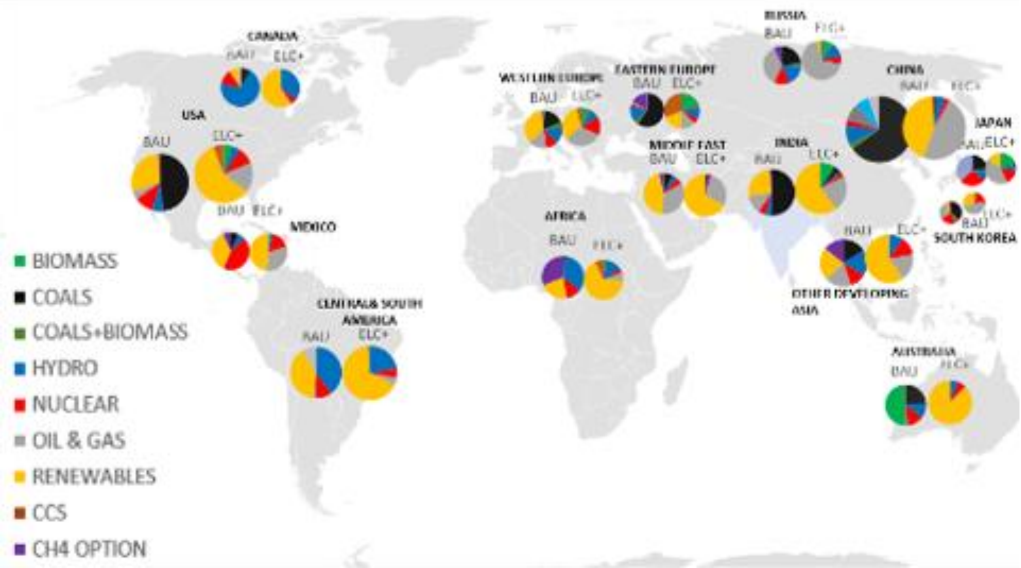


R. Cluet, N. Maïzi, V. Mazauric, space analysis of Reliability-constrained scenarios with increasing shares of renewables for the french power sector in 2050, in proceedings of the International Conference on Applied Energy (Vasteras, Sweden) paper 1091, Aug. 12-15 2019.

From « country » to « All Electric world »

Under climate constraint but w/o reliability

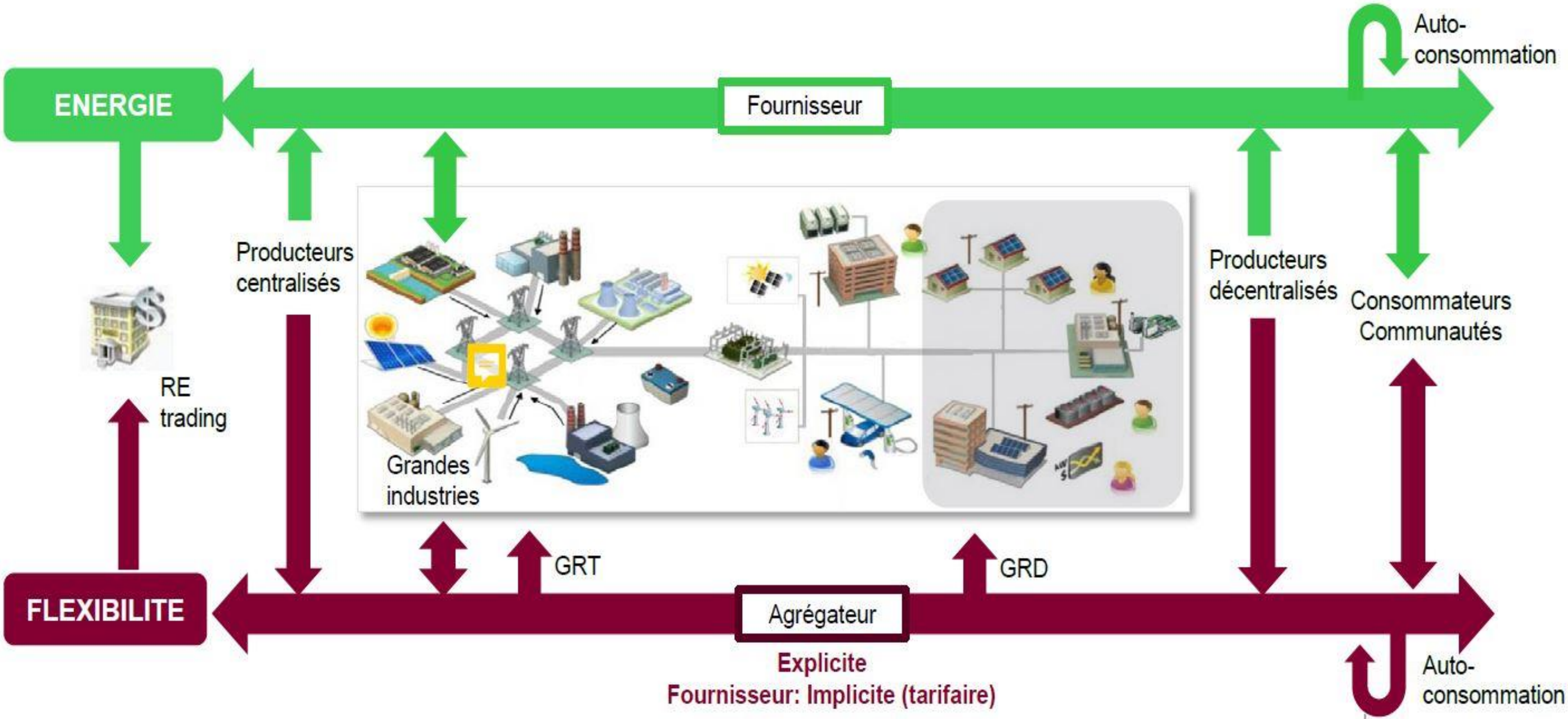




Total final energy by 2050:

- Final energy 549EJ
- Power generation: 169 261 TWh

Power generation mix per region

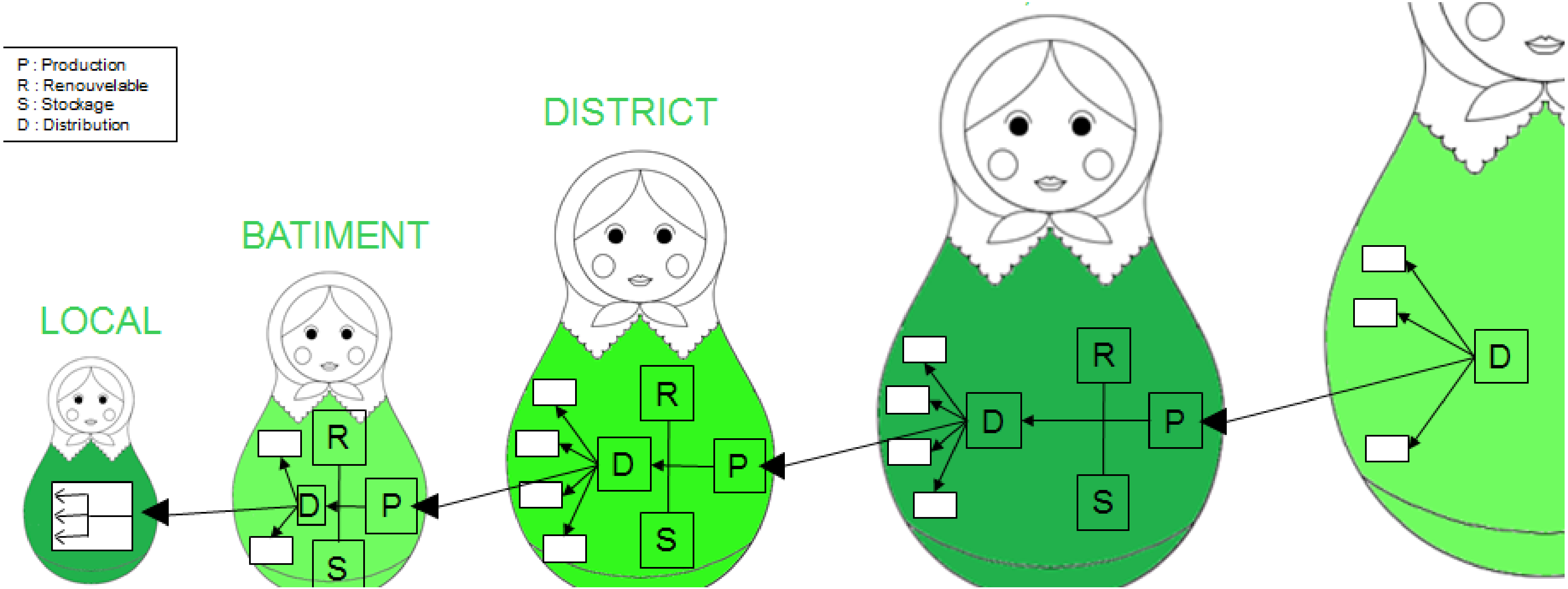


Forthcoming technical issues and externalities

From umbrella to cluster organization

Multi-scale issue

P : Production
R : Renouvelable
S : Stockage
D : Distribution



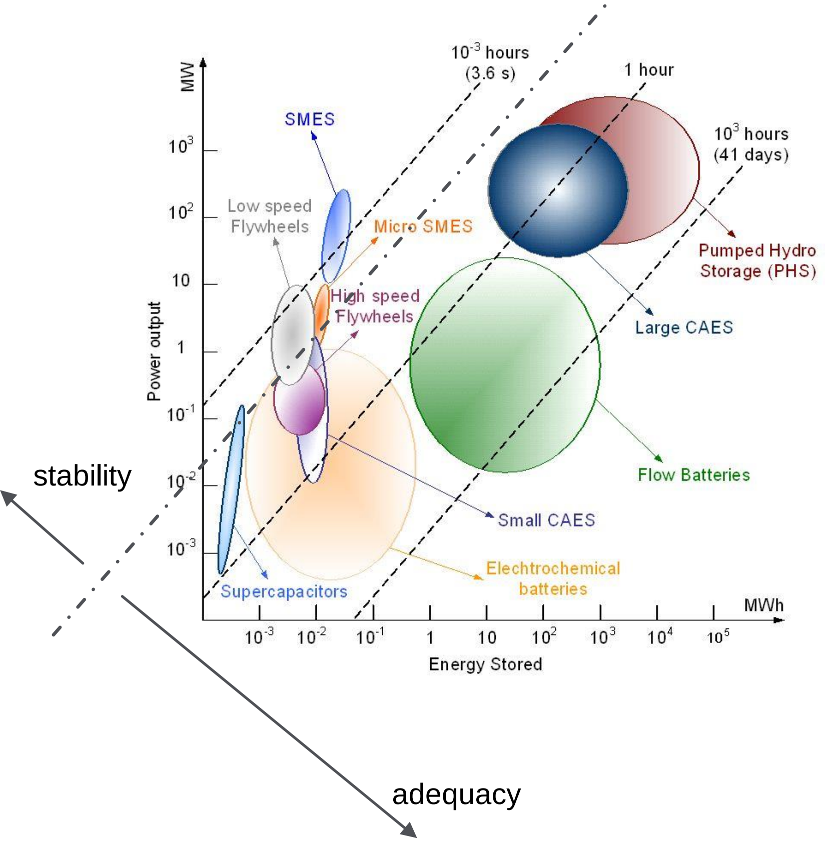
Power management: Forthcoming competitions

Naturally expressed within the second principle:

	Flexibility	variability	dispatchability	inertia	synchronism	coupling	Joule losses
2nd Law	P_{elec}		$+P_{mech}$	$-\frac{dE_{kin}}{dt}$	$-\frac{dG}{dt}$	$= \min \frac{d}{dt}\int (\mathbf{B}\cdot\boldsymbol{H} + \mathbf{D}\cdot\boldsymbol{E})d^3r$	$+\int_c \sigma^{-1}(\mathbf{curl}\boldsymbol{H})^2 d$
Contribution	adequacy			stability		coupling	Joule losses
	Flexibility	variability	dispatchability	inertia	synchronism		
Sources & Loads	• Storage • Demand Side Management	• Solar • Wind • Versatile loads	• Hydro (w/ dam) • Nuclear power plant • Fossil power plants				
Interfaces	Grid-supporting inverters				Grid-forming inverters		
Functional materials	• Si(C) • Ga • Dy, Nd… • Li • Fe (structure)			kg	• Fe (magnetic) • Si(C) • Ga	• Cu • Ag • Al • Au	
Drivers	Migration towards electricity CO_2-free		Decommissioning of fossil power plant		• copper plate • grid-forming inverters • uniform implementation of renewables	Distribution	
Trends	↑	↑	↓	0↘		↘0	
Energy for Externalities	Infrastructure ↑		Carbon Capture & Sequestration (CCS) ↑				Agility & Control ↑

Life Is On Schneider Electric

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.

ICT in energy systems

Control:

- Provide energy efficiency strategies in a context of tension between demand and supply
- Balance supply and demand in “real time” in a context of decreasing inertia
- Manage highly diluted assets and versatile loads within a general migration of the energy towards electricity
- Signal quality under variability: Enforce synchronism (clock) to provide the lowest dissipative grid

Forecast:

- Local weather to mitigate intermittency
- Predictive maintenance for highly dispersed energy assets

Role:

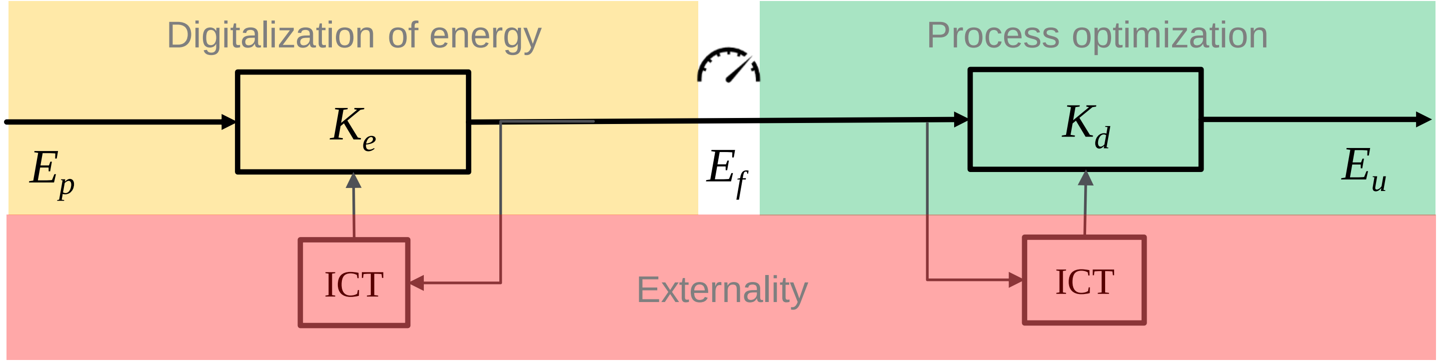
- Increase the knowledge on the energy system by decreasing its missing information; but
- Spoil the natural evolution of a system (2nd principle)
- Require a **processor** to gain information on the system… And reject a larger amount of missing information elsewhere!

Issue:

- Is accurate information (local, real-time) sustainable from a thermodynamic viewpoint?

Energy and digitalization: Which comes first ?

Our today intent…



- Energy service
- Digital service

Provide insights on the use of digitization:

- to improve Energy Efficiency (EE)
- to reduce CO_2 emissions

Address the limits of digitalization regarding:

- the actual and forthcoming levels of ICT
- the energy system itself!

IT energy footprint

All purpose: digital society and commodities!

Studies rooted from quasi-unique reference:

- A. Andrae (Huawei, Sweden)
- quoted by Shift Project, Vilanni Report…
- Reduced perimeter: power regulation beyond the meter not included, no inclusion of embedded IT in transportation and isolated plant…

Globally (20??):

- 3% of primary energy,
- 7% of electricity supply,
- 5% yearly growth (1.5% for electricity)
- 5% of CO2 emissions

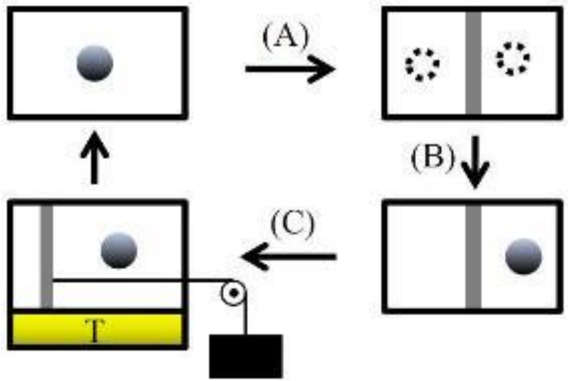
remark: F. Bordage (greenIT): 5.5% (2019)

Same level of:

- Air transportation
- 2/3 Marine bunkers

1. N. Jones, Nature 561, 163 (2018)
2. The Strategic Energy Technology Plan 2019, https://bit.ly/2WKJiHP
3. M. Avgerinou et al, Energies 10, 1470 (2017); H. Zhang et al., Renew. Sustain. Energy Rev. 58, 674 (2018)

Energy viewpoint



Szillard's engine (1928)

L. Szillard: Über die entropyverminderung in einem tehermodynamischen system bei eingriffen intelligenter wesn, Zeitschrift für Physik 53, 840 (1929)

2nd principle of thermodynamics:

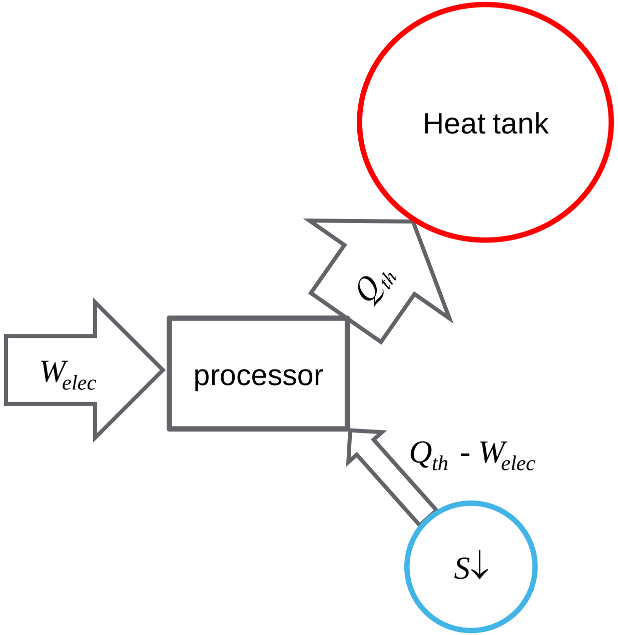
- Fix the minimum work W for any energy transaction (reversibility)
- Complement the energy transaction by heat Q (1st principle)
- The higher the degree of irreversibility, the larger the gap between the actual and the minimum works

Information/Entropy/Heat intimacy:

- H-Theorem (Boltzmann, 1872)
- Concept of missing information (Shannon, 1948)
- Equivalence between missing information and entropy S (Brillouin, 1956)
- 2nd principle is restored by the Maximum Entropy Principle to describe steady-states and provide time-arrow (Jaynes, 1957)

Processor appears as a cooling (but computing!) machine

C. E. Shannon, "A mathematical theory of communication," The Bell System Technical Journal, vol. 27, pp. 379-423, 1948.
L. Brillouin, Science and information theory. New York, USA: Academic Press, 1956
E. T. Jaynes, "Information theory and statistical mechanics," *Physical Review*, vol. 106, pp. 620-630, 1957.



$$COP = \frac{Q_{th} - W_{elec}}{W_{elec}}$$

Life Is On Schneider Electric
Public

Computational viewpoint (so far)

Erasing a memory is an irreversible operation because, at the end of one cycle of the computing machine, the knowledge of the final state cannot provide the initial state

Information immunity:
- Binary coding
- Damping and barriers

From logical switches to gates:
- *Reversible: NO*
- Irreversible: AND, **NAND**, OR, **NOR**, XOR, NXOR
- Requires up to 6 switches per gate

Combinatory circuits (the output depends only on the inputs):
- Karnaugh tables
- Applications:
  - Operations (AND, no carry),
  - Comparators (NXOR),
  - Coding/decoding…

Sequential circuits (the output depends on the inputs and history):
- 1-bit latch (2 NAND or 2 NOR)
- **Memory stack** (carry)
- …

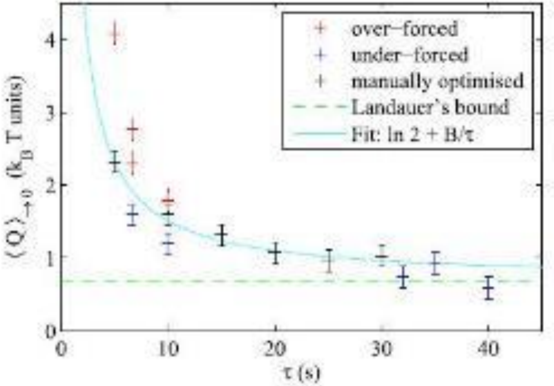


Figure 8. Mean dissipated heat for several procedures, with fixed τ and different values of f_{max}. The red points have a force too high, and a $P_{S\,force} \geqslant 99\%$. The blue points have a force too low and $91\% \leqslant P_{S\,force} < 95\%$ (except the last point which has $P_{S\,force} \approx 80\%$). The black points are considered to be optimised and have $95\% \leqslant P_{S\,force} < 99\%$. The error bars are $\pm 0.15\,k_B T$ estimated from the reproductibility of measurement with same parameters. The fit $\langle Q \rangle_{\to 0} = \ln 2 + B/\tau$ is done only by considering the optimised procedures.

R. Landauer: Irreversibility and heat generation in the computing process, IBM Journal of Research and Development, 5 (3) pp. 261-269 (1961).
Figure from: A. Berut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider, E. Lutz: Experimental verification of Landauer's principle linking information and thermodynamics, Nature, 483, pp. 187-192, 2012.

Landauer's paradigm (current):

Is it possible to perform logical/binary operations without energy?

- Erasing a bit releases the entropy: k_B Ln2; whereas
- The energy to set a bit is given by the logical technology

➔ Value distribution between data and energy results from:
- Boltzmann constant $k_B = 1.381 \times 10^{-23}$ J/K
- Coefficient of Performance of IT systems

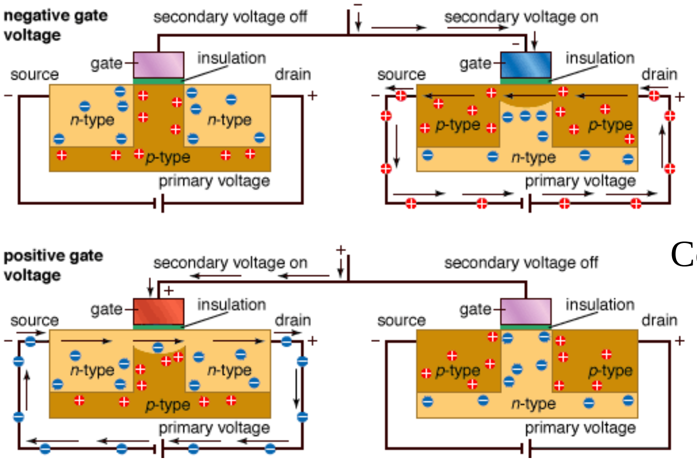
Life Is On Schneider Electric

Logical structures and technologies

Maturity of the state of the art (on shelves)

Combinatory MOS Field Effect Transistor (µm scale):

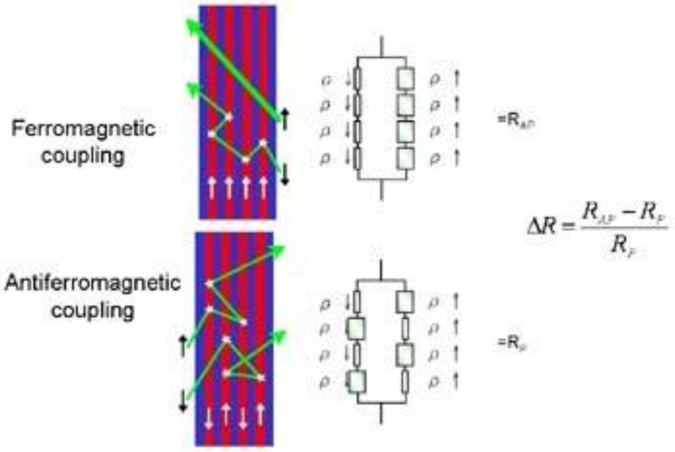
- Voltage on the gate acts on depletion layer (2V)
- Measure logical state with source-drain current
- Switching energy: 40,000 $k_B T$ (dynamic losses)
- Static losses: leakages currents (polarization)



CoP≈10^{-6}–10^{-5}

Giant Magneto Resistance effect (nm scale):

- Magnetic field acts on anti-ferromagnetic multilayer structure
- Electron diffusion by the magnetic structure is spin-dependent, leading to logical states
- Switching energy: $20k_B T$ (dynamic losses)

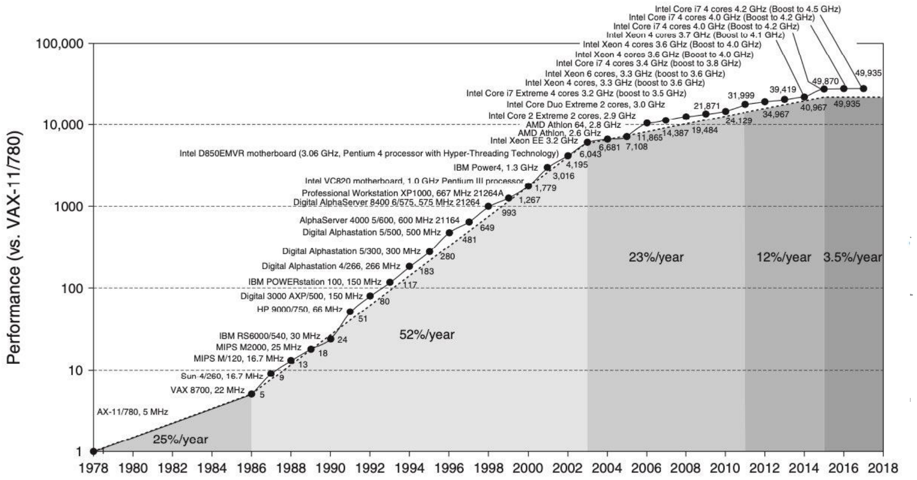


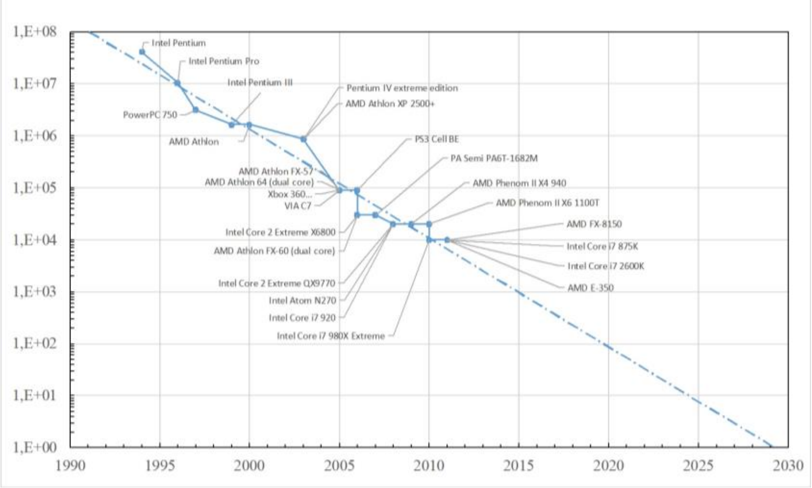
$$\Delta R = \frac{R_{AP} - R_P}{R_P}$$

CoP≈10^{-3}–10^{-2}

N. Gershenfeld: Signal entropy and the thermodynamics of computation, IBM Systems Journal, 35, (3&4), pp.577-586, 1996.
V.K. Joshi: Spintronics: a contemporary review of emerging electronics devices, Engineering Science and Technology, an International Journal ,19, pp. 1503–1513 (2016).
Semiconductor Industry Association/Semiconductor Research Corporation (SIA/SRC) : “Rebooting the IT revolution” (Sept. 2015): https://www.semiconductors.org/resources/rebooting-the-it-revolution-a-call-to-action-2/ .

Moore’s law as a marketting response to Landauer principle





From: J.L. Hennessy and D.A. Pattersson, “Fundamentals of Quantitative Design and Analysis” in Computer architecture: A quantitative approach (5th edition), Amsterdam, Netherlands: Elsevier (2018): 1-97.
The Koomey’s law is derived in: Koomey, Jonathan; Berard, Stephen; Sanchez, Marla; Wong, Henry;, « Implications of Historical Trends in the Electrical Efficiency of Computing », IEEE Annals of the History of Computing, vol. 33, no 3, 29 mars 2010, p. 46–54.

Koomey’s law reported to Landauer’s bound (per switching transistor) from: V. Mazauric, A. Auffèves, O. Ezratty, S. Ciliberto: « Quid after Moore’s and Koomey’s laws? » in Annales de Mines, Avril 2023.

Process optimization

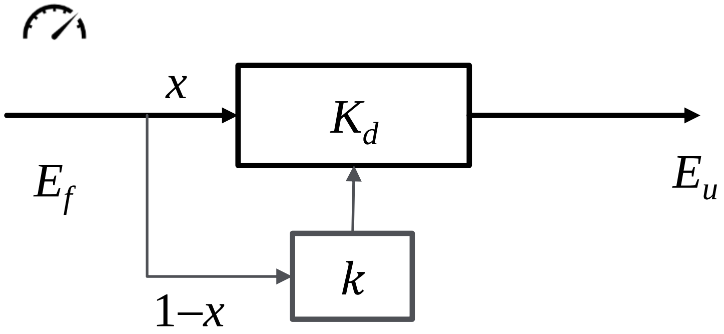
(active) energy efficiency "beyond the meter"

Any process is characterized by an efficiency K_d depending on:

- Intensive variables (state variables of the Gibbs free-energy)
- Extensively and linearly from the input xE_f

Maximize the end-use service E_u regarding the final energy E_f :

- Digitalization is efficient for large enough E_f ;
- The higher the COP, the bigger the potential for global efficiency



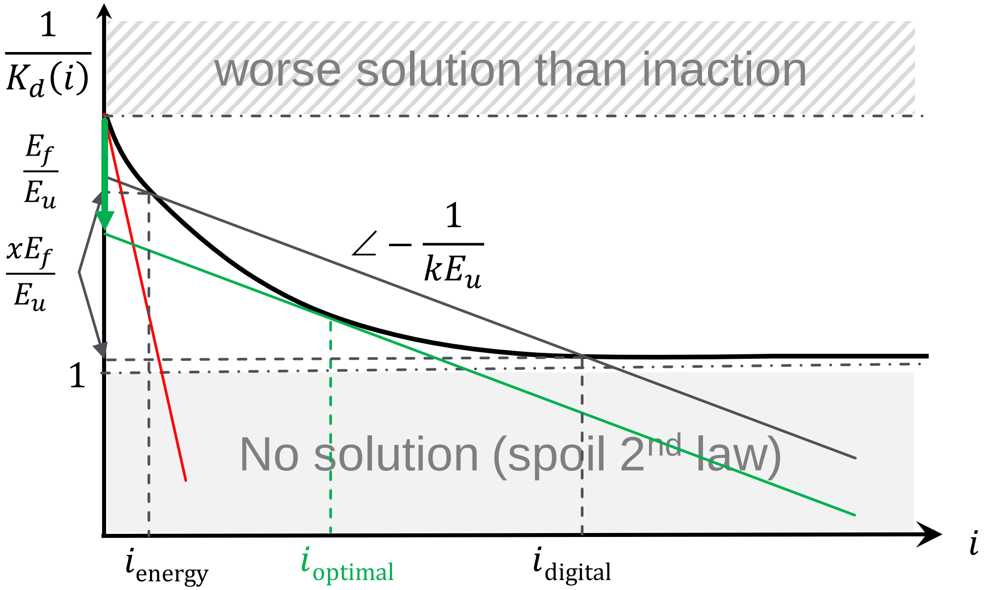
$$\frac{E_f}{E_u} - \frac{1}{kE_u} i = \frac{1}{K_d(i)}$$

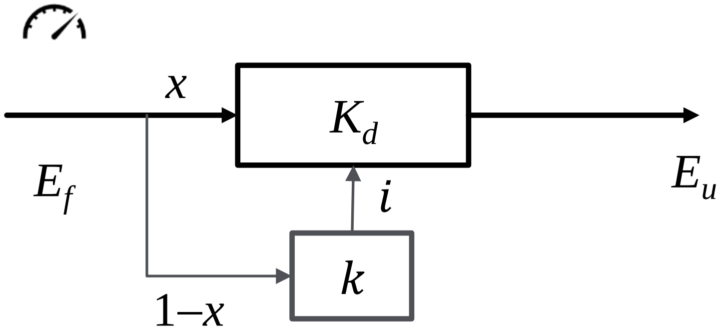
$$\min_{1>x>0} \frac{E_f}{E_u}$$

$0<K_d<1$ acts linearly from the input and depends on the information carried out by digitalization
k is the coefficient of performance of data-processing

Process optimization

(active) energy efficiency "beyond the meter"





$$\frac{E_f}{E_u} - \frac{1}{kE_u} i = \frac{1}{K_d(i)}$$

$$\min_{1>x>0} \frac{E_f}{E_u}$$

- EE potential increased with E_u and IT CoP k (no upper limit)
- Lower limit for process optimization is given by:
  $$\dot{K_d}(0) > K_d^2(0)/kE_u$$
- $E_f(k)$ is the Legendre's transformation of $E_u/K_d(i)$

$0<K_d<1$ acts linearly from the input and depends on the information carried out by digitalization

k is the coefficient of performance of data-processing

Life Is On Schneider Electric

Digitalization of energy

IT endogenization in Reference Energy System

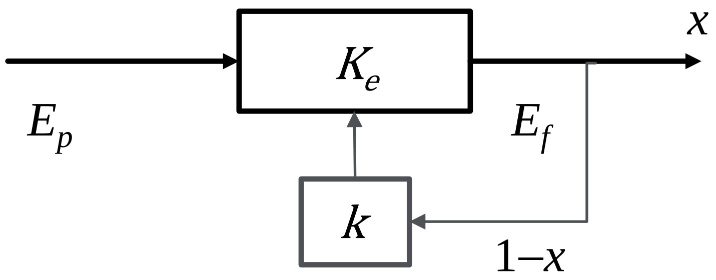
Control:

- Balance supply and demand in “real time” in a context of decreasing inertia
- Manage highly diluted supplying and stability assets with versatile loads (negative resistance) in a context of migration
- Traceability of energy (from cardinal to factorial complexity)
- Signal quality under variability: Enforce synchronism (clock) to provide the lowest dissipative grid
- Cybersecurity, redundancy and resilience

Forecast:

- Local weather to mitigate intermittency effect
- Predictive maintenance to keep productive highly dispersed energy assets

Maximize the residual final energy xE_f regarding primary energy E_p



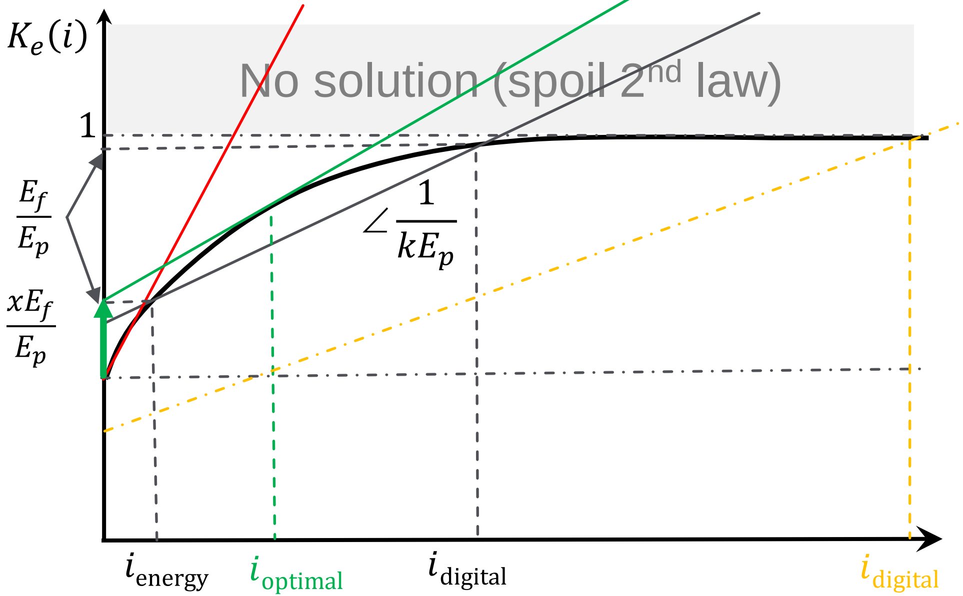
$$\frac{xE_f}{E_p} + \frac{1}{kE_p} i = K_e(i)$$

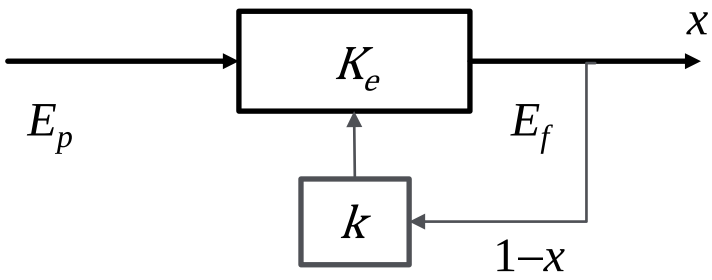
$$\max_{1>x>0} \frac{xE_f}{E_p}$$

$0<K_e<1$ acts linearly from the input and depends on the information carried out by digitalization
k is the coefficient of performance of data-processing

Digitalization of energy

IT endogenization in Reference Energy System





$$\frac{xE_f}{E_p} + \frac{1}{kE_p} i = K_e(i)$$

$$\max_{1>x>0} \frac{xE_f}{E_p}$$

- Energy demand xE_f is limited by the productible E_p and the IT CoP k
- $xE_f(k)$ is the Legendre's transformation of $E_p K_e(i)$
- Lower limit for optimal solution is given by: $\dot{K}_e(0) > 1/kE_p$
- Below, consider a decoupling between harvested-E_p and the demand-xE_f energies leading to a mainly digital solution

$0<K_e<1$ acts linearly from the input and depends on the information carried out by digitalization
k is the coefficient of performance of data-processing

Life Is On Schneider Electric

Forthcoming and long-term ICT issues

Sustainability of digitalization:

- is at concern with CMOS technology; and
- depends on forthcoming IT technology efficiency and its implementation (e.g., spintronics)

Due to energy footprint of digital solution:

- Digital and energy transitions (<2050-70) appear intricated; and
- Require long-term planning exercises including IT functional resources availability (energy/information/material);
- Magnetism is at the crossroads between energy generation and digitalization!

Value distribution between data and energy also results from physics considerations

Controversy:

- Physical entropy (Boltzmann):
  - Irreversibility is due to finite-time process
  - Dissipation is due to fluctuation of macro-state to reach equiprobability of micro-states
- Computational entropy (Shannon):
  - Irreversibility is due to the loss of memory of the inputs
  - Dissipation is due to stepping voltage charging of switches (50%) and erasure (50%)

➔ From Landauer's to Reversible computation paradigm

C.H. Bennett: Logical reversibility of computation, IBM J. Res. Develop. 17(6), pp.525-532 (1973); Notes on the history of reversible computation, IBM J. Res. Develop. 32(1), pp.16-23 (1988).

W. Porod: The thermodynamic of computation: A contradiction, in: Energy limits in computation, C.S. Lent, et al. Eds, pp. 141-154, Springer (2019).

Adiabatic logic:

- Process switching energies through ramping voltage sources
- "Rewind" computation to recover switching energies
- Trade-off between extra-memories management and erasure

Massive parallelization:

- Slower computation to allow the latter; but
- Need to consider new programming recipes and new competencies

Quantum Computing… and its thermodynamic limit!

M. Konopik,T. Korten,.E Lutz and H. Linke: Fundamental energy cost of finite-time computing, https://arxiv.org/abs/2101.07075, (2021).

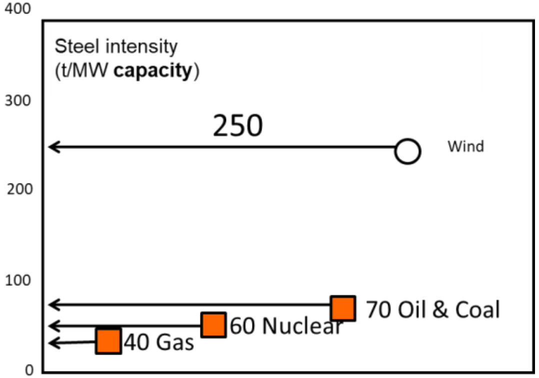
A. Auffèves: Optimiser la consommation énergétique des calculateurs quantiques: un défi interdisciplinaire, Reflets de la Physique, 69, 16-20 (2021)..

N. Margolus, L. Levitin : The maximum speed of dynamical evolution, Physica D120 (1998) 188-195

Energy system materiality

Dilution of energy infrastructures under decarbonation :

- Material intensity of renewables is higher than conventional



Geostrategic stake:

- From primary energy to functional material tension
- Low potential in developed countries (except China)

Business model constraint for mining industries:

- Change the merit order and subsequent value of ores
- Modify the profitability of extraction sites

Circularity issue:

- Recycling is 80% less energy intensive than extraction
- Emerging countries have no recycling potentials


CLIMATE CHANGE IS CAUSED BY TWO THINGS: HUMAN ACTIVITY ...
... AND HUMAN INACTION!
Time to act!

Conclusion

Conclusion

Power system has currently a very negative impact on CO_2 emissions (45%). However:

- It benefits from a natural reversibility property provided that
- Carbon-free technologies are implemented

The systemic aspect of energy sector claims for long-term planning studies to achieve the energy transition

- with dedicated models and tools

“ All electric world “ contributes to the future towards a clean energy system. However:

- Carbon-free generation must be drastically controlled, including ancillary services!
- Grid synchronism is a critical issue to correctly aggregate kinetic energy and face to fluctuations
- Due to local generation, µ-grid and decentralized concepts allow:
  - reducing congestion throughout the grid while improving the synchronism indicator at the transmission scale
  - the constraint on synchronism is rejected on the distribution network (with lower voltage and extra losses) inducing investment at this stage
- Extra costs are expected:
  - to constrain kinetic energy to a relevant level over the prospective horizon (compared to BAU)
  - for local empowerment, claiming for on-grid concept of µ-grid as an enabler of the whole grid transformation towards decarbonation
- US, India and China are critical regions regarding reliability constraints under “All electric world” option

Externalities such as digitalization and extra-materiality of diluted energy sources claim for endogenized planning exercises.

Life Is On

Schneider Electric