From Thermodynamics to Planning Studies:
Multi-scale approaches dedicated to sustainable, smart and low-carbon power systems

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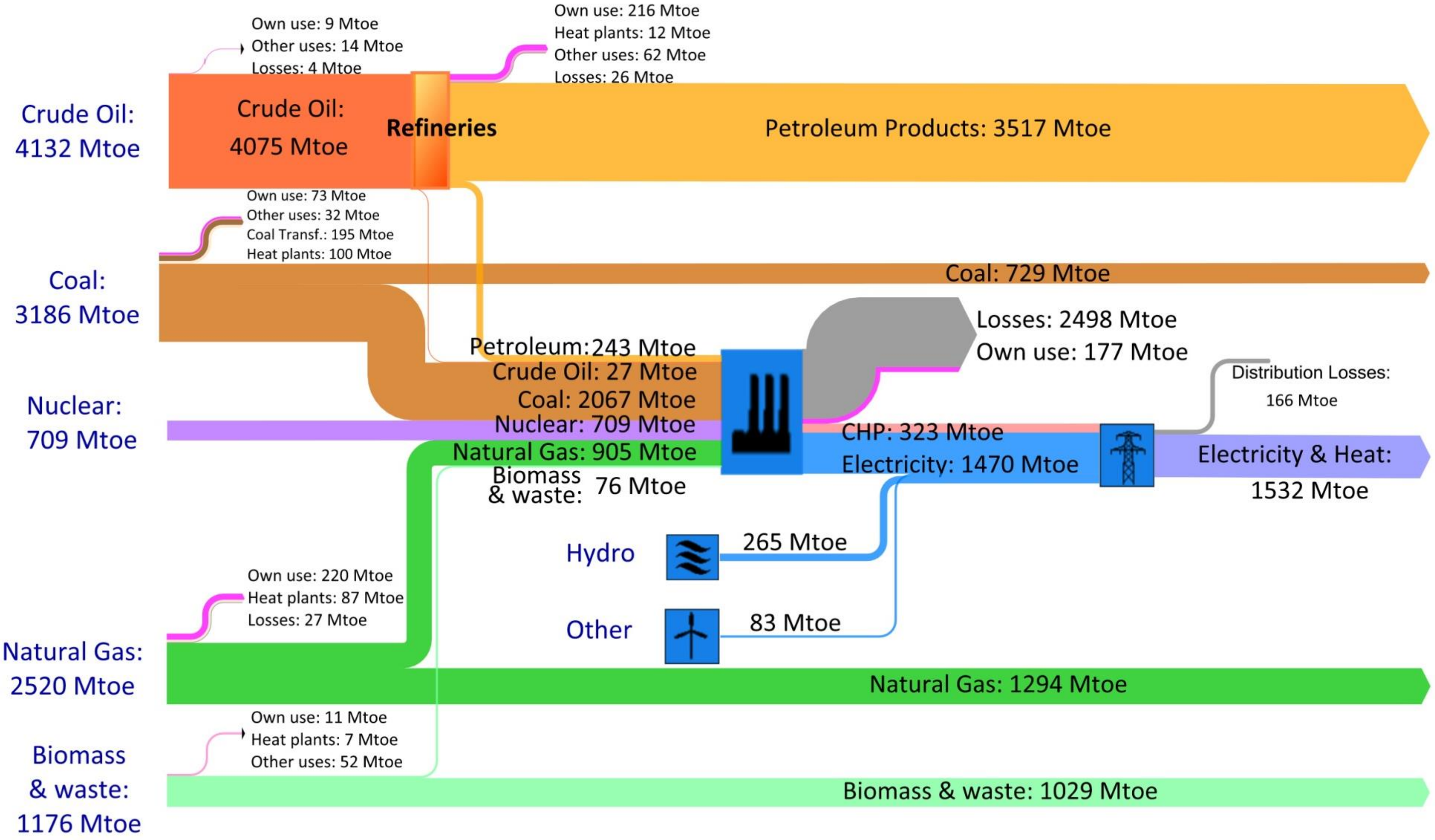
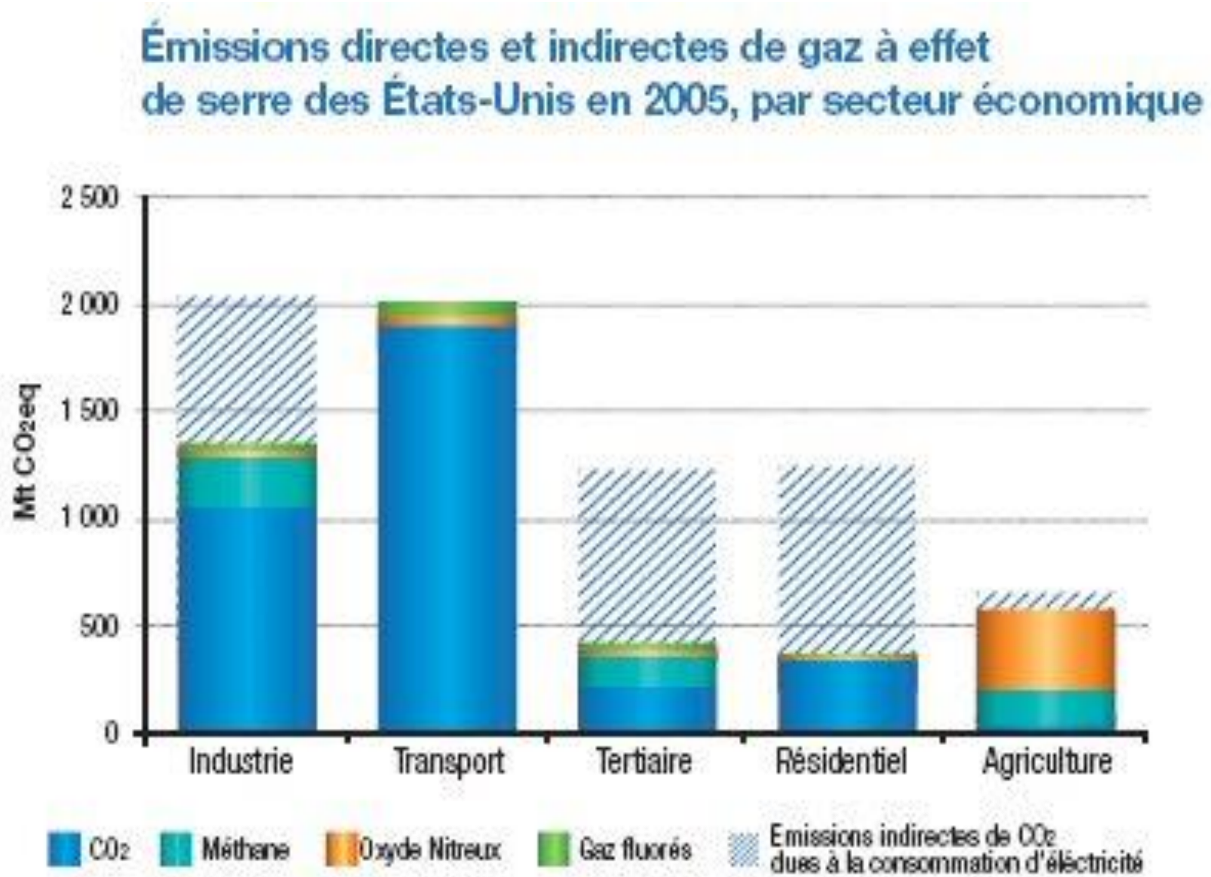
Energy supply Chain (from IEA 2007)



US CO_2 emissions inventory per sector



Source : US EPA, GHG Inventory 2005; US EIA, Electric Power Annual

A tight equation towards sustainability

- 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 networks
- *The Earth*: An isolated chemical system
  - Fossil (and fissil) fuels depletion:
    - 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 CO_2 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

From Thermodynamics to Electromagnetism
Saving (« private ») electricity

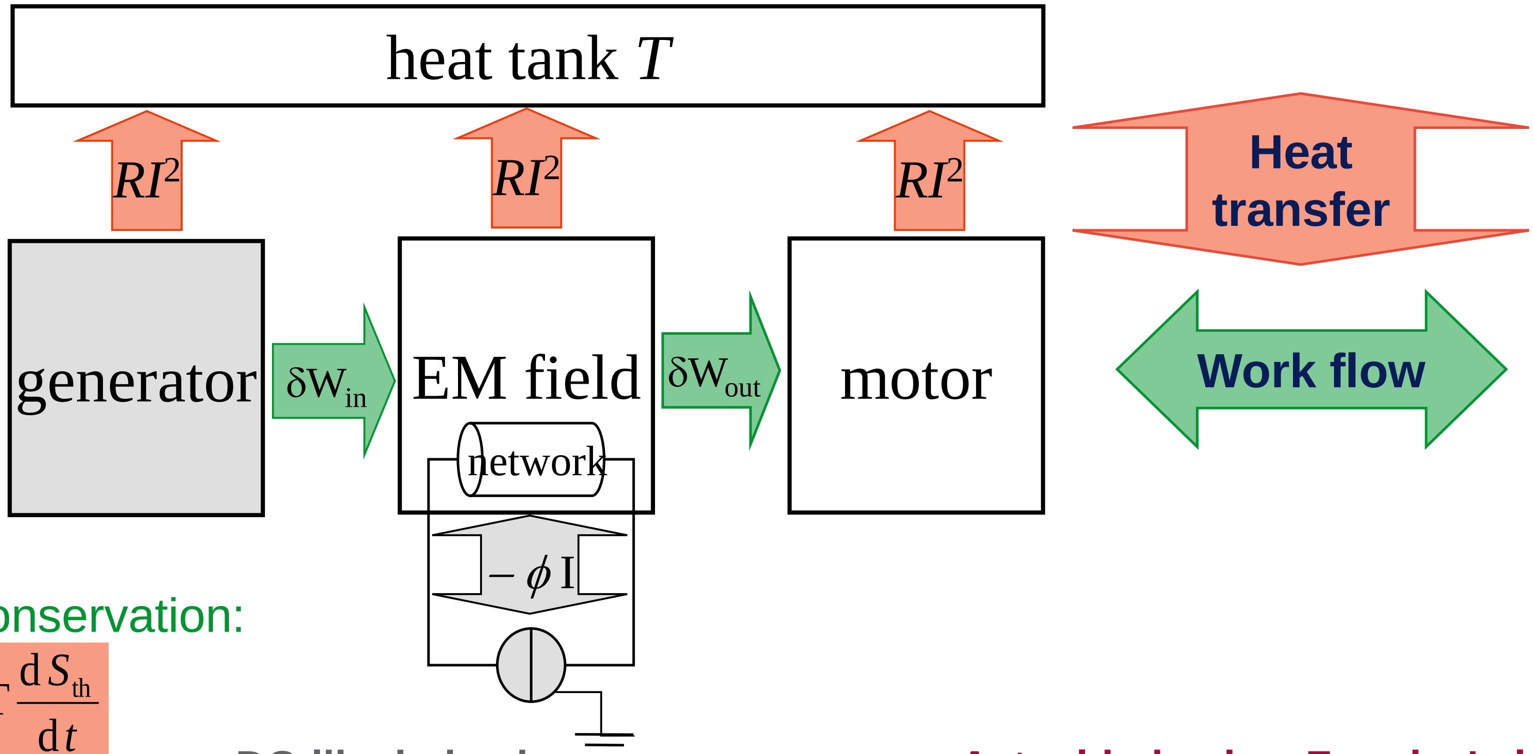
- Thermodynamic description:
  - A natural trend toward reversibility
  - FEM validation
  - Multi-scale issues
- Power management:
  - Stability of the power system

[V. Mazauric, "From thermostatistics to Maxwell's equations: A variational approach of electromagnetism," *IEEE Transactions on Magnetics, vol. 40, pp. 945-948, 2004*.]

Electromagnetism...

	Relativity (1905)	Axiomatic (1870)	Thermodynamics
Sources		$\mathrm{div}\,\mathbf{j} + \frac{\partial \rho}{\partial t} = 0$	
Source fields	$\mathrm{div}\,\mathbf{D} = \rho$	$\mathrm{div}\,\mathbf{D} = \rho$ $\mathbf{curl H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}$	
Electromagnetic fields	$\mathbf{curl\ E} = 0$	$\mathbf{curl\ E} = -\frac{\partial \mathbf{B}}{\partial t}$ $\mathrm{div}\,\mathbf{B} = 0$	Weak-reversibility 1st principle
Behavior laws	$\mathbf{D}(\mathbf{E})$	$\mathbf{B}(\mathbf{H}), \mathbf{D}(\mathbf{E}), \mathbf{J}(\mathbf{E})$	2nd principle
Mechanical coupling	$\mathbf{f} = q\mathbf{E}$	$\mathbf{f} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$	1st principle
Invariance	Lorentz	Spoilt/Galilean	losses/Galilean
Lack	Matter, Ohm law		High frequency
	5 hypotheses (1 from relativity)	7 hypotheses	5 hypotheses (4 from energy)

A natural tendency towards reversibility



➔ Energy conservation:

$$\frac{dU}{dt} = P_m - T\frac{dS_{th}}{dt}$$

DC-like behavior

Actual behavior: Faraday's law

- State function:

$$F = U - TS \quad \text{(Helmoltz)}$$

$$G = U - TS - \phi I - Q V_0 \quad \text{(Gibbs)}$$

➔ 2nd principle (Clausius):

$$P_m - \frac{dF}{dt} = \underbrace{T\left(\frac{dS}{dt} + \frac{dS_{th}}{dt}\right)}_{P_{Joule}} \geq 0$$

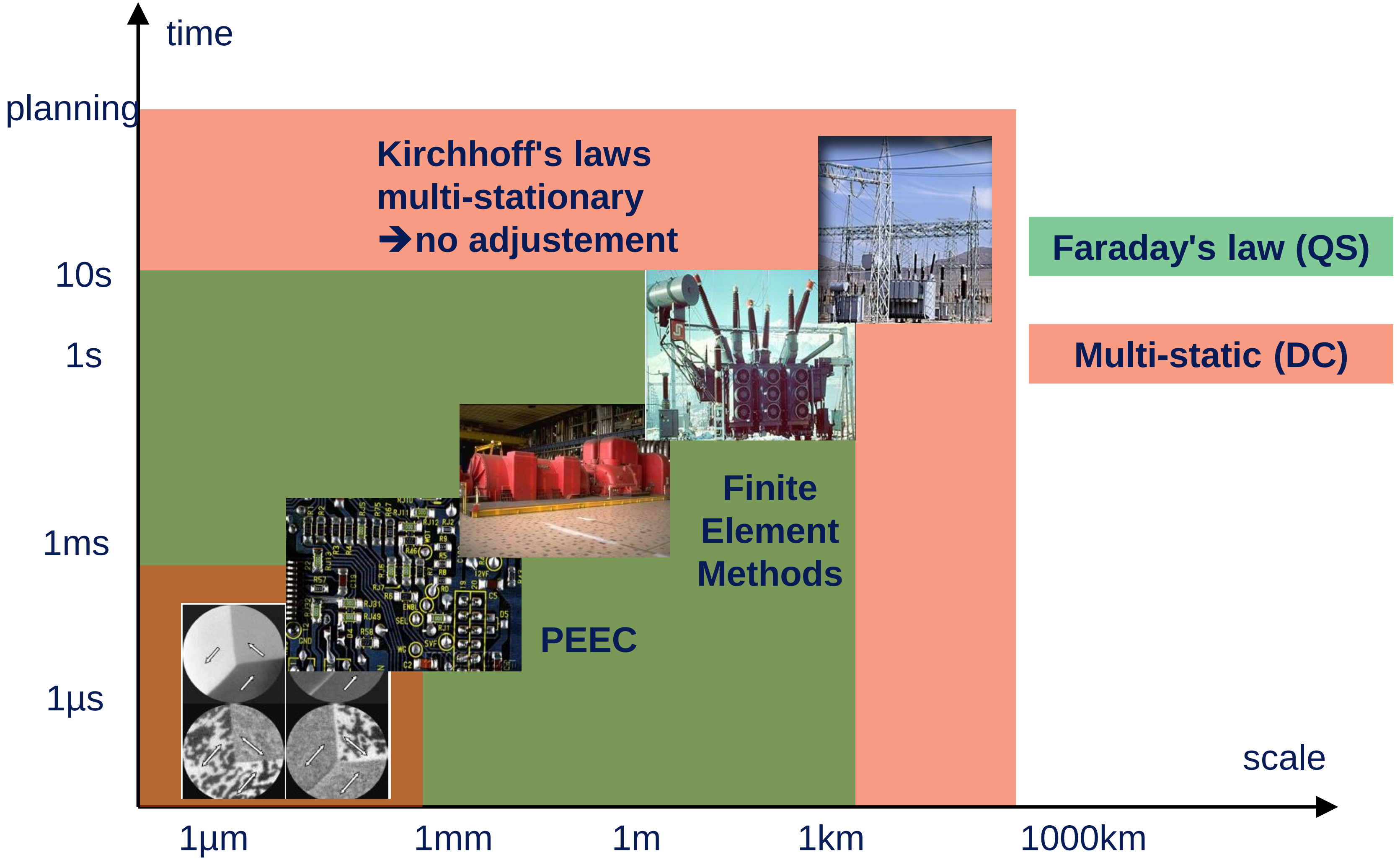
$$P_m - \frac{dG}{dt} = \underbrace{T\left(\frac{dS}{dt} + \frac{dS_{th}}{dt}\right)} + \frac{d(\phi I + Q V_0)}{dt}$$

➔ Weak reversibility:

$$P_m - \frac{dF}{dt} = \min(P_{Joule})$$

$$< P_m - \frac{dG}{dt} = \min_{H,E}\left(\int_C \sigma^{-1}(\mathbf{curl}\,\boldsymbol{H})^2 d^3r + \frac{d}{dt}\int(\mathbf{B}\cdot\boldsymbol{H} + \mathbf{D}\cdot\boldsymbol{E})d^3r\right)$$

Space- and time- multi-scale decomposition



Global Poynting equation (with variational RHS)

(hν) *matter* *field* *field* *matter*

$$\left(P_{elec}\right) + P_{mech\,ext} - \frac{dE_{kin}}{dt} - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d\left(\phi I\right)}{dt} + \frac{d\left(Q V\right)}{dt} \right)$$

- Properties:
  - RHS: contains Maxwell equations
  - LHS: provides power conservation
  - Dedicated to multi-scale analysis due to quadratic functional (spectral analyis)
- Energy-based invariants:
  - ➔existence justified by time-uniformity
  - Gibbs free-energy
  - Kinetic energy
  - ➔Conversely, provide means for time-reconciliation and space-analysis
- Reserves:
  - Field (on-grid): friction- and resistance- limited > rush
  - Matter (on/off-grid): delayed by matter (mass, charge) transfert > slow

Validation at the design scale

- FEM validation

V. Mazauric, "Des principes thermodynamiques aux équations de Maxwell: Une approche variationnelle de l'électromagnétisme," in Champs et équations en électromagnétisme. vol. 1, G. Meunier, Ed., ed Paris, France: Hermès, 2003, pp. 147-262.

- *Quasi-static regimes*

V. Mazauric, N. Addar, L. Rondot, P. Wendling, and M. Barrault, "From Galilean covariance to Maxwell equations: Back to the Quasi-Static regimes," IEEE Transactions on Magnetics, vol. 50, p. 7200804, 2014.

- *Dynamic losses in ferromagnetic materials*

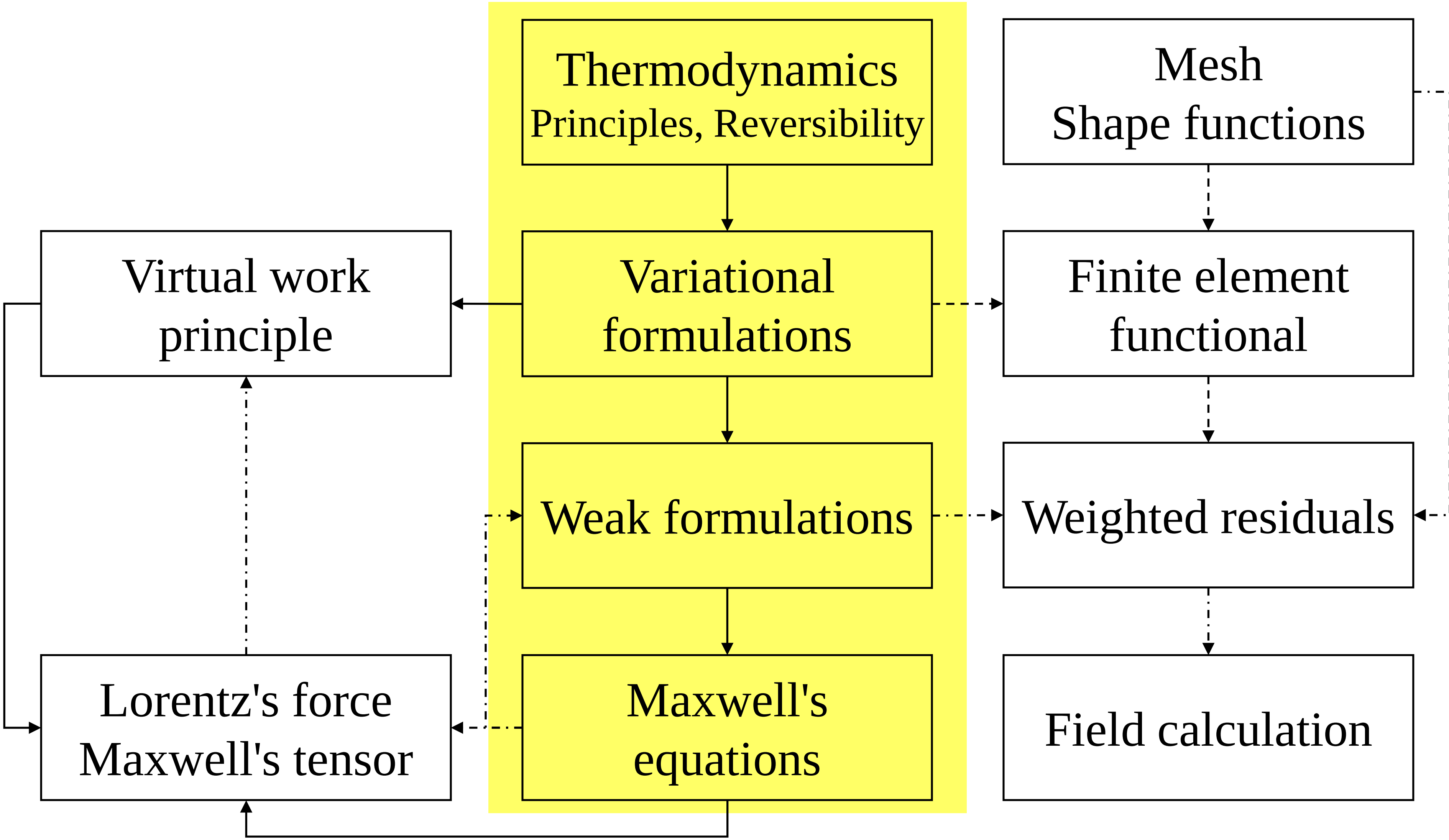
V. Mazauric, O. Maloberti, G. Meunier, A. Kedous-Lebouc, and O. Geoffroy, "An energy-based formulation for dynamic hysteresis and extra-losses," IEEE Transactions on Magnetics, vol. 42, pp. 895-898, 2006.

- Adaptative meshing for eddy current calculations

L. Rondot, V. Mazauric, and P. Wendling, "An energy-compliant magnetodynamic error criterion for eddy-current calculations," IEEE Transactions on Magnetics, vol. 46, pp. 2353-2356, 2010.

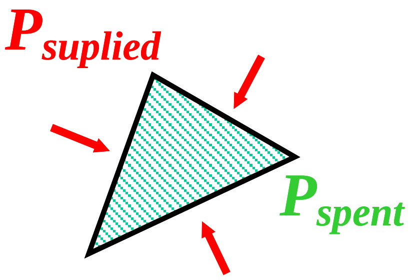
D. Dupuy, D. Pedreira, D. Verbeke, V. Leconte, P. Wendling, L. Rondot, V. Mazauric, "A magnetodynamic error criterion and an adaptive meshing strategy for eddy current evaluation," *IEEE Transactions on Magnetics,* vol. 52, p. 7402504, 2016.

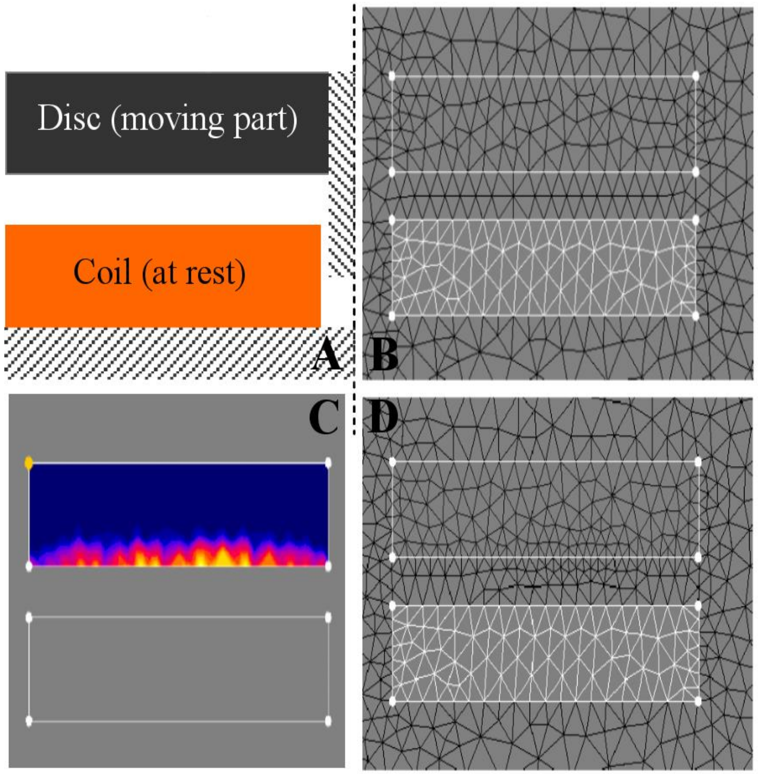
Power Conversion device modeling



Basic validation: Thomson effect device
2D-transient, no-magnetic material, no-motion

- Overcome classical error criteria:
  - geometrical
  - flux-density divergence free





- Poynting identity check:

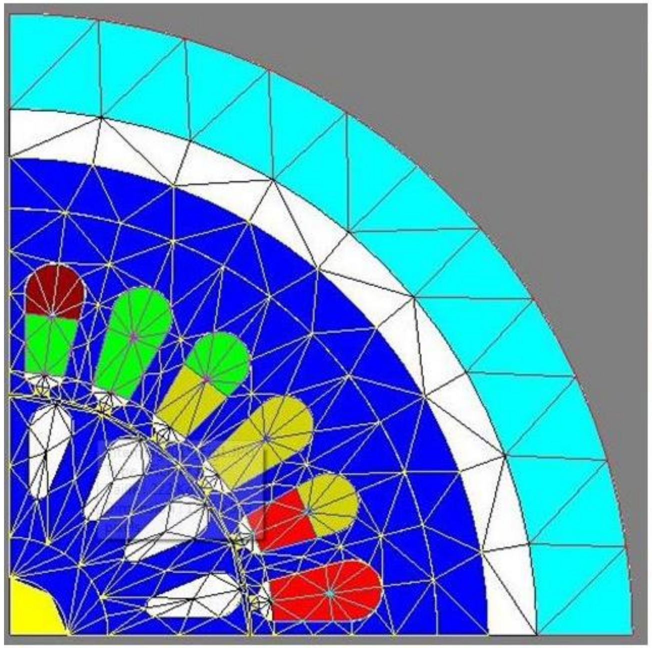
$$\varepsilon(\Omega) = P_{elec}(\Omega) - P_{Joule}(\Omega) - \frac{dF}{dt}(\Omega) + P_m(\Omega)$$

$\Delta t = 0.5 \cdot 10^{-6}$ s	**Number of Time Step : 2**	**Number of Time Step : 3 (before remeshing)**	**Number of Time Step : 3 (after remeshing)**
U *(V)*	$3.1 \cdot 10^{-1}$	$5.9 \cdot 10^{-1}$	$5.9 \cdot 10^{-1}$
I *(A)*	$7.3 \cdot 10^{-4}$	$2.1 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
G(*J*)	$-1.61 \cdot 10^{-9}$	$-1.34 \cdot 10^{-8}$	$-5.89 \cdot 10^{-9}$
G/I^2 *($J.A^{-2}$)*	$-3.05 \cdot 10^{-3}$	$-3.06 \cdot 10^{-3}$	$-3.09 \cdot 10^{-3}$
$P_m - dG/dt + P_{elec}$		$2.5 \cdot 10^{-2}$	$9.4 \cdot 10^{-3}$

Global validation: Induction machine
2D, time-harmonic, magnetic material, motion

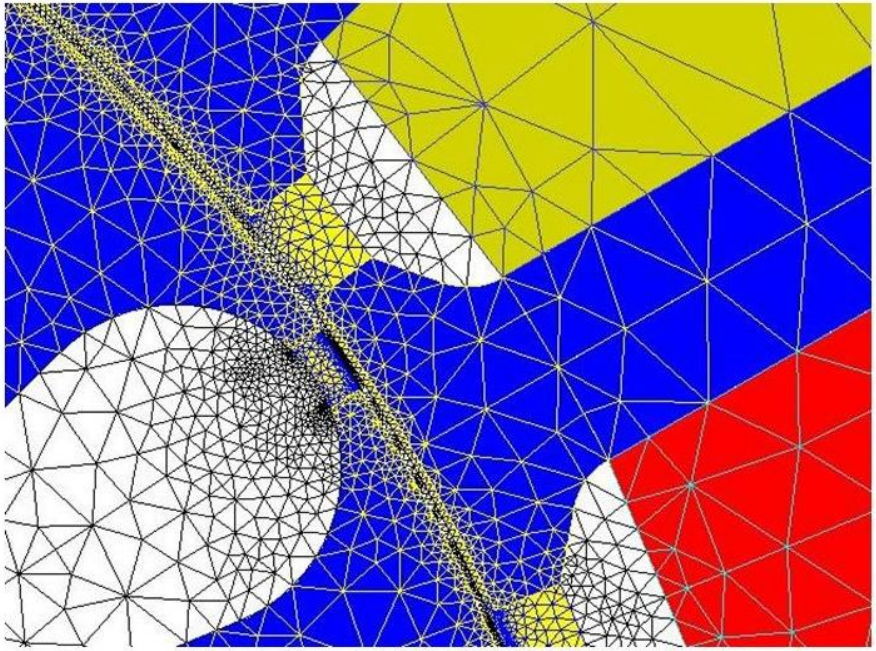
Initial mesh:

Geometric-based



Mesh after 4 iterations:

Refinement at ill-checked nodes



Global validation: Induction machine
2D, time-harmonic, magnetic material, motion

Convergence of the:

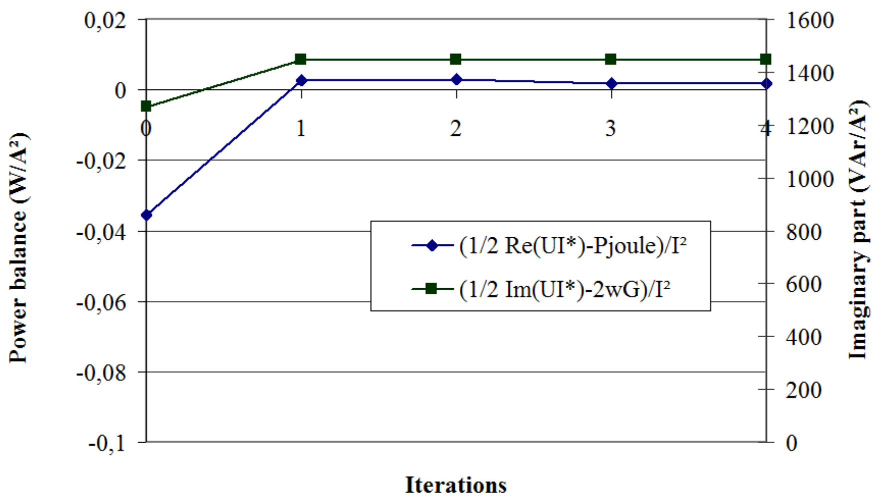
- Power balance (vanishing slip)
- Power functional (Imaginary part)

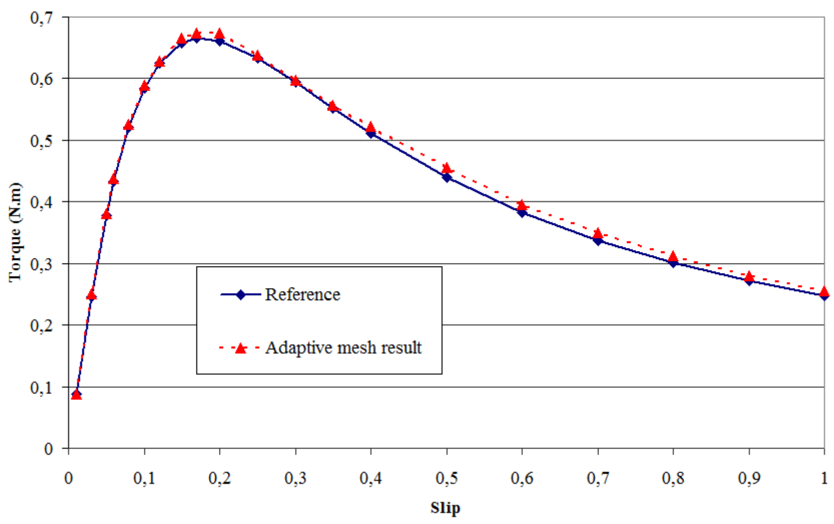
after 2 iterations

Convergence of the

- Torque vs. Slip curve

after 4 iterations

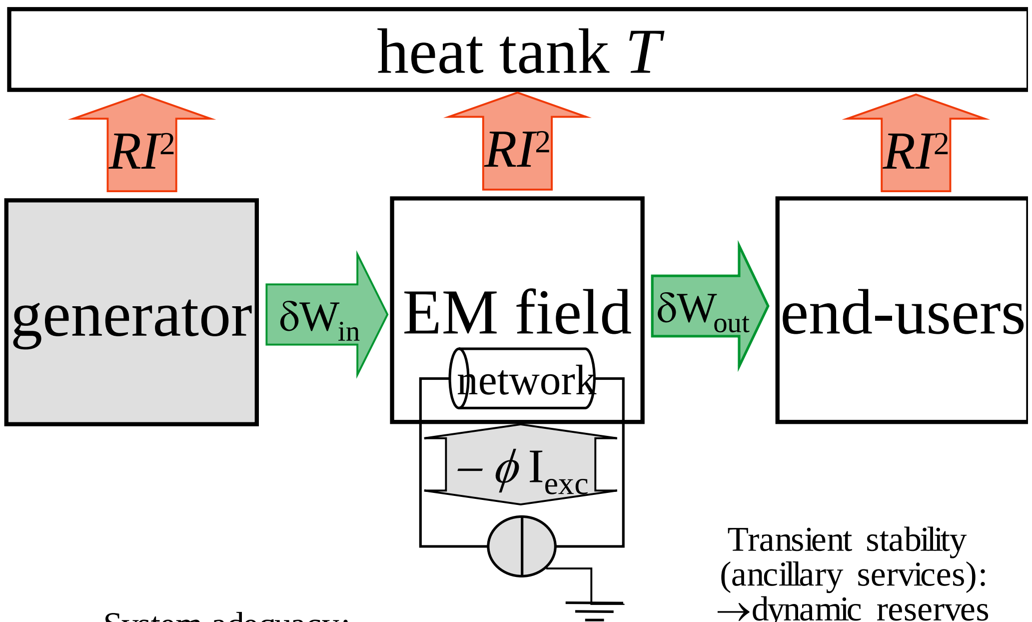




Upper scale

[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.*]

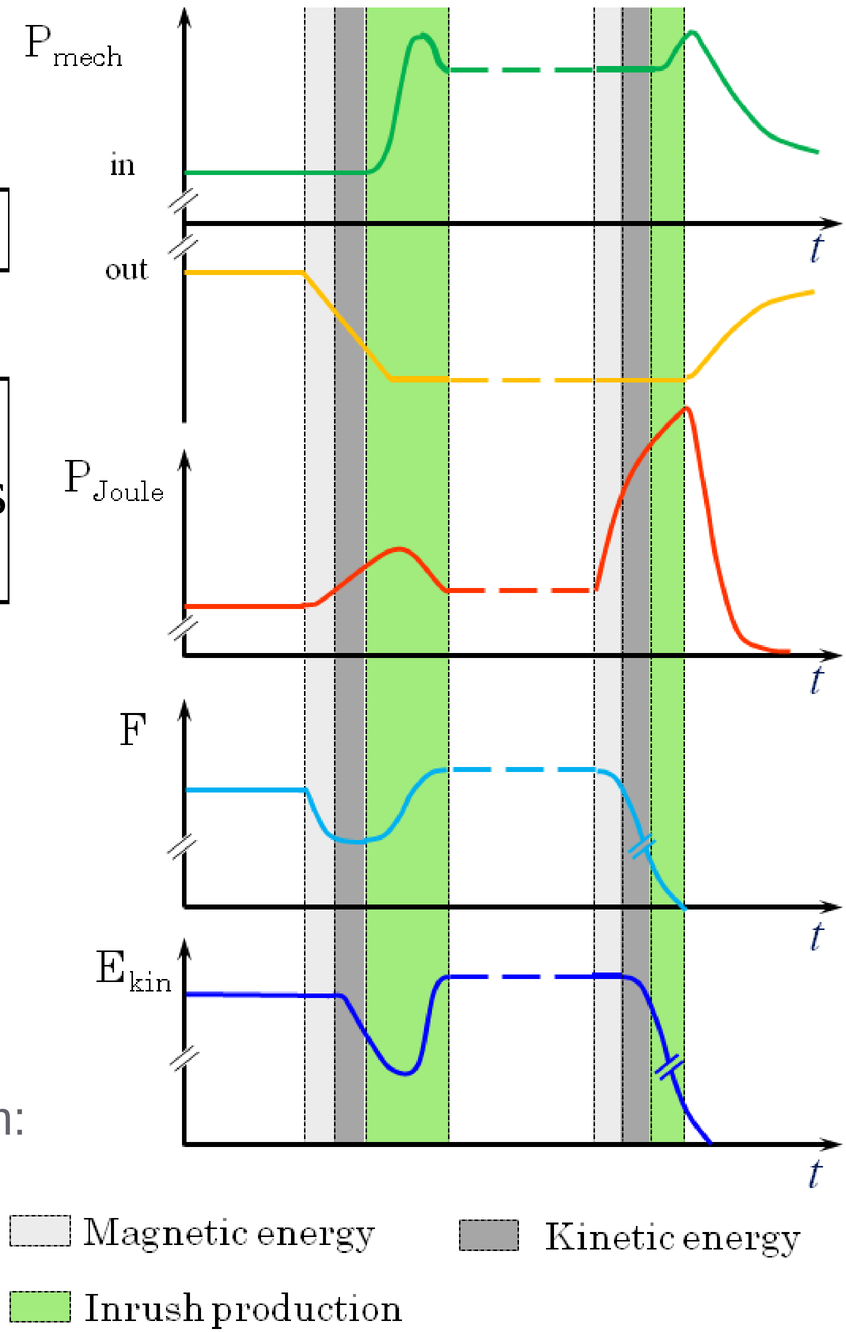
Power Management



Transient stability (ancillary services): → dynamic reserves

System adequacy: → primary/secondary/tertiary control

$$\underbrace{\overbrace{P_{mech}}}_{\text{mn}\rightarrow\text{hour}} = P_{Joule} + \overbrace{\underbrace{\frac{dE_{kin}}{dt}}_{\text{s}} + \underbrace{\frac{dF_{mag}}{dt}}_{\text{ms}}}$$

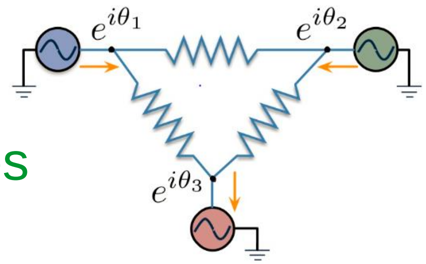


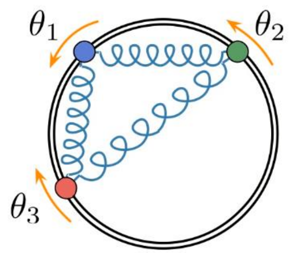
Upper bound equality is enforced by synchronism:

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

Why and How to keep synchronism?

- A mechanical analogy for 3 linked bodies





➔ Capture the critical behavior thanks to a dedicated lattice model

- Coherence of fully-correlated oscillator population with noise [Kuramoto,1984]

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

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

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

- Disordering factors:
  - $N \to \infty$ (long range disordering modes)
  - Intensive use of transmission lines
- Ordering factors:
  - Lattice interaction and admittance
  - Locally balanced connection point

- Synchronization is not inconditionnally stable! [Kosterlitz-Thouless, 1973]

Stability and inertia of the power system

- Steady-state mode:
  - Electricity consumption = generation
  - Frequency and Voltage: constant
  - Embedded kinetic and magnetic free-energies are time-invariant

- Transient state:
  - Magnetic energy:
    - spread the fluctuation over the grid
    - Provide stiffness between distributed kinetic reserves
  - Kinetic energy: inertia for the power system

Reliability indicators

Patent FR 11 61087

$$H_{syn} = \frac{\lambda_2(G)}{\max_{\langle i,j\rangle \in G} |P_i - P_j|} \geq 1$$

$$H_{kin} = \frac{E_{kin}}{Max(S, Peak - S)}$$

Then:
- Primary reserve: get back to a balance between consumption and production
- Secondary reserve: restore frequency and voltage to their set points
- Tertiary reserve: economic optimum

➔The greater the indicators, the smaller the frequency and voltage deviations

From Electromagnetism to Energy:
Some long-term planning exercises

- *Climate-dedicated policies*
  - *Energy Efficiency vs. Clean generation*

V. Mazauric, M. Thiboust, S. Selosse, E. Assoumou, and N. Maïzi, "Arbitrage between Energy Efficiency and Carbon Management in the Industry Sector: An Emerging vs. Developed Country Discrimination," in *International Energy Workshop (IEW 2015), Abu Dhabi, EAU, 2015*.

  - *Carbon Pricing*

N. Maïzi, A. Didelot, V. Mazauric, E. Assoumou, and S. Selosse, "Impacts of Fossil Fuels Extraction Costs and Carbon Pricing on Energy Efficiency Policies," in *International Energy Workshop (IEW 2016), Cork, Eire, 2016.*

[N. Maïzi, A. Didelot, V. Mazauric, E. Assoumou, and S. Selosse, "Balancing Energy Efficiency And Fossil Fuel : The Role of Carbon Pricing," *Energy Procedia, 2016.*]

  - *Pledges and INDCs assessment*

S. Selosse and N. Maïzi, " What commitments for the future climate regime: Long-term decoding using TIAM-FR " in *International Energy Workshop (IEW 2014), Beijing, China, 4-6 June, 2014.*

- Technical issues
  - Intermittency and non-dispatchable sources: time reconciliation
  - Synchronism issue: space aggregation
  - *Reuniese* and French cases

M. Drouineau, E. Assoumou, V. Mazauric, and N. Maïzi, "Increasing shares of intermittent sources in Réunion island: Impacts on the future reliability of power supply," *Renewable and Sustainable Energy Reviews, vol. 46, pp. 120-128, 2015.*

S. Bouckaert, V. Mazauric, and N. Maïzi, "Expanding renewable energy by implementing Demand Response," *Energy Procedia, vol. 61, pp. 1844-1847, 2014.*]

[S. Bouckaert, P. Wang, V. Mazauric, and N. Maïzi, "Expanding renewable energy by implementing Dynamic support through storage technologies," *Energy Procedia, vol. 61, pp. 2000-2003, 2014.*

N. Maïzi, V. Mazauric, E. Assoumou, S. Bouckaert, V. Krakowski, X. Li, et al., "Maximizing intermittency in 100% renewable and reliable power systems: A holistic approach applied to Reunion Island in 2030," Applied Energy, vol. 227, pp. 332-341, 1 october 2017.

The energy dilemma is here to stay

The facts

×2

Energy demand

By 2050

Electricity up 80% by 2035

Source: IEA 2010

VS

The need

÷2

CO_2 emissions to avoid dramatic climate changes by 2050

Source: IPCC 2007, figure (vs. 1990 level)

Energy scarcity,
Demography
Resource access
Energy prices

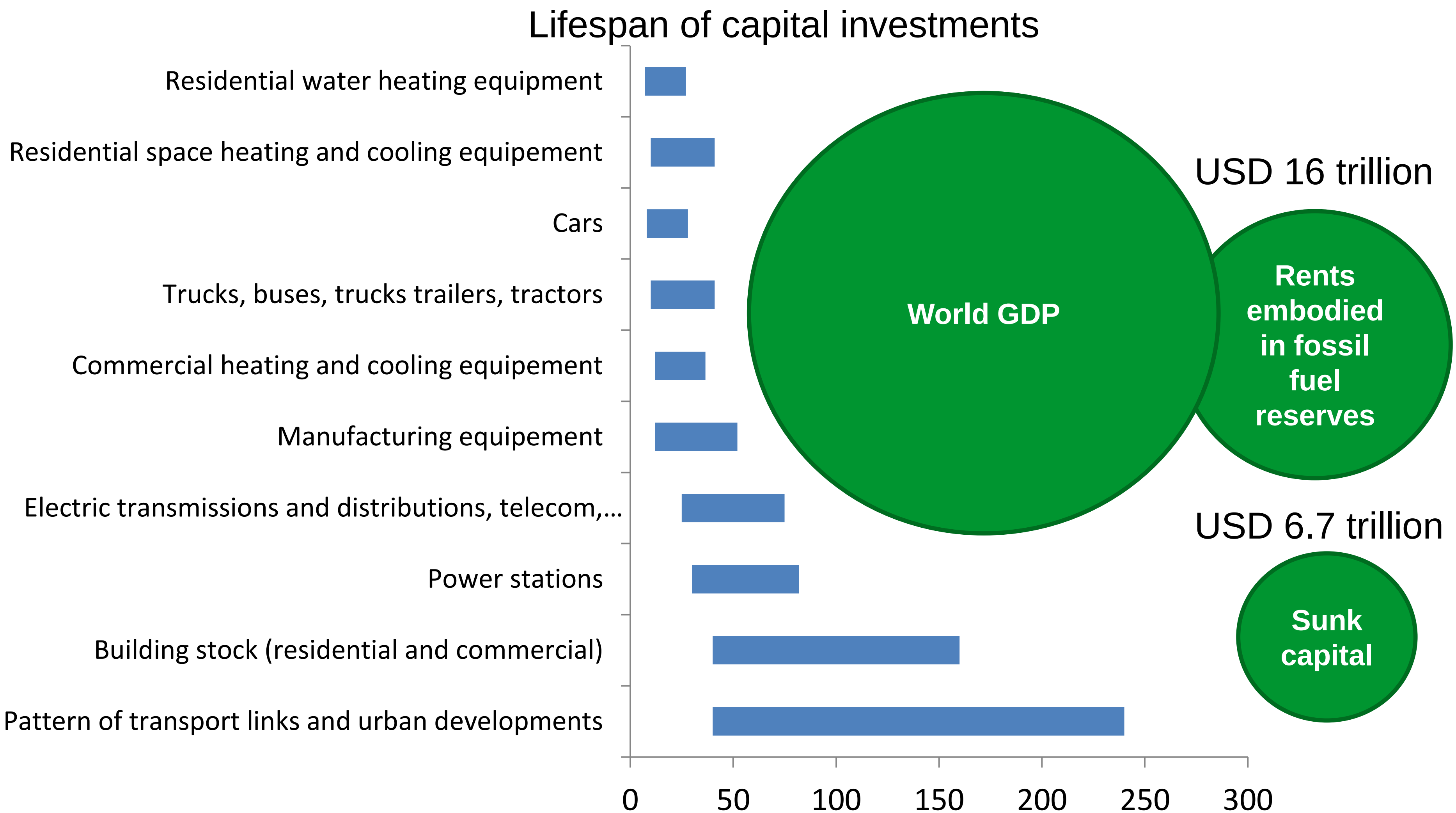
GHG emissions
Climate change

Dispersed generation
vs.
dense urban zone

Reliability of supply
Business models

The “big picture” for changing

Overcome the inertia to walk to our future

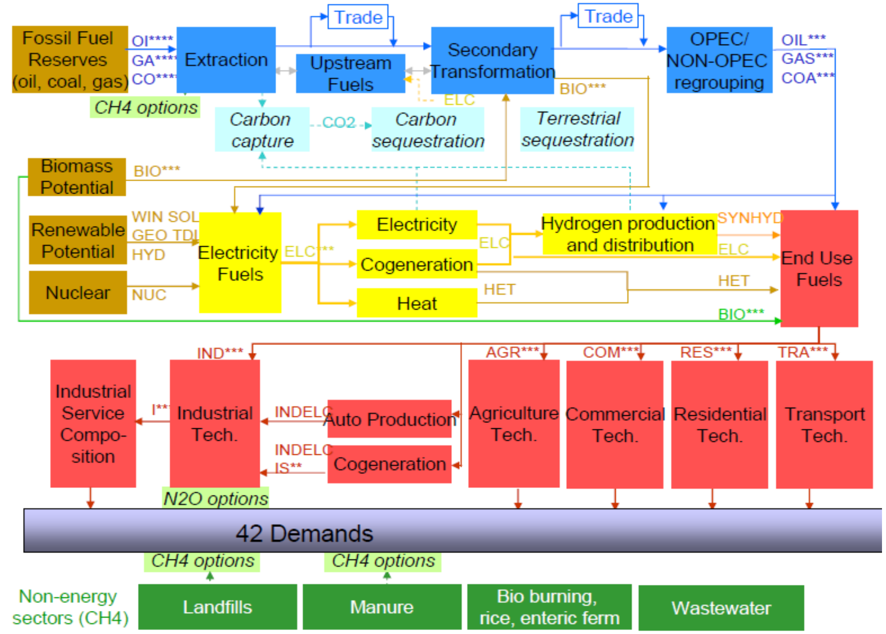


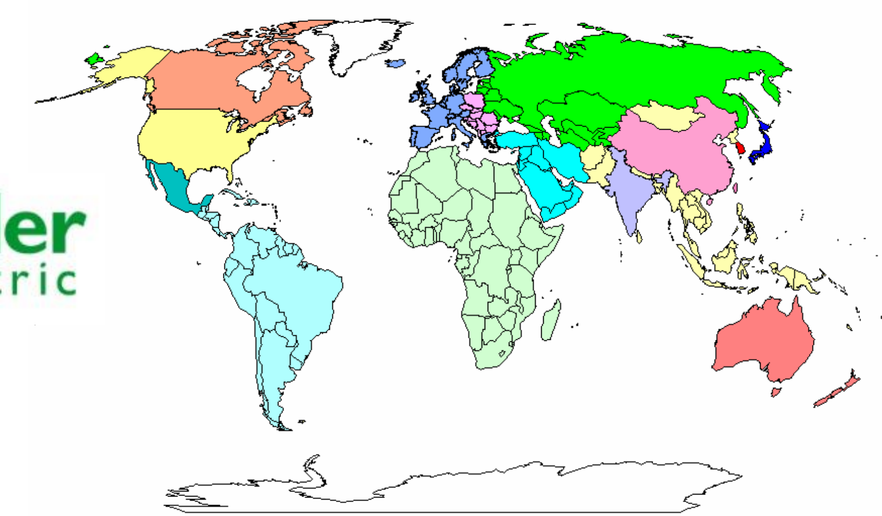
Source: OECD (Forthcoming) Green Growth Studies: Energy; World Bank.

Modeling issues

- The TIAM-FR model:

  A 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
  - over a definite horizon, typically long-term (50 years)
  - 15 regional areas





French case issues

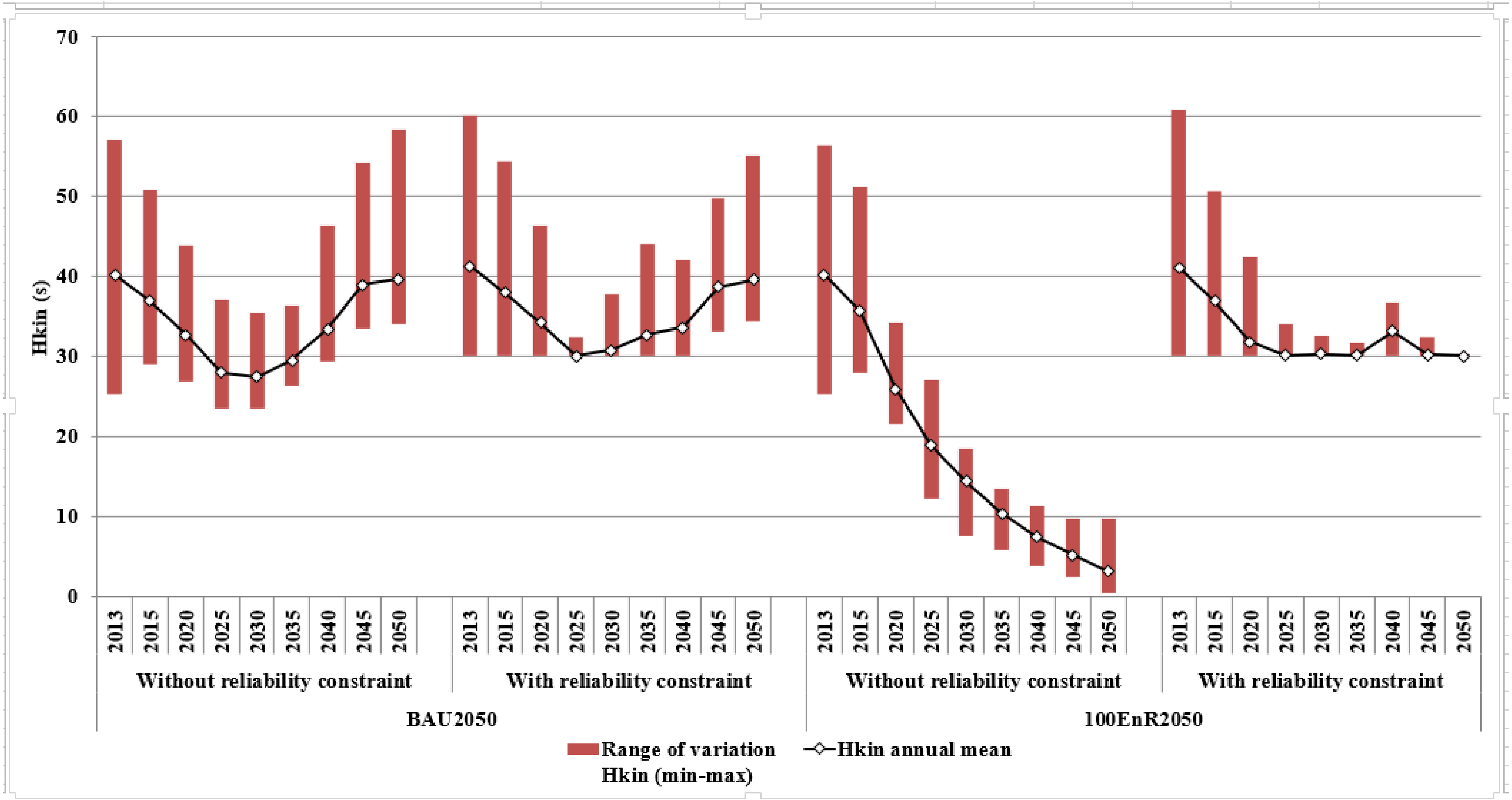
- Nuclear phase out
- Decarbonation of the power system with REN

[N. Maïzi, E. Assoumou. “Future prospects for nuclear power in France”. *Applied Energy*, 2014, 136, pp.849-859.]

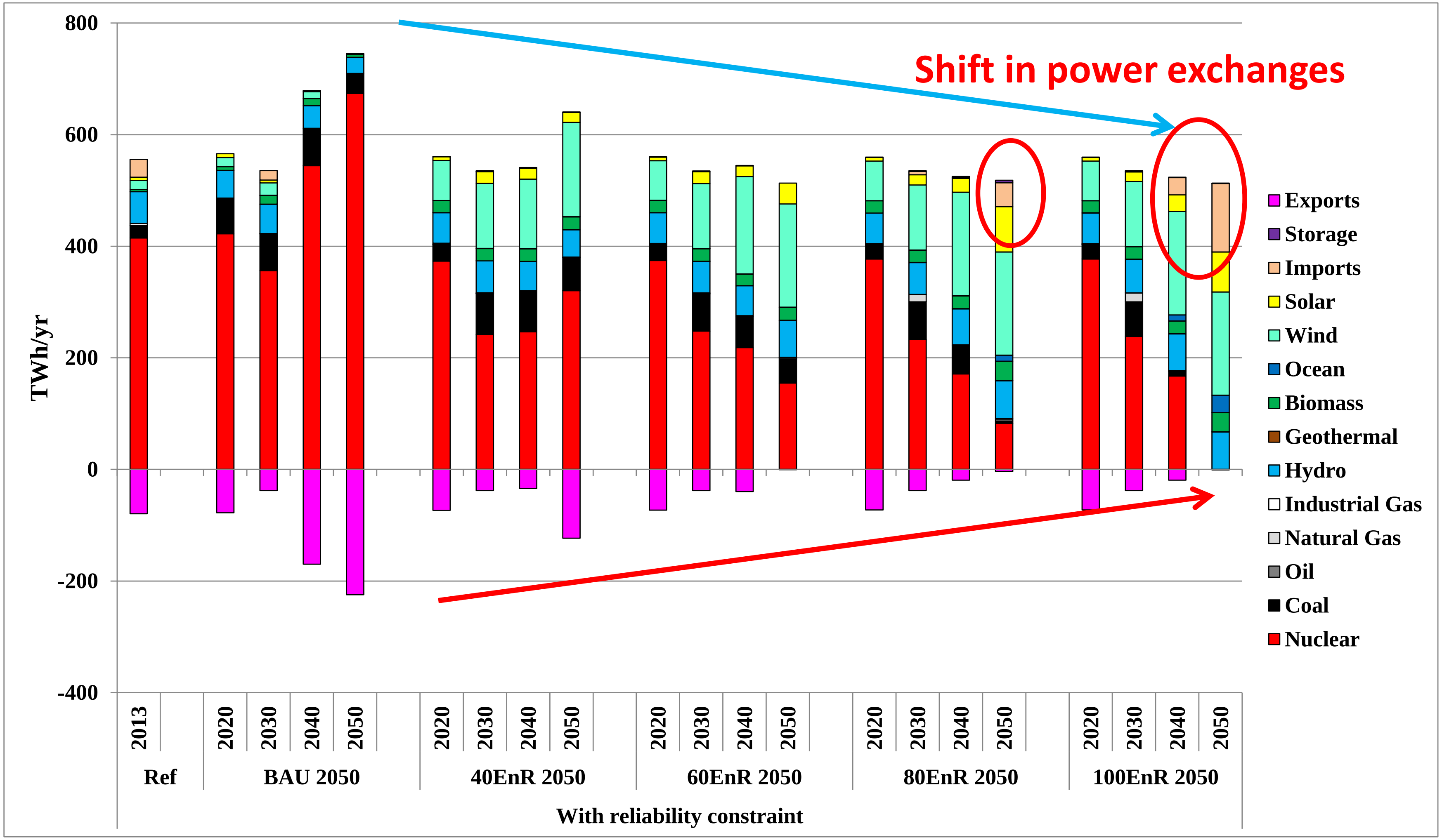
[V. Krakowski, E. Assoumou, V. Mazauric, N. Maïzi, “Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis”, *Applied Energy*, 2016, 171, pp. 501-522.]

[G. S. Seck, V. Krakowski, E. Assoumou, N. Maïzi, V. Mazauric, “Reliability-constrained scenarios with high shares of renewables for the power sector in 2050“, *Energy Procedia*, 2018.]

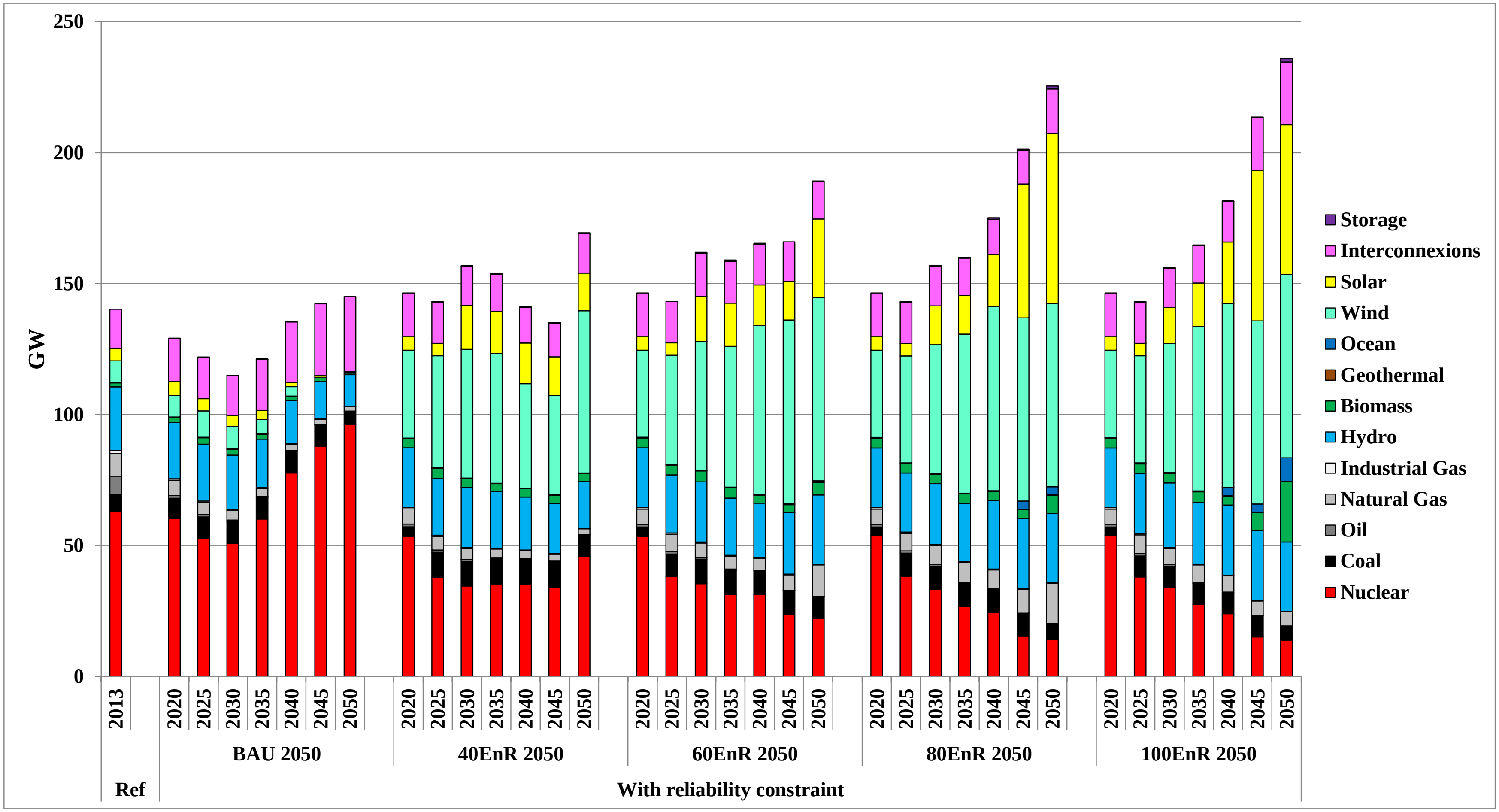
Reliability constraint



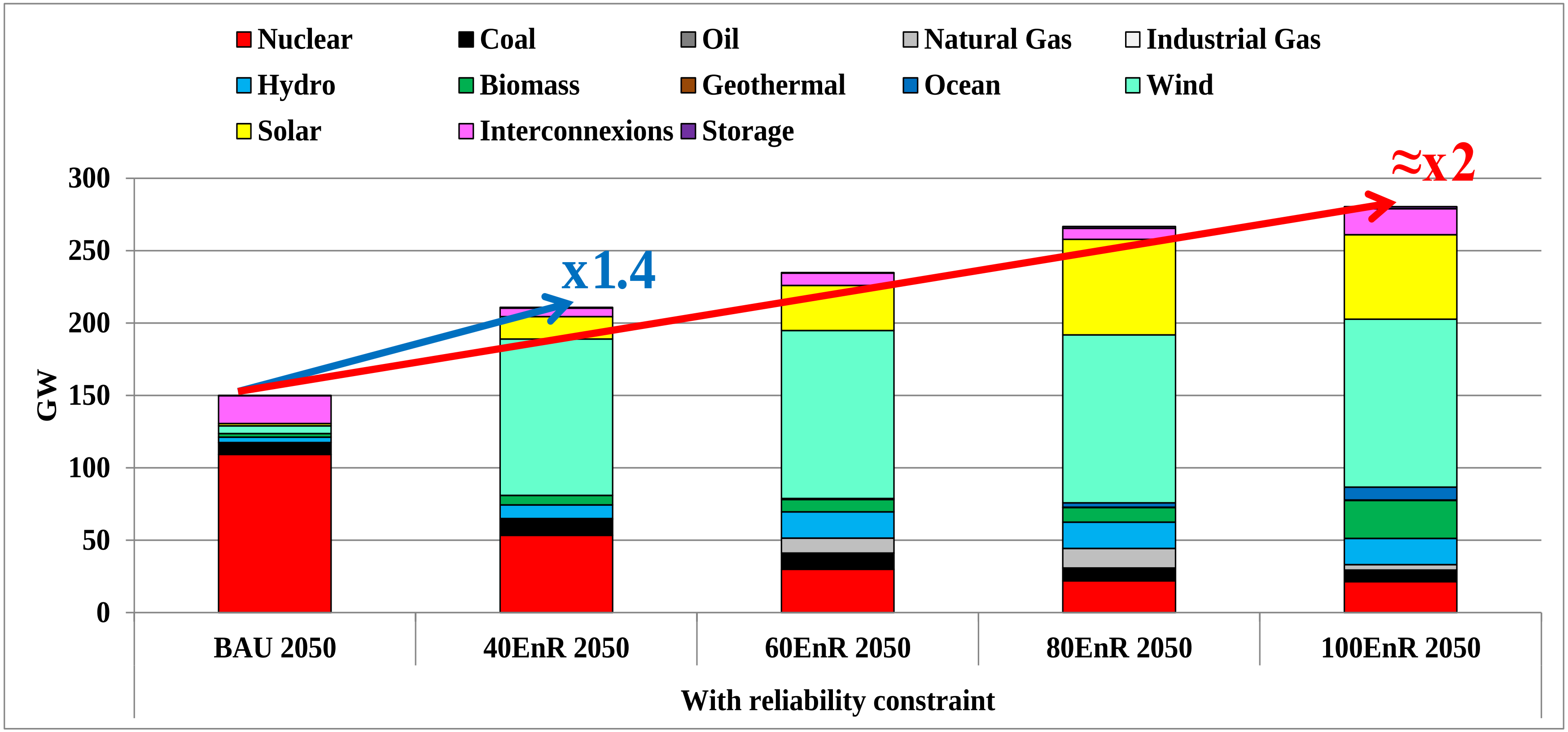
Yearly generation



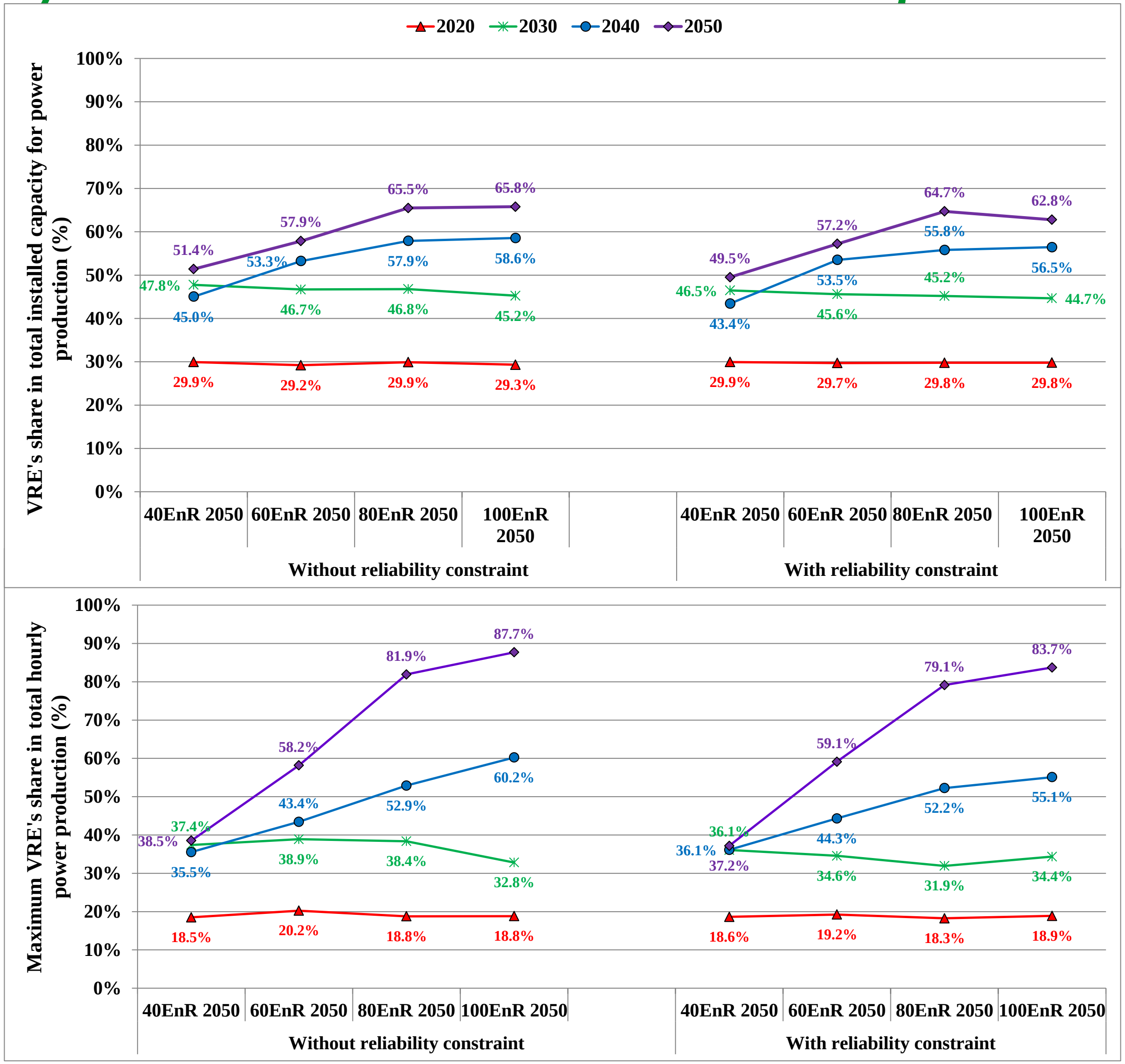
Installed capacity



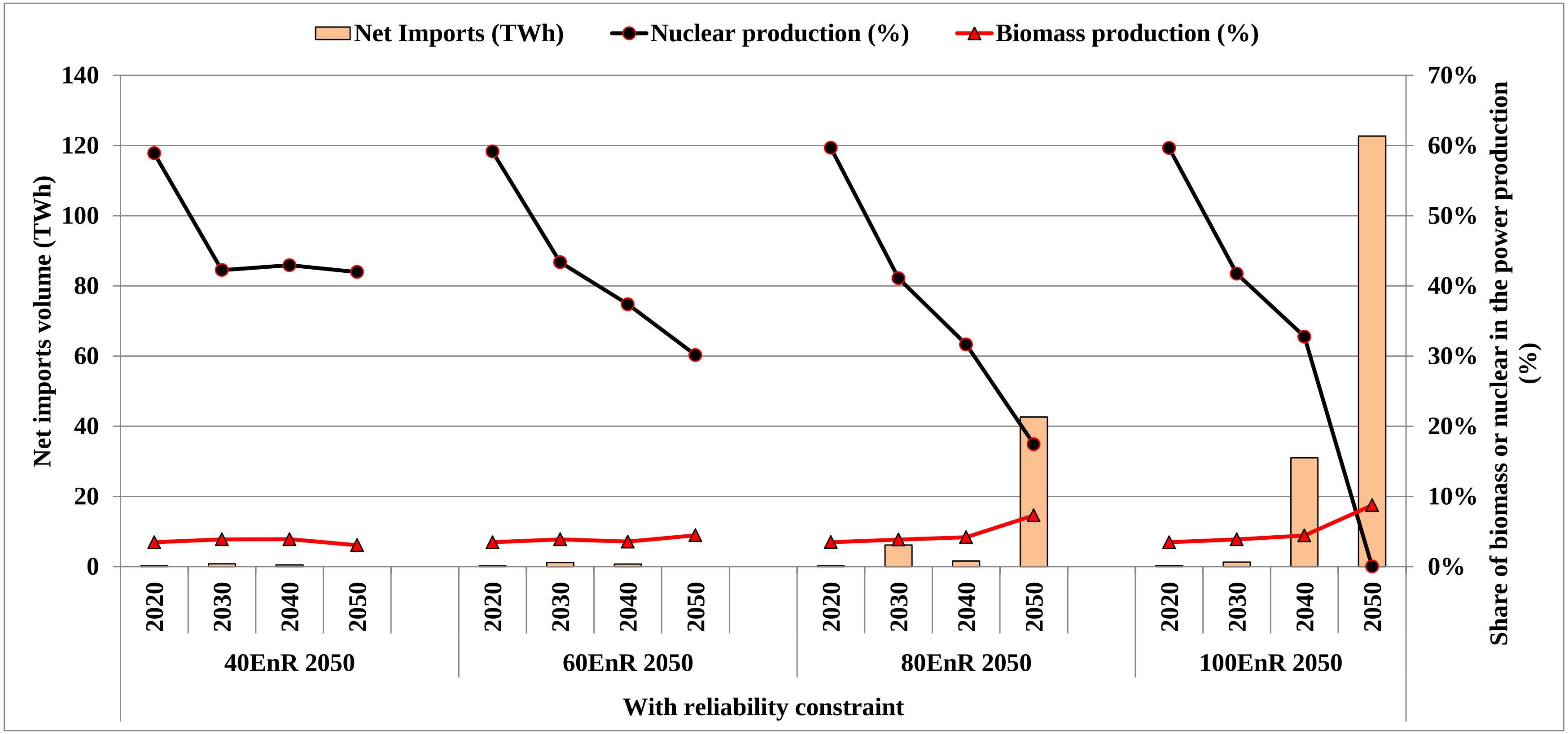
Installed capacity in 2050 (MW)



Share of intermittency for:
Capacity and Power *vs.* %REN generation

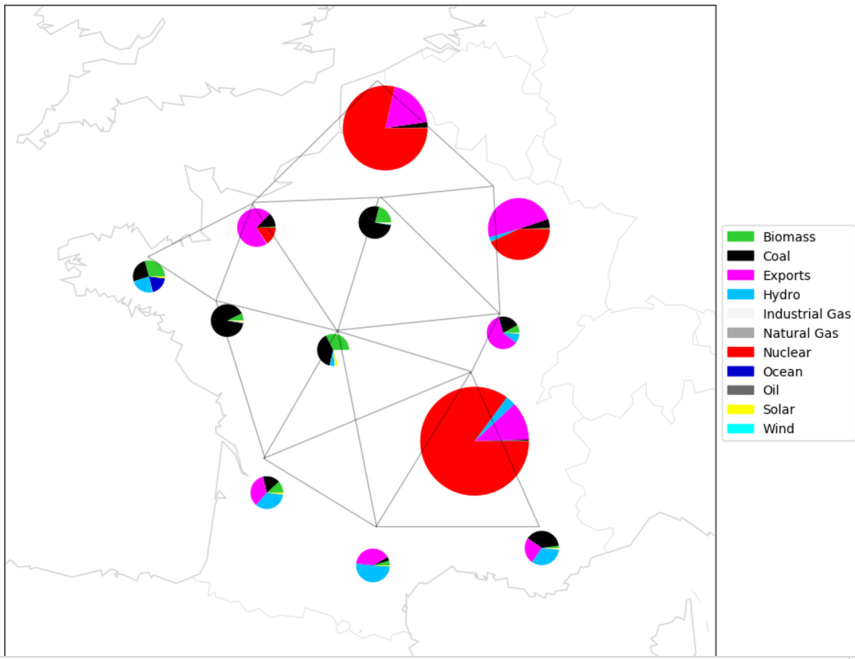


Sensitivity analysis to some critical issues

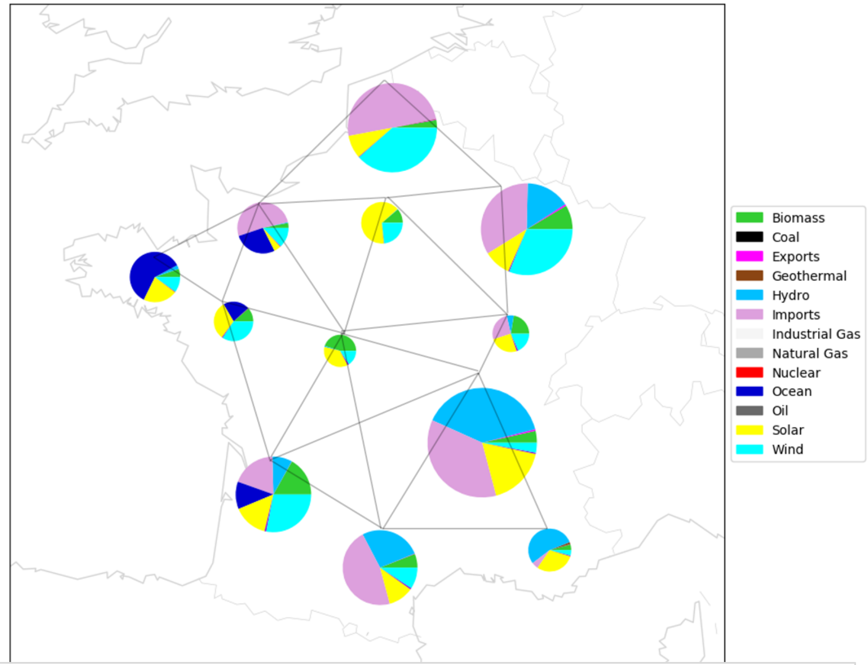


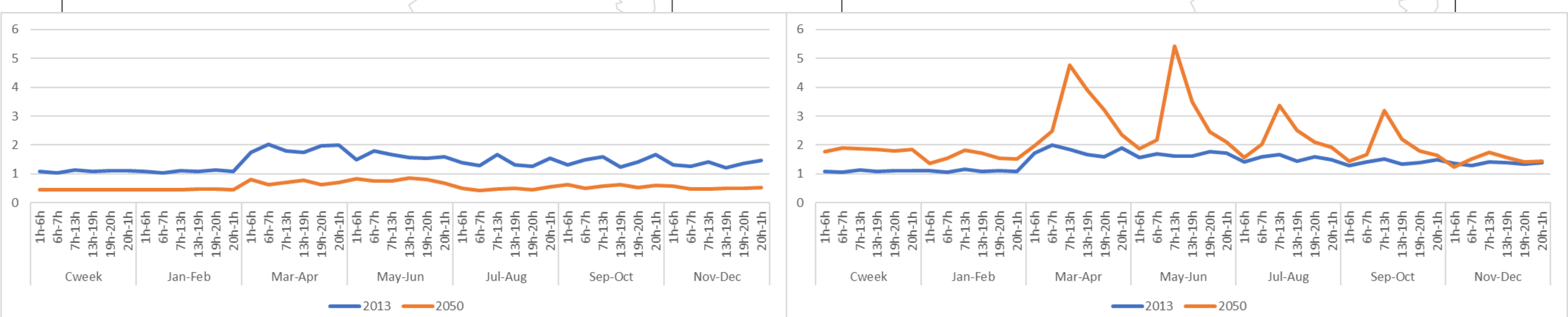
Regional mix under fiability constraint

BAU generation



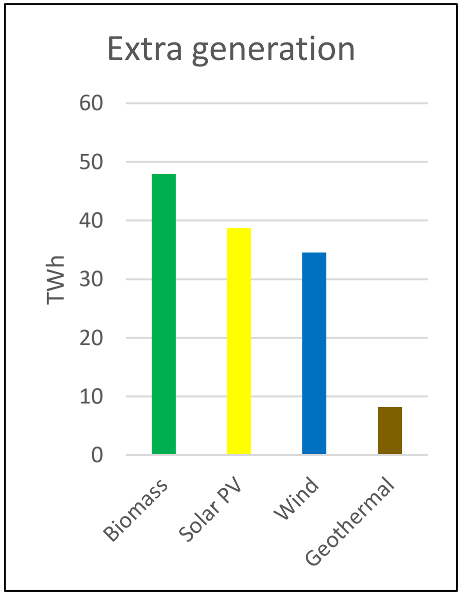
100% renewables

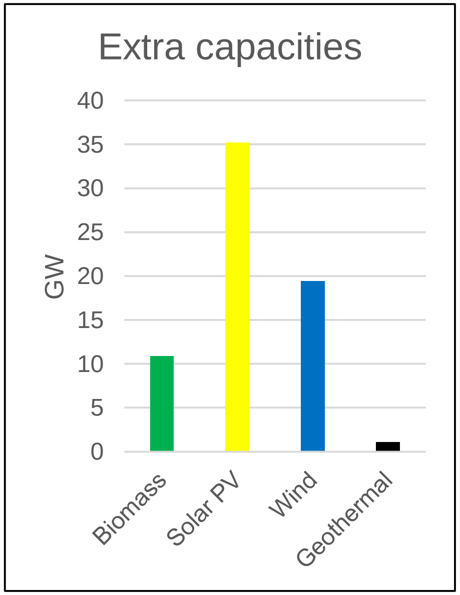


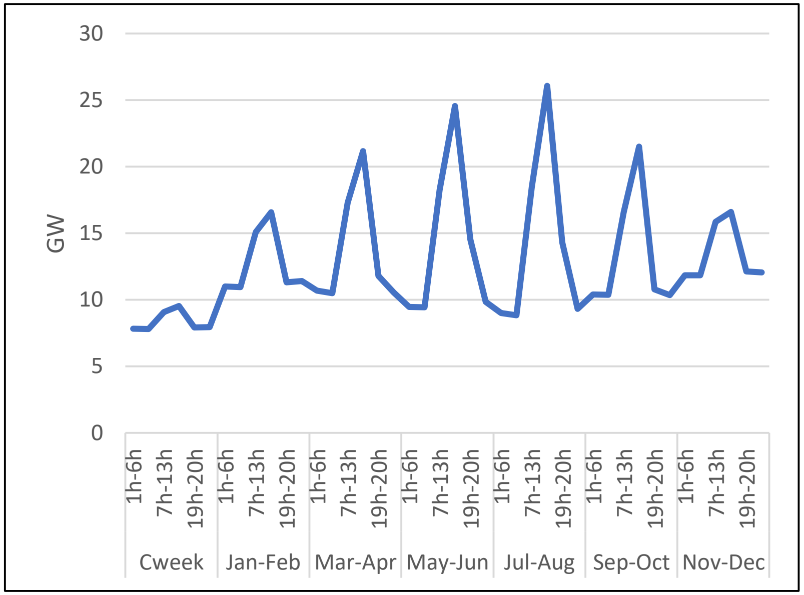


Regional vs. National REN empowerment

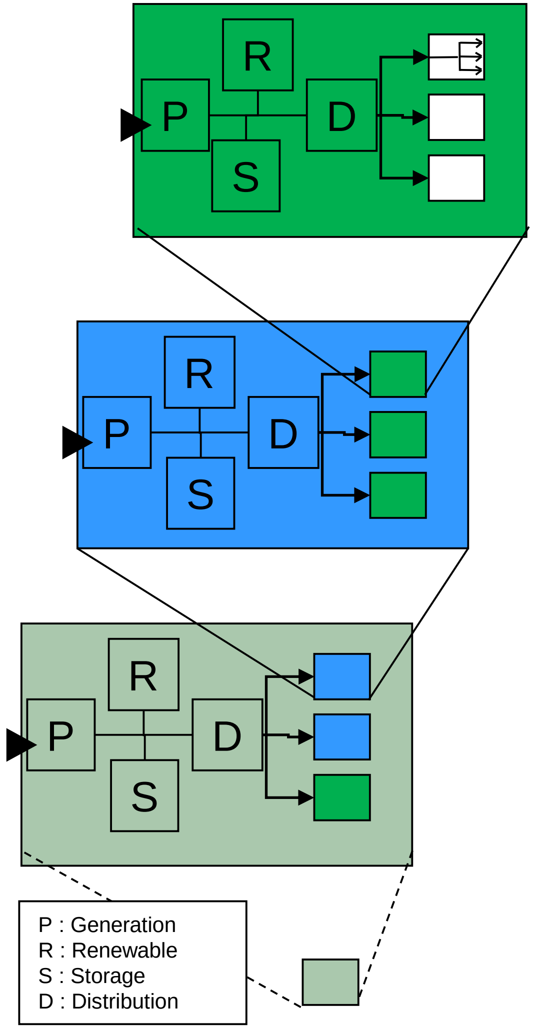
- Realistic in active energy for all regions except IdF (25 to 46%)
- Low autonomy for ancillary services:
  - Except RAA, HdF and Normandy
  - High contribution of Biomass, Hydro and geothermy
  - Implementation of 4GW storage (current STEP capacity)
- Overgeneration of 124TWh







Towards an embedded and optimized/smart energy system



- **Room, floor and residential level:**
  - **Load :** devices
  - **Room control:** Decrease demand without jepardize comfort and productivity

comfort
productivity

- **Building level:**
  - **Loads:** rooms, floors…
  - **Building control:** Optimize commodities, i.e. « smart grid ready »

efficient
flexible

- **Campus and District levels (smart district)**
  - **Loads**: Buildings and small plants
  - **District control:** leverage Renewables and flexibilities to perform peak shaving, promote self-generation and define a new technico-economic optimum.

optimised,
positive energy

- **Cities and State (smart cities)**
  - **Loads** : districts and intensive plants
  - **City control**: Lower CO_2 emissions, increase resiliency, expand to other commodities and public services (mobility, health, security, water, data…)

autonomous
résilient

- **Whole power system (smart grid):**
  - **Loads**: cities, states…
  - Ensure safety, stability and grid availability: balancing demand/suply, incenzitive demand response, manage ancillary services.

stable
well balanced
available

Conclusion

Thermodynamics principles and reversibility trend provide a global framework for:

- Deriving electromagnetics (Maxwell equations) in quasi-static regimes
- A multi-scale description:
  - Space aggregation (Kuramoto universality class)
  - Time reconciliation (from operation to planning)

Due to local generation, µ-grid and decentralized concepts allow reducing transmission throughout the grid and improving the synchronism indicator at the transmission scale. However:

- the constraint on synchronism is rejected on the distribution network (with lower voltage and extra losses) inducing investment at this stage
- constraining kinetic energy to the 2008 level over the prospective horizon induces extra-costs to enforce reliability (compared to BAU)
- the solar appears in the 3rd rank after wind and hydro (no self-consumption).

To summarize:

- µ-grid concept is compliant with energy transition by fixing the first step of the grid transformation towards decarbonation;
- Capital intensity needed to achieve a decarbonation compliant with COP21 pledges (>90% with migration) is not realistic so far without nuclear generation

Conclusion

- Many R&D fields to explore:
  - Expand and maintain technical fields:
    - Thermodynamics, operational research, electrical engineering, CAE…
  - Assess continuously environmental impacts:
    - Banish: ceteris paribus, techno-push, rebound effect…
- From Research to Innovation:
  - Risk-assessment, regional analysis…
  - Customers and Business stakeholders (ICC, IBF, WEC…)
  - Policy makers (UNEP, UNFCCC…)
- Sharing knowledge:
  - Publications (bifurcation not BAU)
  - patenting and IP strategy
- Business implementation

Make the most of your energy[SM]