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

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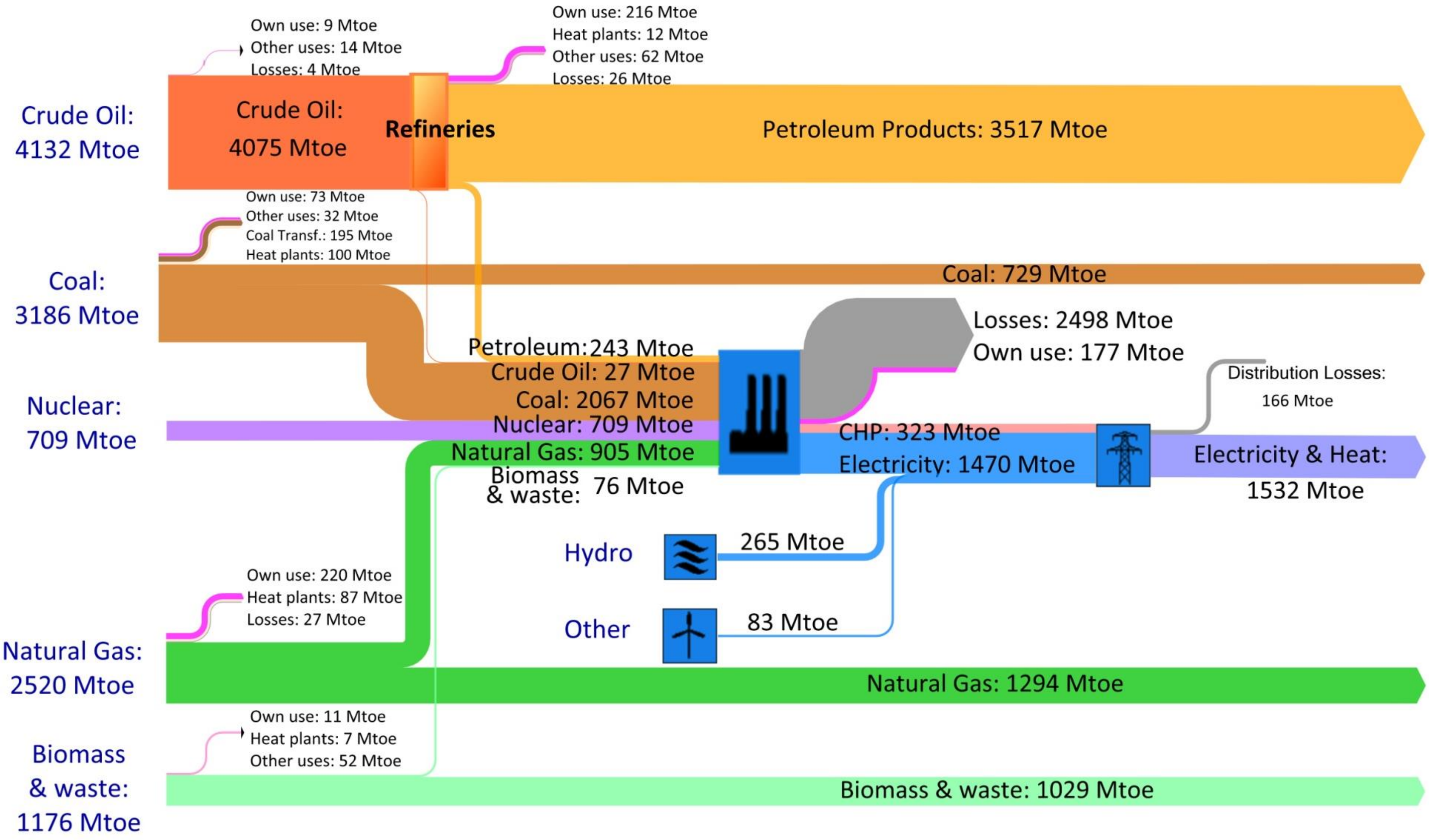
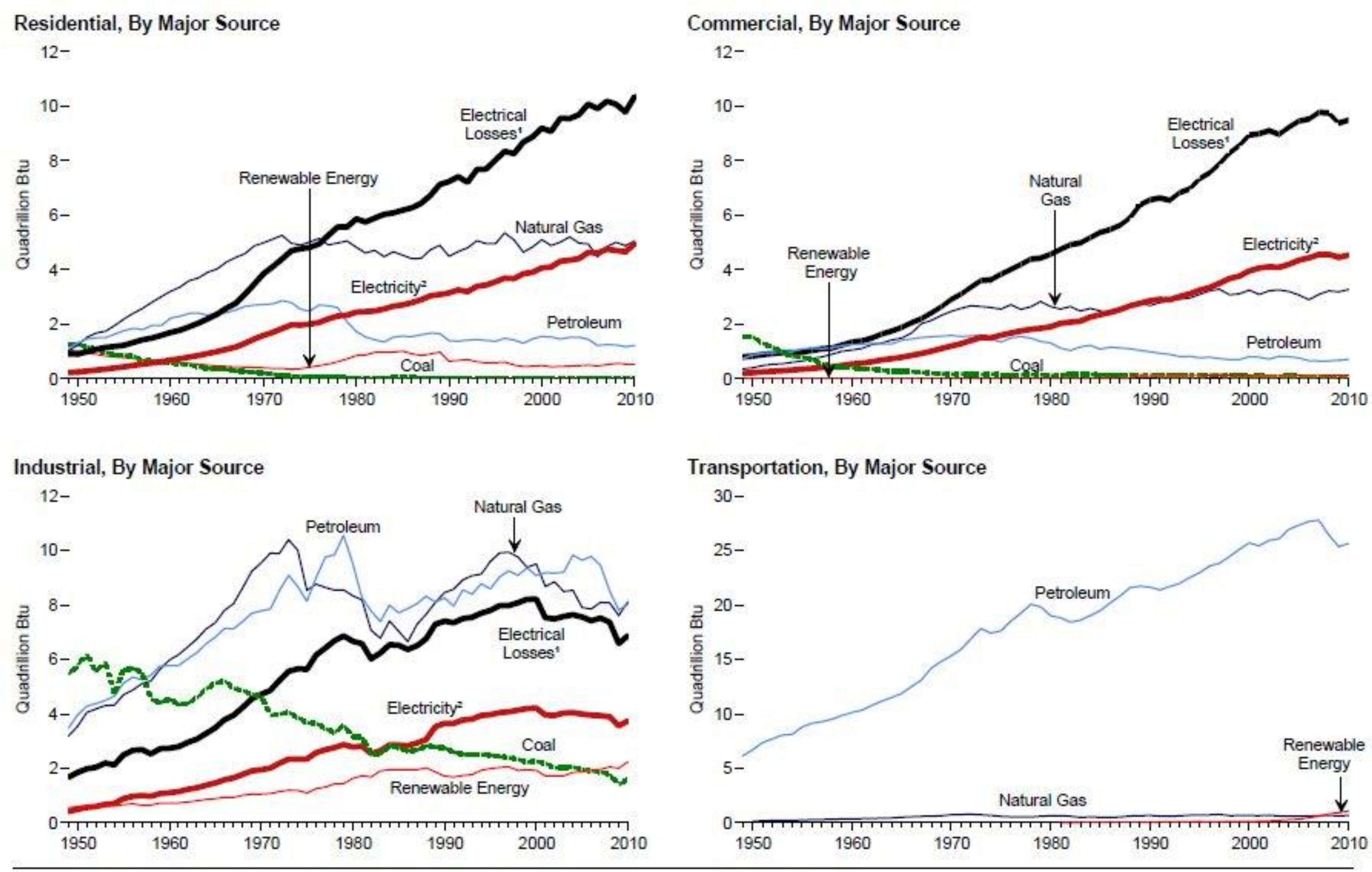
Tuesday, January 23rd, 2018

Ecole des Mines – Nancy

Energy supply Chain (from IEA 2007)



US energy consumption



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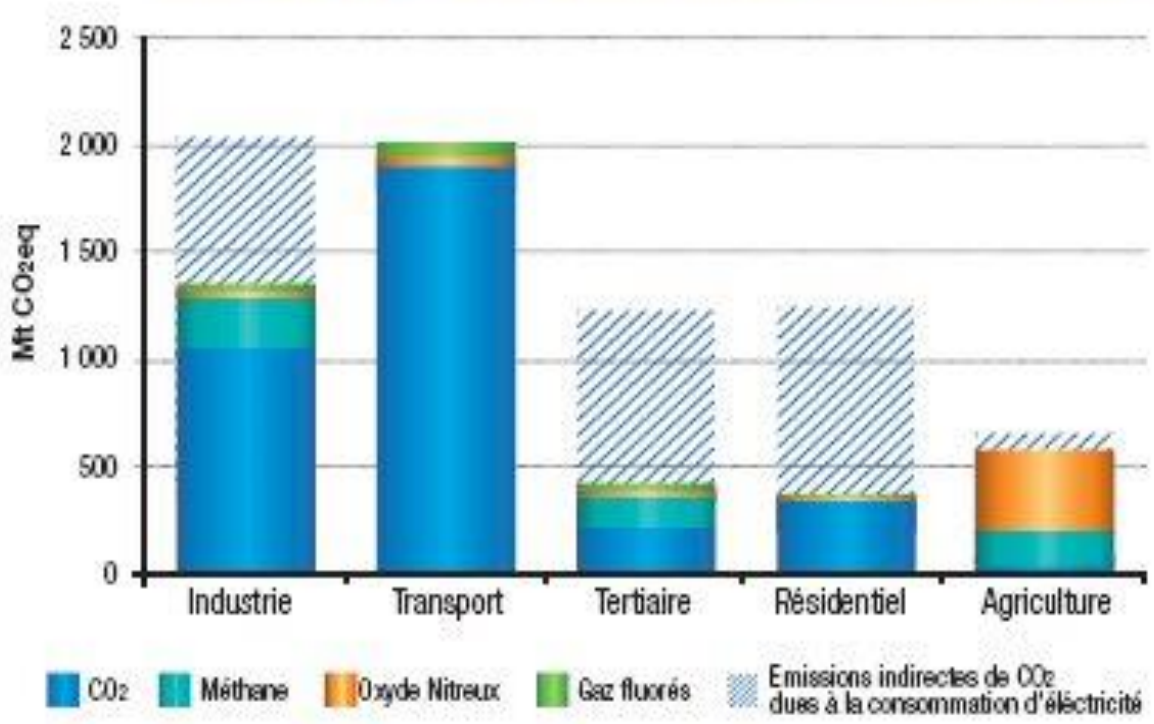
[1] Electrical system energy losses associated with the generation, transmission, and distribution of energy in the form of electricity.

[2] Electricity retail sales.

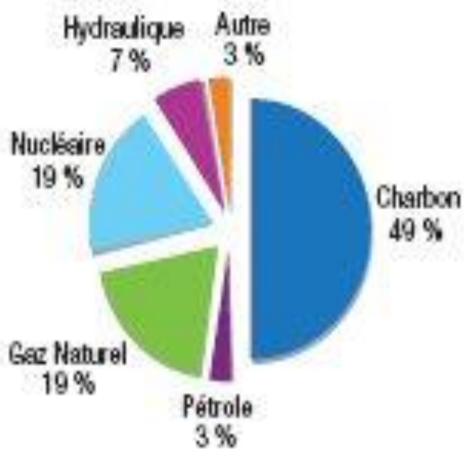
Sources: Tables 2.1b–2.1e.

US CO_2 emissions inventory per sector (1)

Émissions directes et indirectes de gaz à effet de serre des États-Unis en 2005, par secteur économique



Production d'électricité par source d'énergie



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

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

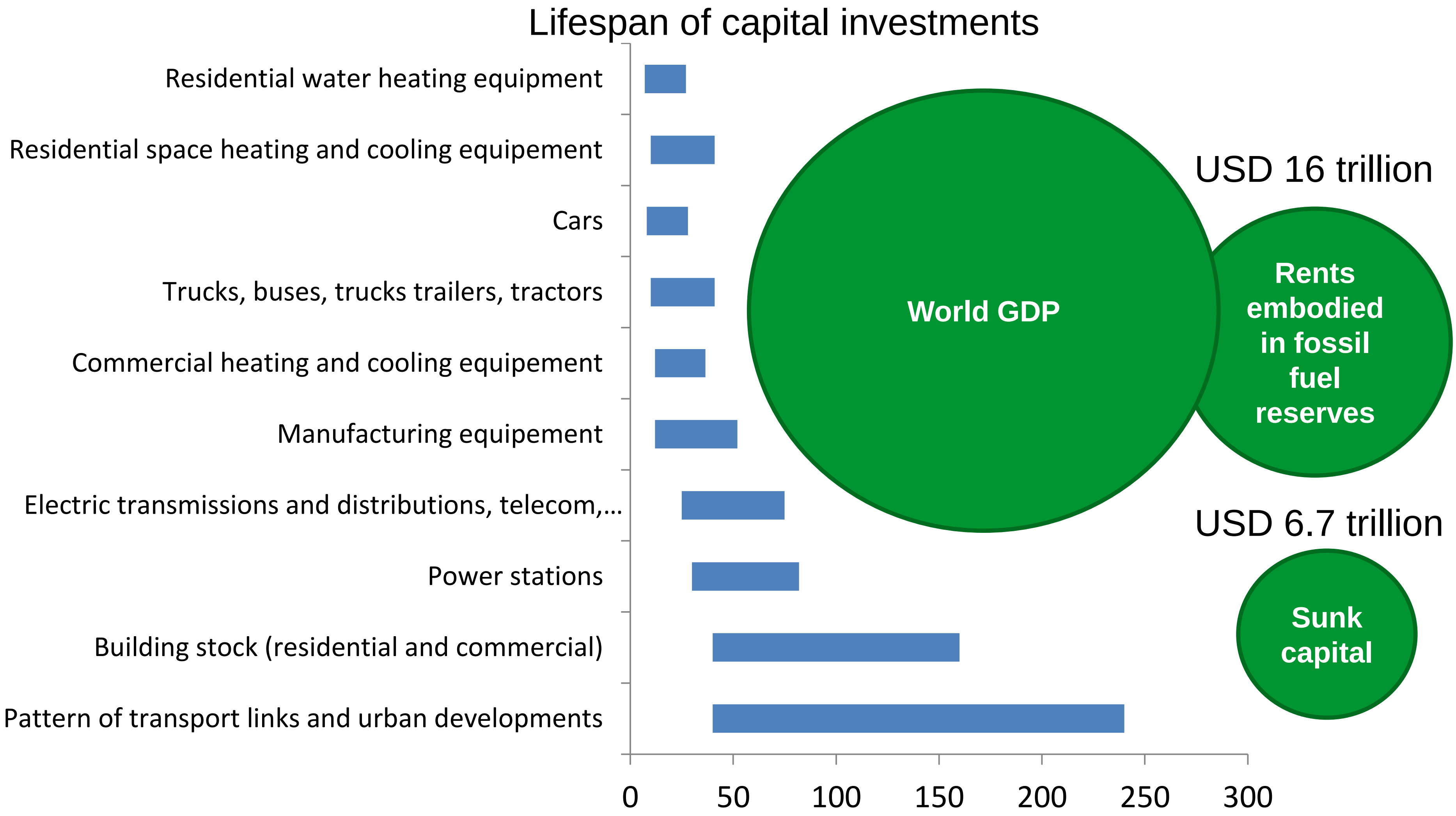
GHG emissions
Climate change

Dispersed generation
vs.
dense urban zone

Reliability of supply
Business models

The “big picture” for changing

Overcome the inertia to walk to our future

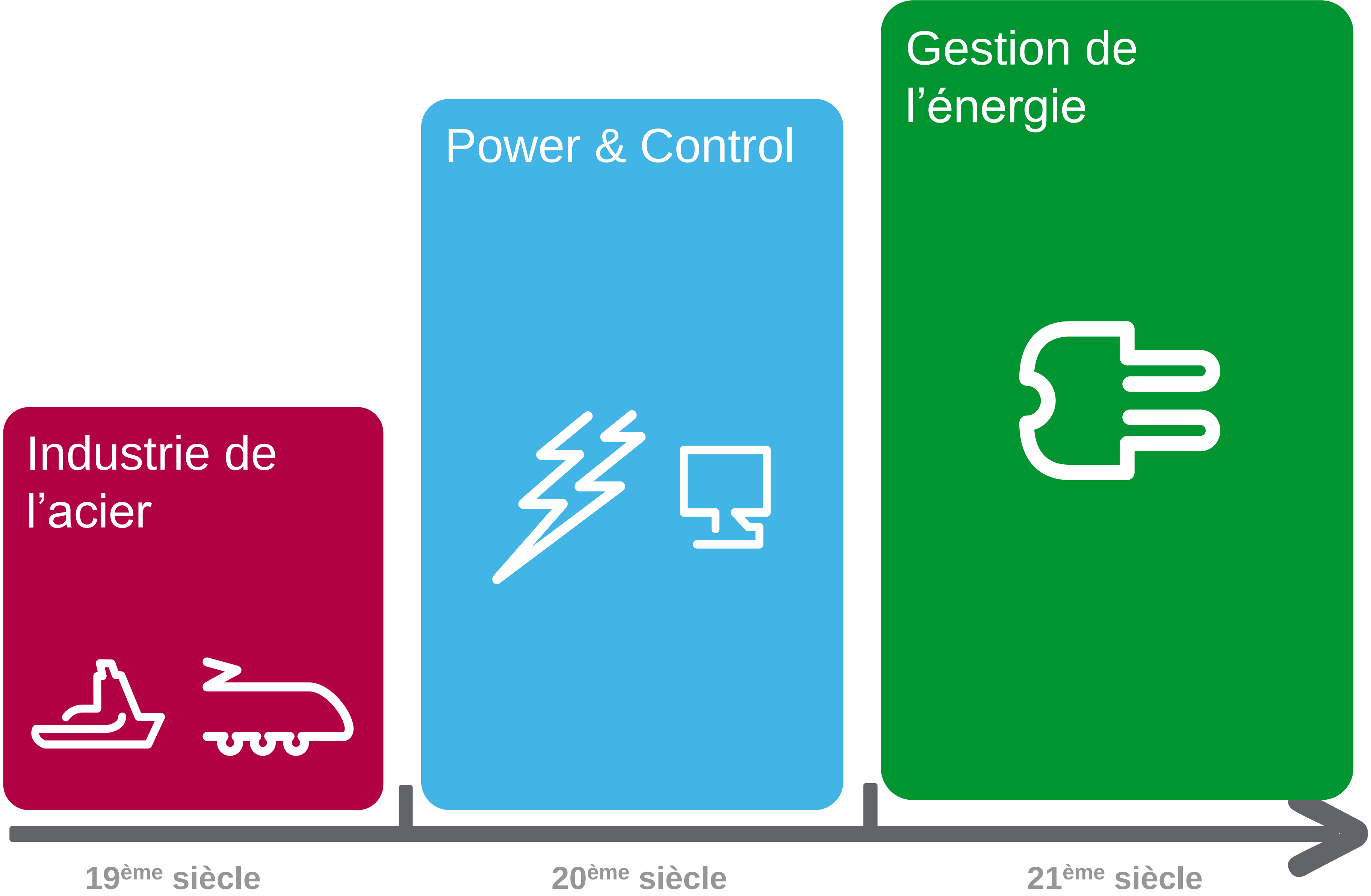


Source: OECD (Forthcoming) Green Growth Studies: Energy; World Bank.

Une entreprise globale

Une orthodoxie dédiée à l’énergie

Plus de 170 ans d’histoire



Industrie de l’acier

Power & Control

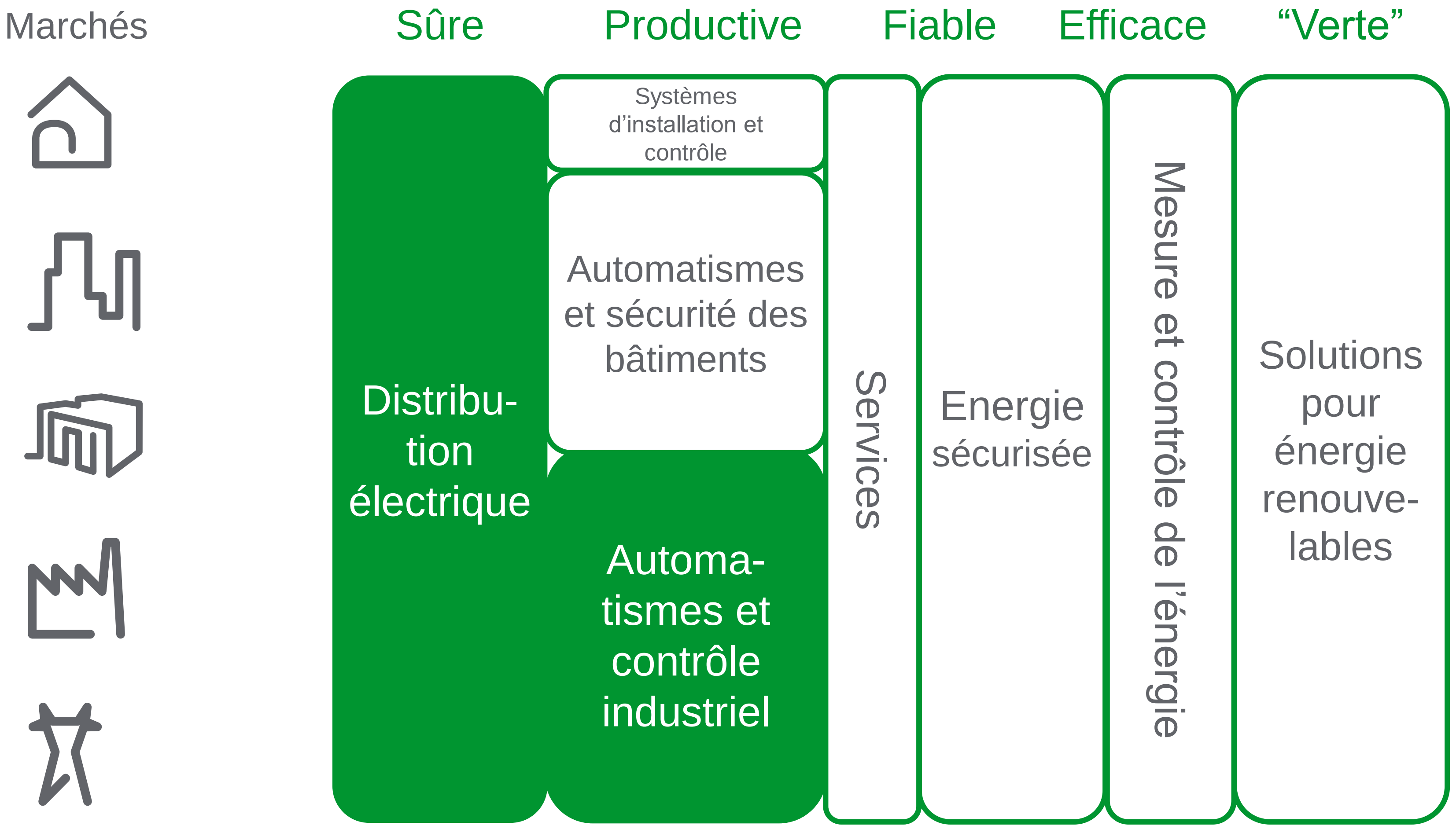
Gestion de l’énergie

19ème siècle

20ème siècle

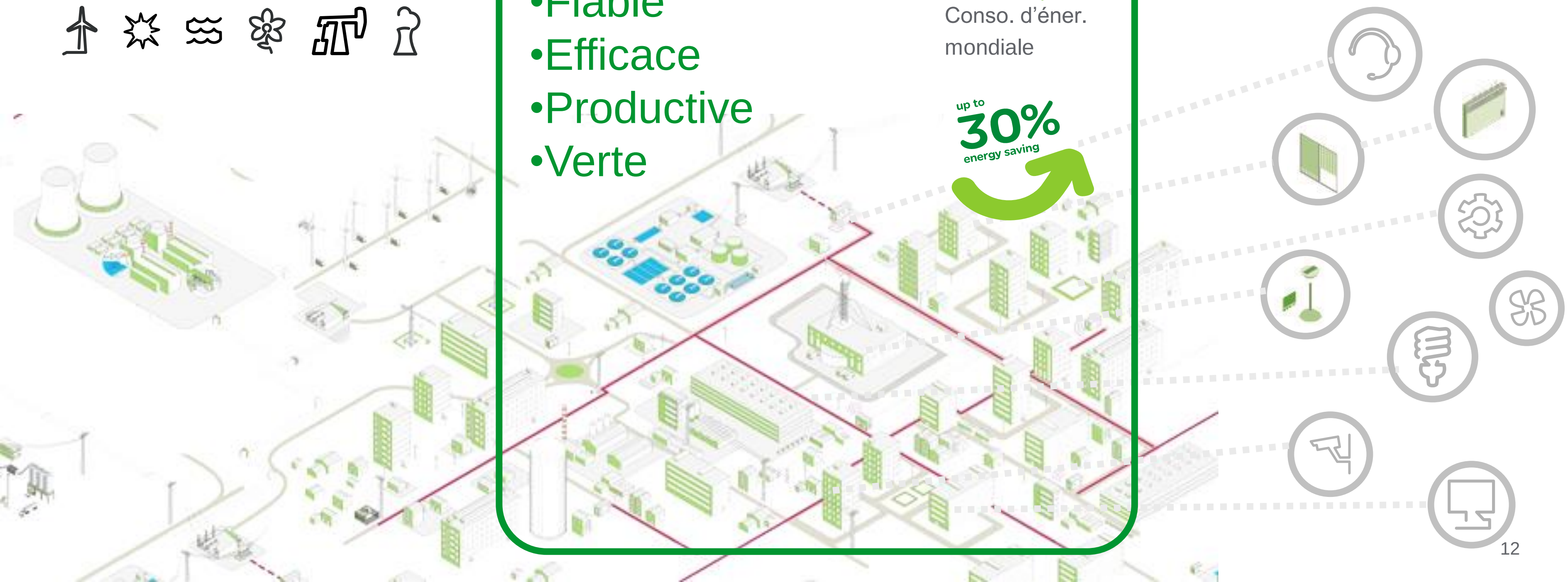
21ème siècle

Un portefeuille d'activités complet et équilibré



🟩 Présence historique ☐ Nouvelles activités

Un positionnement unique



Spécialiste mondial de la gestion de l’énergie

Production et transport de l’énergie

Rendre l’énergie…

- Sûre
- Fiable
- Efficace
- Productive
- Verte

couvre

72%

Conso. d’éner. mondiale

Utilisation finale de l’énergie

Une croissance durable et internationale

€ 27

Mds de chiffre d'affaires en 2015

41

% du CA réalisé
dans les nouvelles économies

160000+

Collaborateurs dans plus de 100 pays

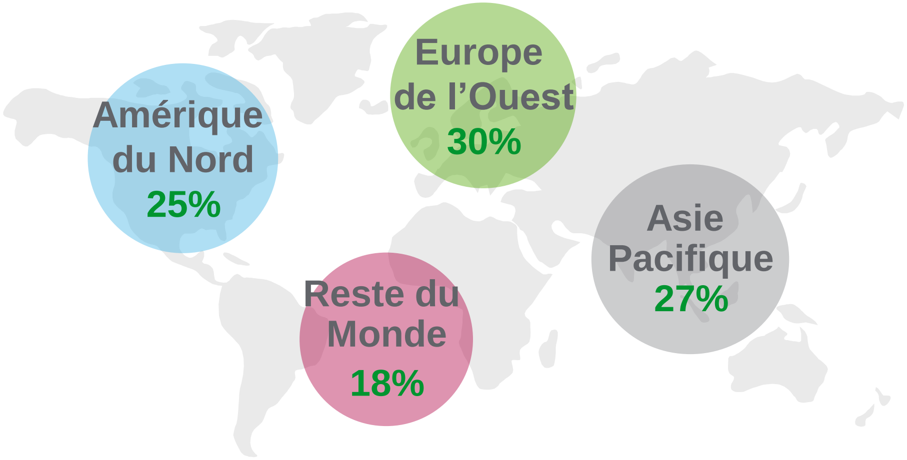
354

Au classement *Fortune 500 (2016)*

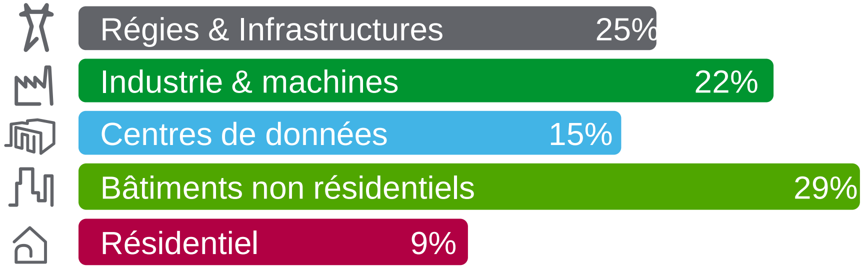
4-5%

Du chiffre d'affaires consacré à la R&D

Des géographies équilibrées – CA 2012



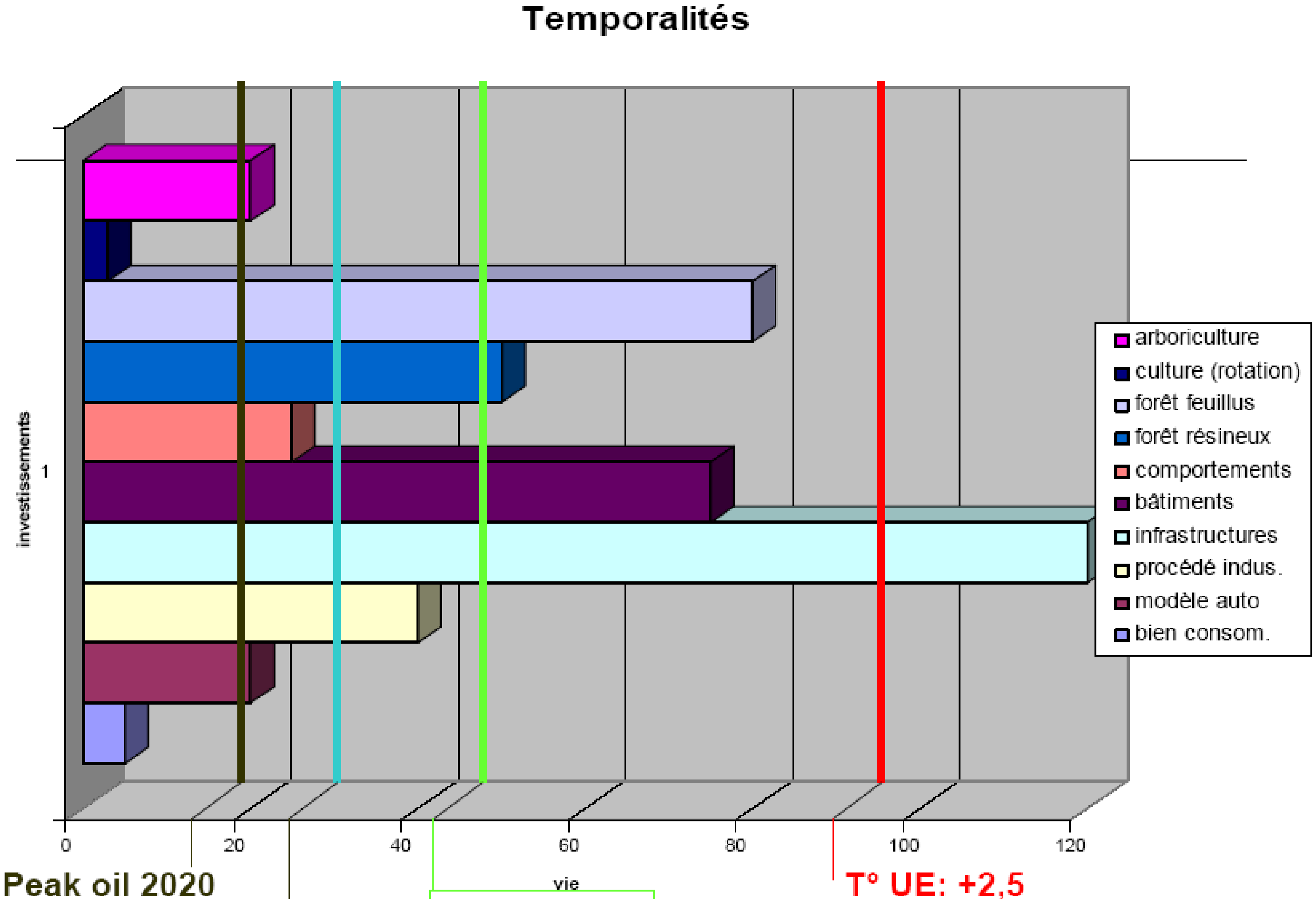
Des marchés finaux diversifiés – CA 2014



Privilégier le « demand side »

Si vous investissez en 2005 dans …

…votre investissement devra vivre…



Peak oil 2020

Peak gaz 2030

Fact 2 ou 4

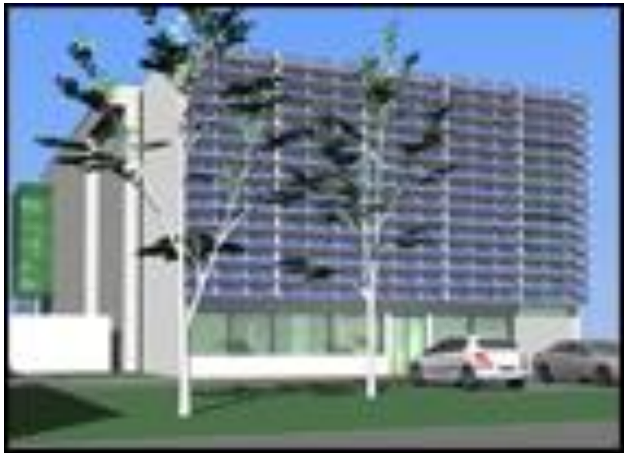
T° UE: +2,5
ou +4°C

Quelques solutions

- GEMASOLAR (Séville, SP):

- 17MW
- 185 ha

- B&D Eolas (Grenoble, FR):



- 700m² IT
- SE, APC, GDF Suez

- Un site dédié aux solutions dans les marchés clés: http://www.schneider-electric.com/sites/corporate/en/solutions/solution-overview.page

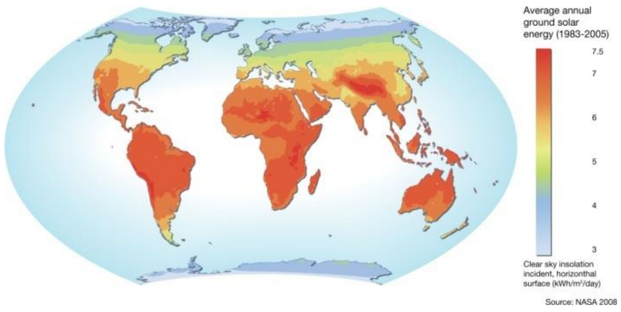
Power Management
Process & Machines Management
IT / Server Room Management
Building Management
Security Management

- 3000 personnes travaillant sur l'EE sur le bassin grenoblois

Quelques programmes d'innovation

MICST

- 2Mds d'individus n'ont pas accès à l'énergie



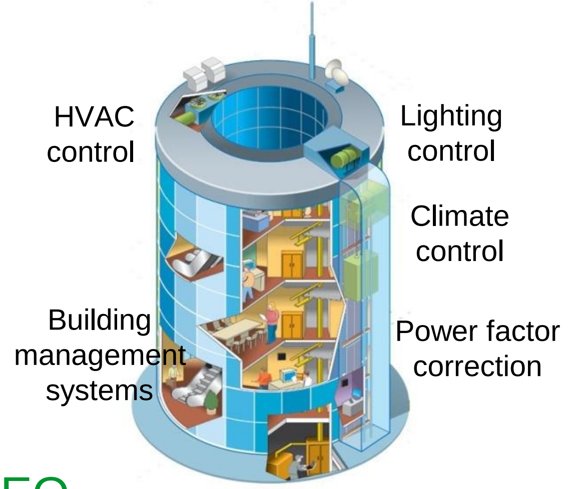
Source: NASA 2008

- Soutenu par l'ADEME
- Labellisé par CapEnergies et Tenerrdis

MECACHROME INTERNATIONAL
barriquand technologies thermiques
Stiral
Défi·Systèmes
Lemta
Sophia Antipolis Energie Développement
GROUPE CEDRAT
ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE
exosun
Leme
Schneider Electric

homes

- Doter chaque bâtiment de solutions d'Efficacité Energétique Active pour atteindre sa meilleure performance énergétique:



- Soutenu par OSEO
- Labellisé par Minalogic et Tenerrdis

cea
PHILIPS LIGHTING
RADIALL
somfy
w@tteco
ST
EDF
DELTA DORE
CIAT
CSTB le futur en construction
wieland
Schneider Electric
PolySpace TECHNOLOGIES

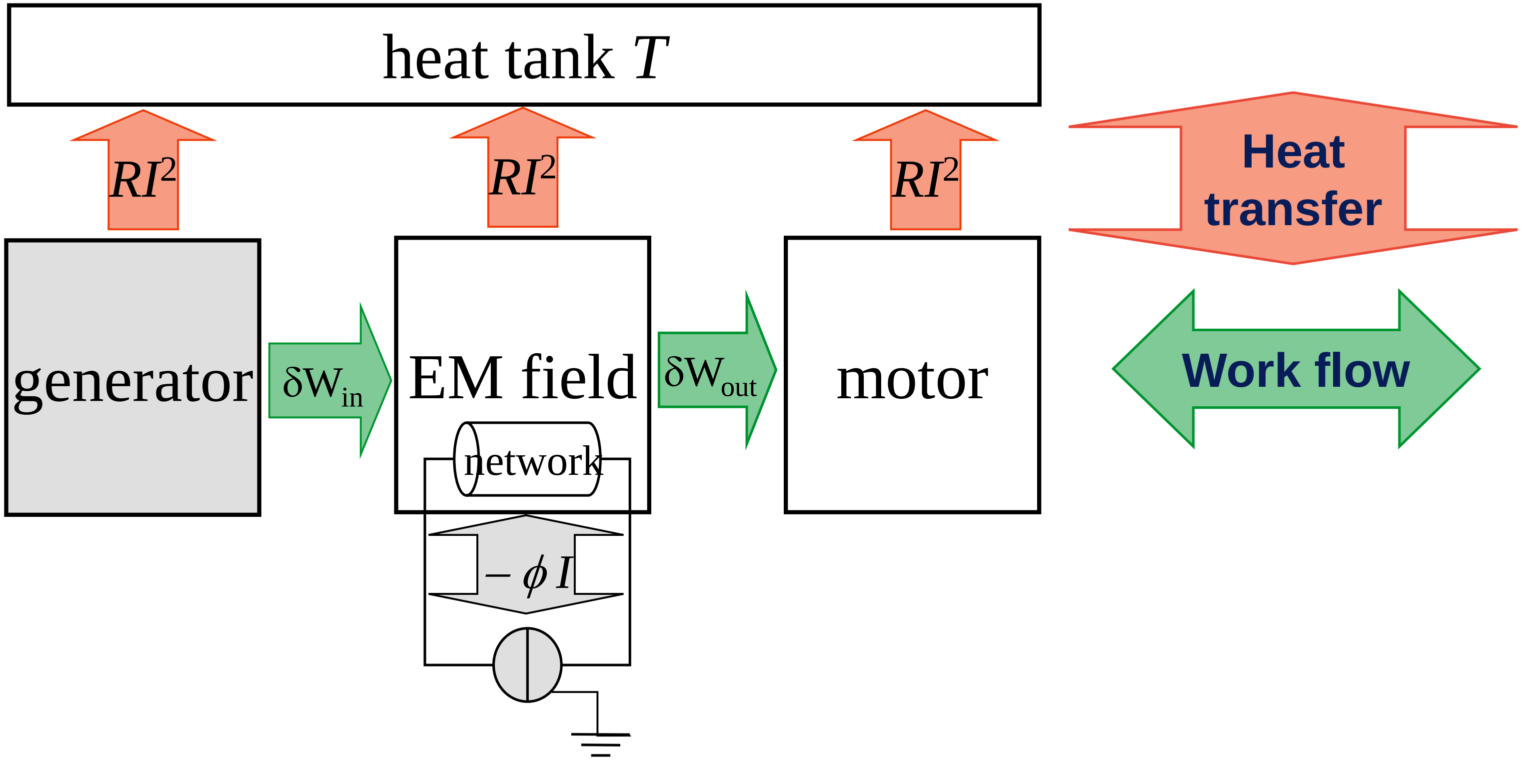
From Thermodynamics to Electromagnetism

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*.]

Electromagnetic field: Power management

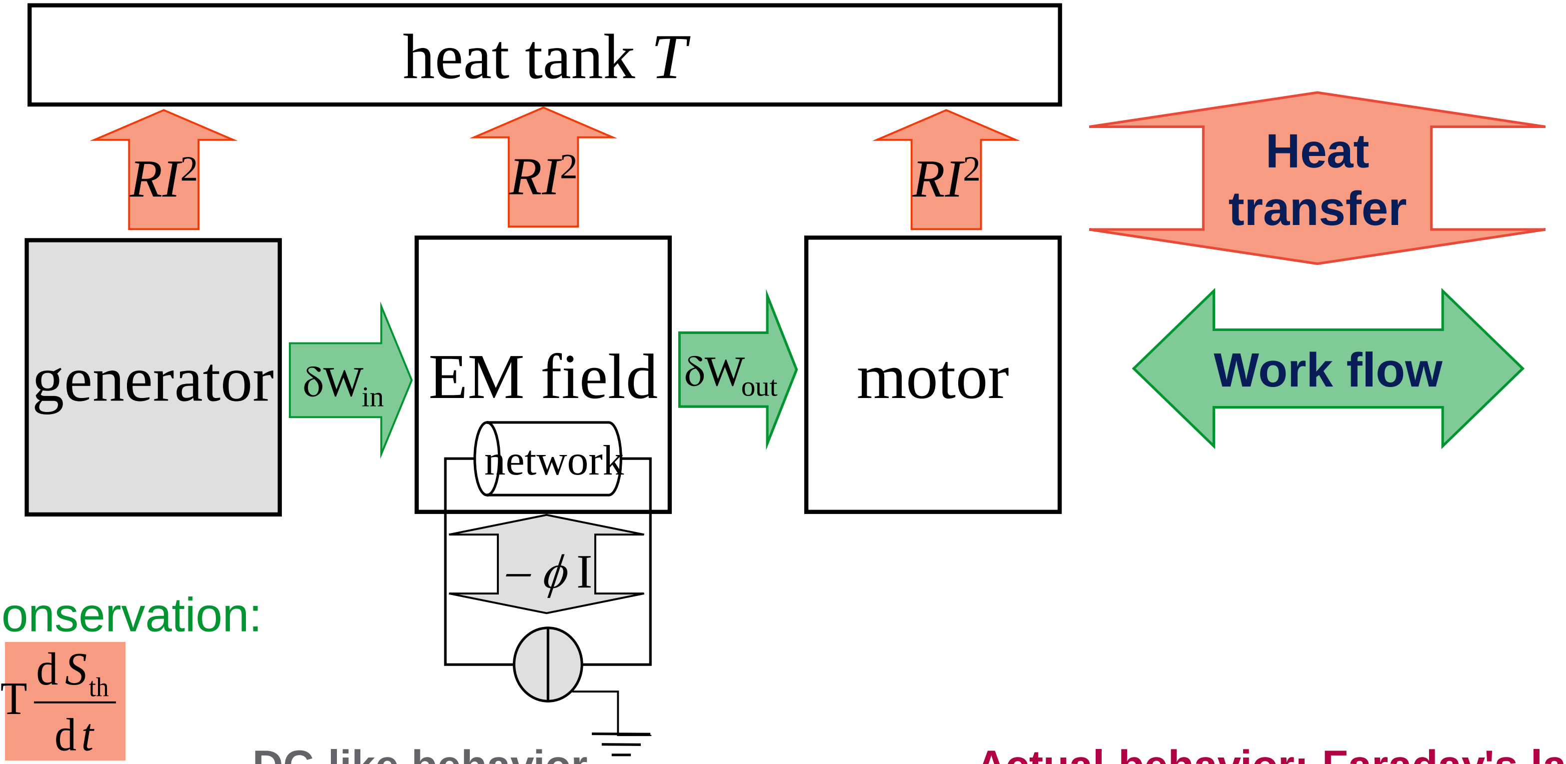


- Couplings:

magnetic	free currents I
Electric	earth potential V_0
heat tank	Joule losses "RI^2"

- The utility acts on:
  - the mechanical power P_m
  - the excitation of the rotor I

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:

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

$$G = U - TS - \phi I - QV_0 \quad \text{(Gibbs)}$$

➔2nd principle (Clausius):

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

$$P_m - \frac{dG}{dt} = T\underbrace{\left(\frac{dS}{dt} + \frac{dS_{th}}{dt}\right)}_{RI^2} + \frac{d(\phi I + QV_0)}{dt}$$

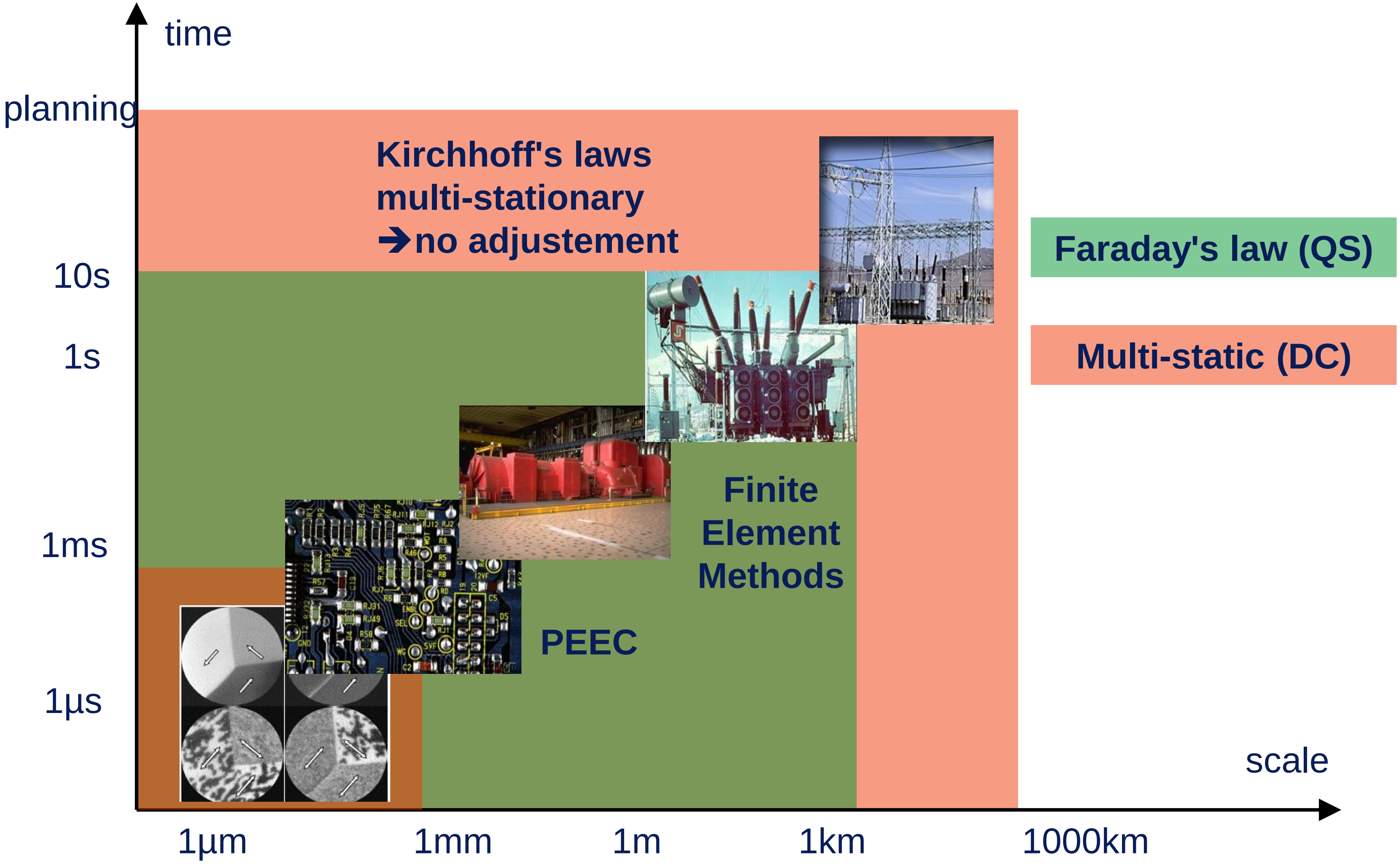
➔Weak reversibility:

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

<

$$\boxed{P_m - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d(\phi I + QV_0)}{dt}\right)}$$

Space- and time- multi-scale decomposition



time

planning

10s

1s

1ms

1µs

scale

1µm

1mm

1m

1km

1000km

Kirchhoff's laws
multi-stationary
➔no adjustement

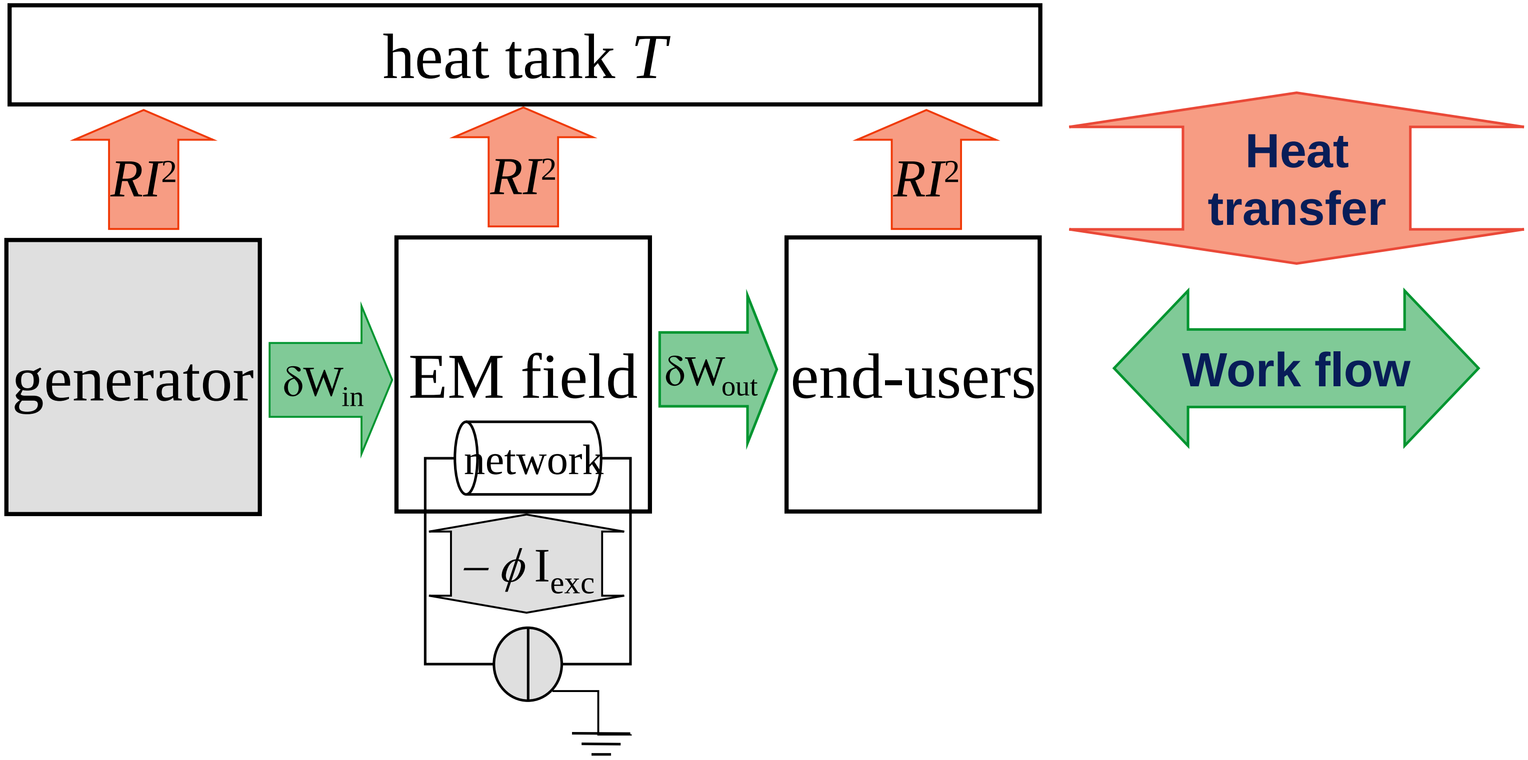
Finite Element Methods

PEEC

🟩 **Faraday's law (QS)**

🟥 **Multi-static (DC)**

An natural trend toward reversibility



- Faraday's law is restored by assuming a reversible evolution:
  - ➔All the energy losses (conversion, distribution, usage) are **attainable**
  - ➔**Multi-scale** framework with successful issues (material law,…, CAD tools,...)

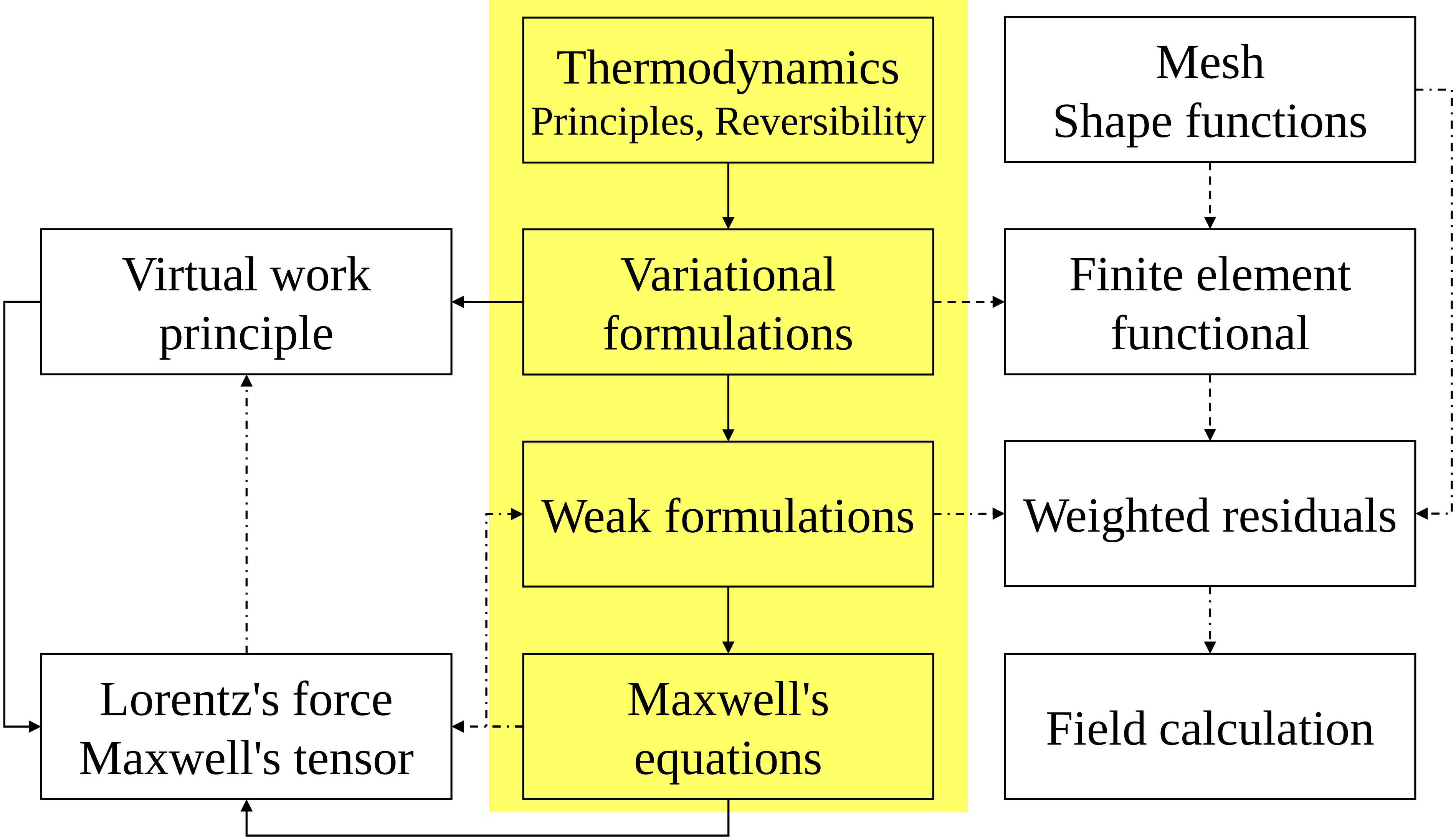
➔Focus until the higher aggregated scale:

- ➔to address long-term planning issue within a dynamic description
- ➔to inspect reliability conditions dedicated to power transmission

Validation at the design scale

[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



Thermodynamics
Principles, Reversibility

Variational formulations

Weak formulations

Maxwell's equations

Virtual work principle

Lorentz's force
Maxwell's tensor

Mesh
Shape functions

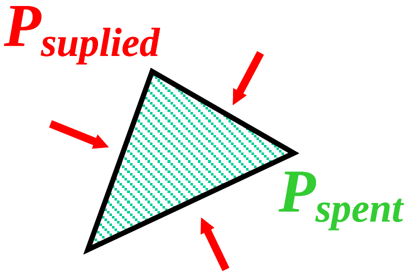
Finite element functional

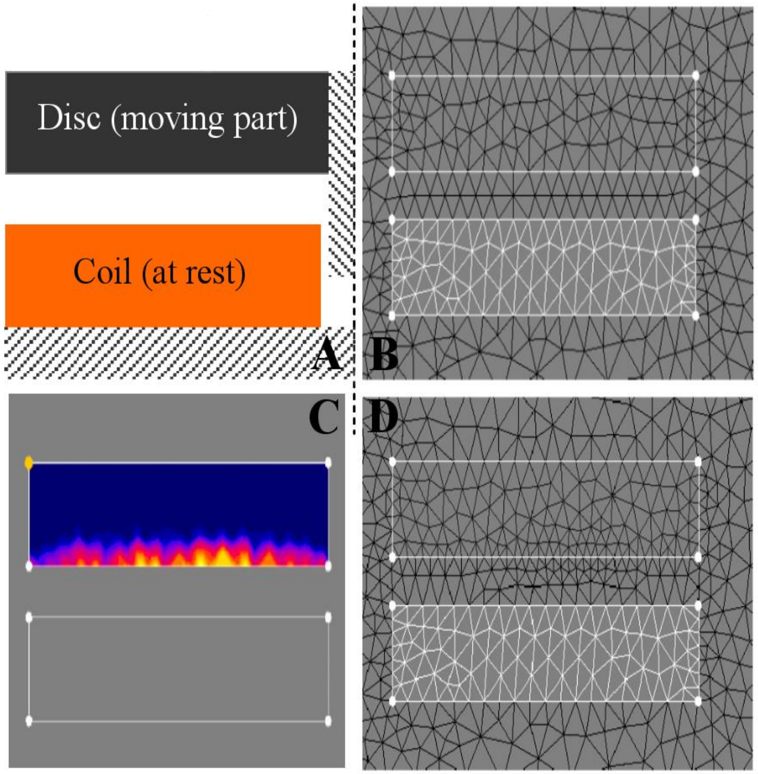
Weighted residuals

Field calculation

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

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





- Poynting identity check:

$$\varepsilon(\Omega)=P_{\mathrm{elec}}(\Omega)-P_{\mathrm{Joule}}(\Omega)-\frac{\mathrm{d}F}{\mathrm{d}t}(\Omega)+\mathrm{P}_{\mathrm{m}}(\Omega)$$

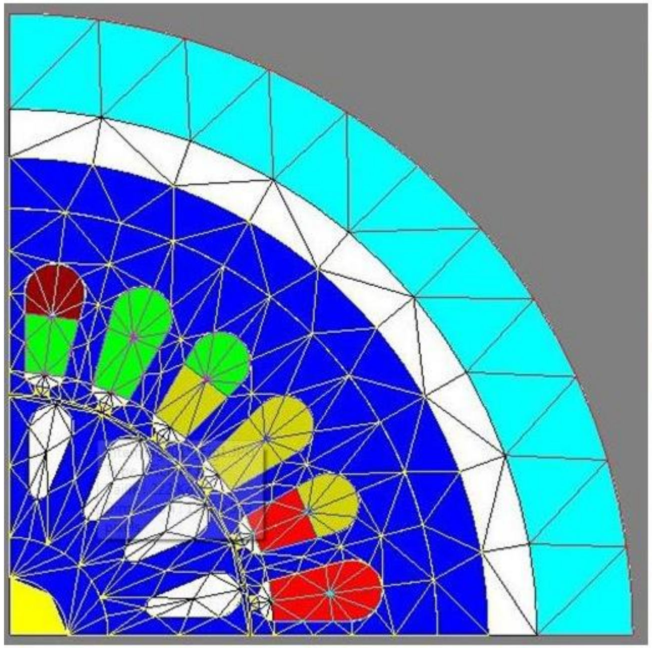
$\Delta t = 0.5\cdot10^{-6}$ s	**Number of Time Step : 2**	**Number of Time Step : 3 (before remeshing)**	**Number of Time Step : 3 (after remeshing)**
U *(V)*	$3.1\cdot10^{-1}$	$5.9\cdot10^{-1}$	$5.9\cdot10^{-1}$
I *(A)*	$7.3\cdot10^{-4}$	$2.1\cdot10^{-3}$	$1.4\cdot10^{-3}$
G(*J*)	$-1.61\cdot10^{-9}$	$-1.34\cdot10^{-8}$	$-5.89\cdot10^{-9}$
G/I^2 *(J.A^{-2})*	$-3.05\cdot10^{-3}$	$-3.06\cdot10^{-3}$	$-3.09\cdot10^{-3}$
P_m-dG/dt+P_{elec}		$2.5\cdot10^{-2}$	$9.4\cdot10^{-3}$

Global validation: Induction machine

2D, time-harmonic, magnetic material, motion

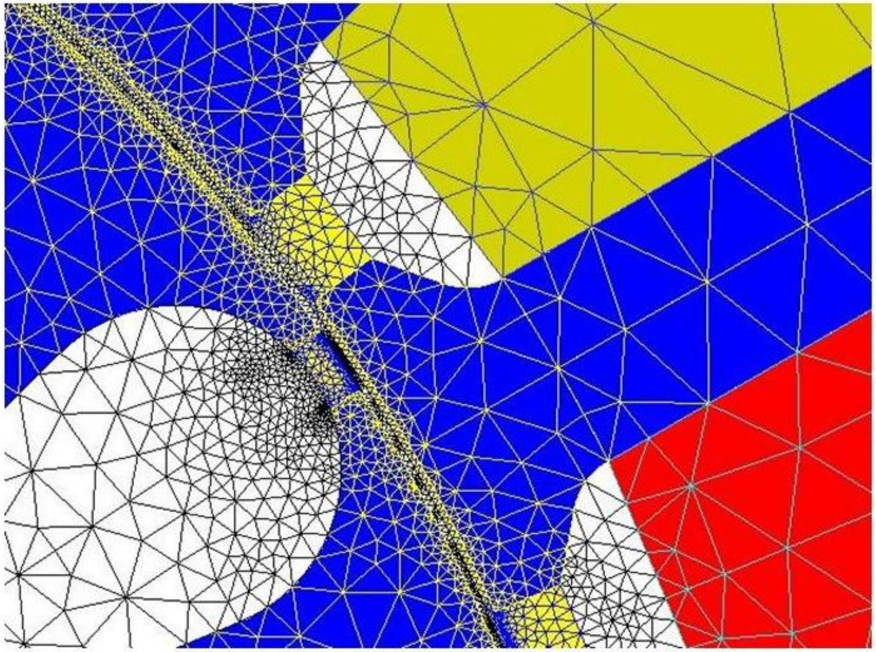
Initial mesh:

Geometric-based



Mesh after 4 iterations:

Refinement at ill-checked nodes



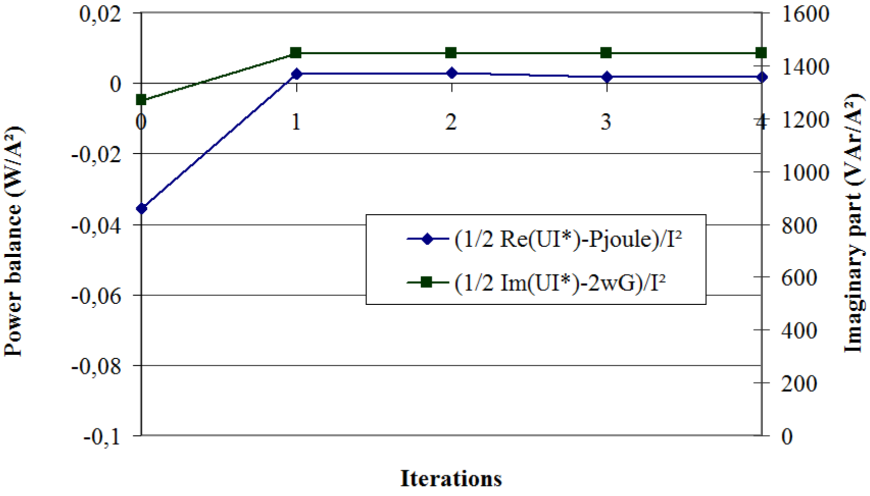
Global validation: Induction machine

2D, time-harmonic, magnetic material, motion

Convergence of the:

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

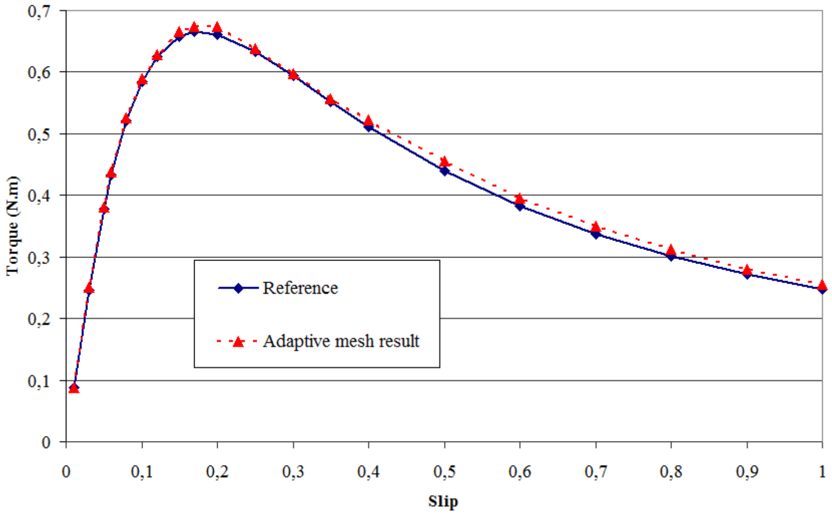
after 2 iterations



Convergence of the

- Torque vs. Slip curve

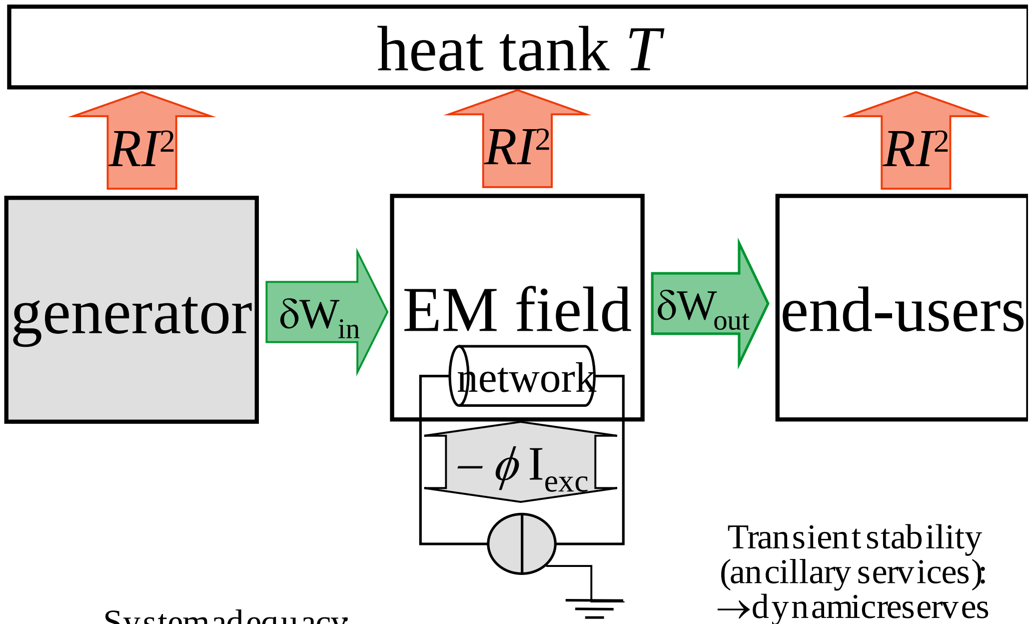
after 2 iterations



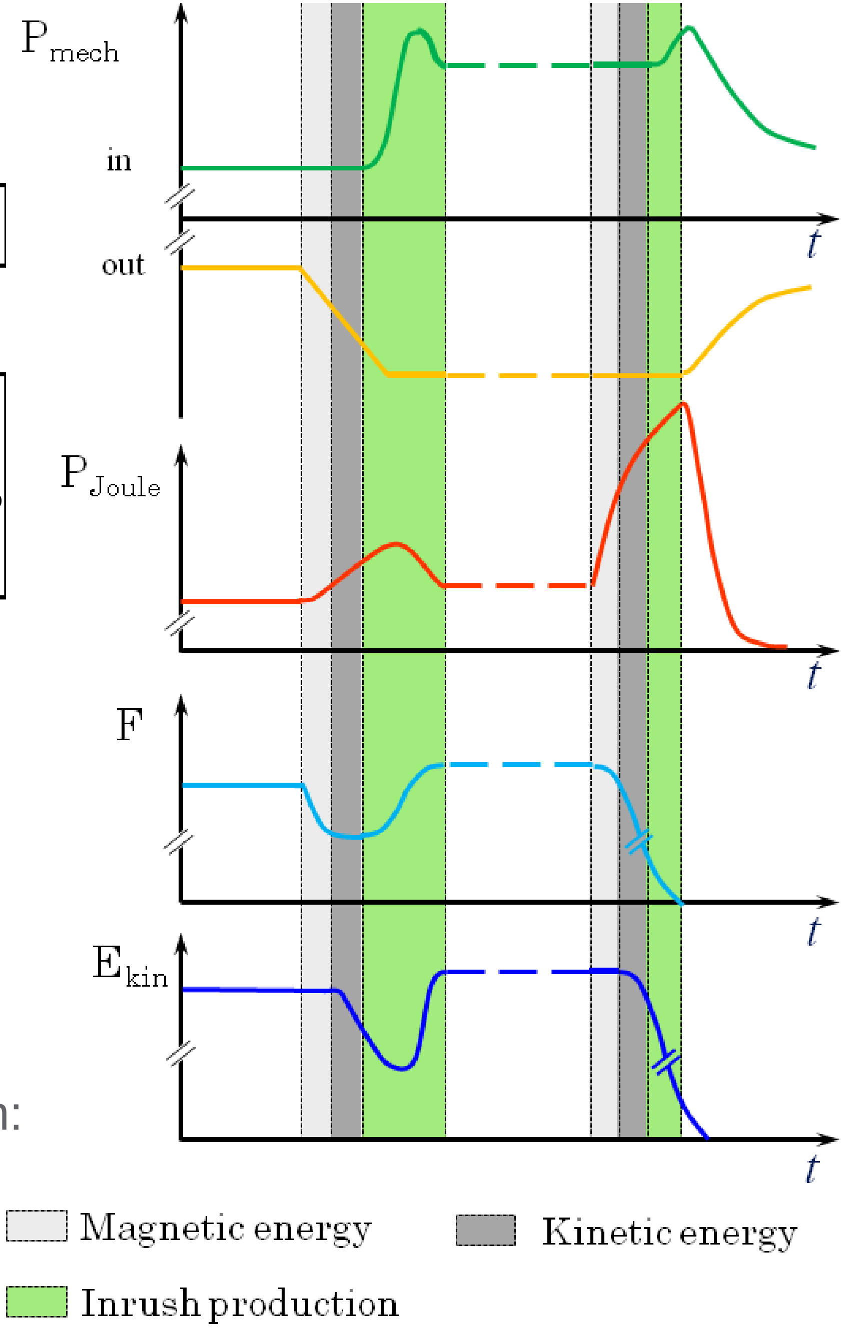
Upper scale

[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



$$\underbrace{\overbrace{P_{mech}}^{\substack{\text{System adequacy:} \\ \rightarrow\text{primary/secondary/tertiary control}}}}_{\text{mn}\rightarrow\text{hour}} = P_{Joule} + \overbrace{\underbrace{\frac{dE_{kin}}{dt}}_{\text{s}} + \underbrace{\frac{dF_{mag}}{dt}}_{\text{ms}}}^{\substack{\text{Transient stability} \\ \text{(ancillary services):} \\ \rightarrow\text{dynamic reserves}}}$$

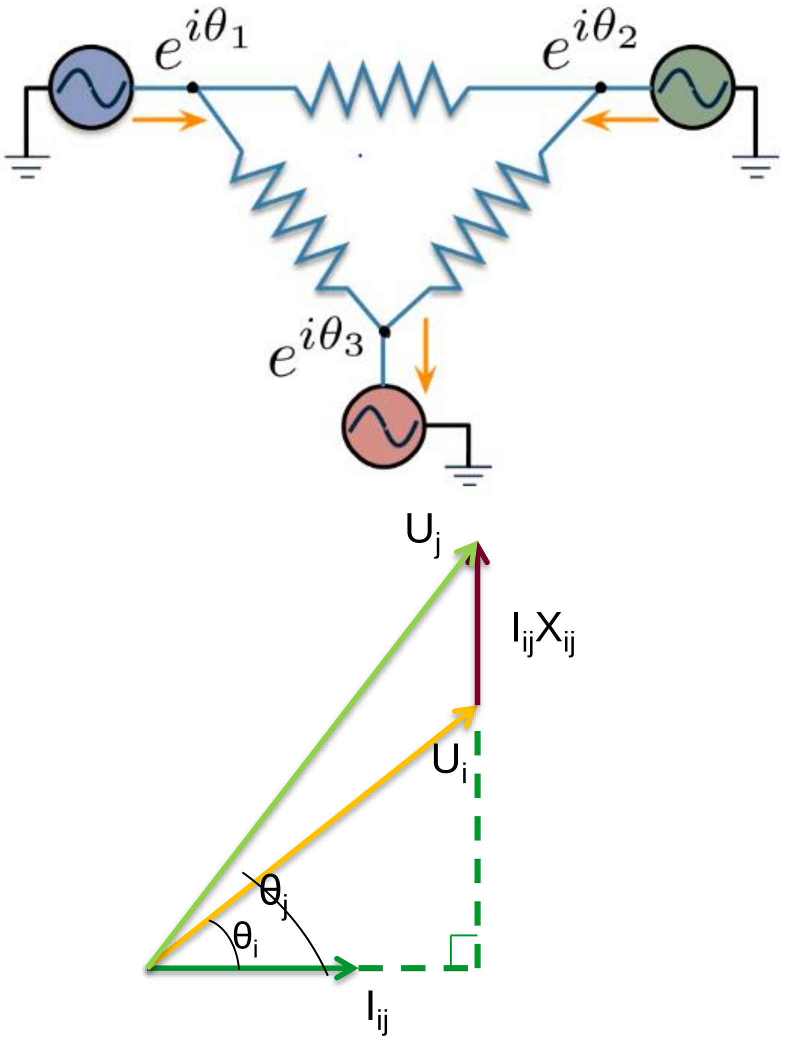


Upper bound equality is enforced by synchronism:

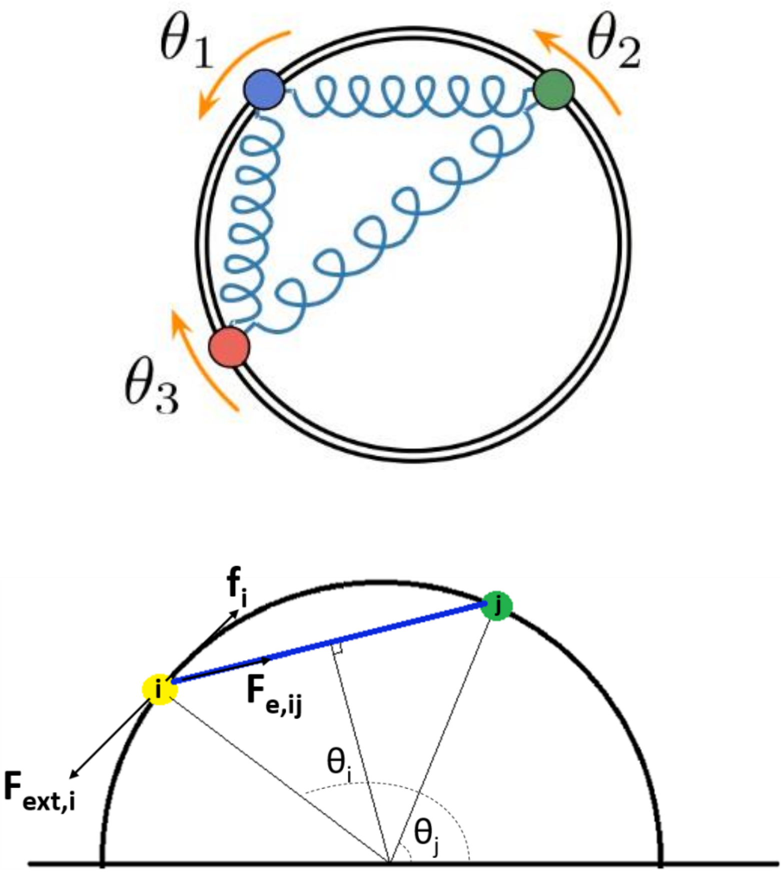
$$E_{kin}(\Omega) \leq E_{kin} \leq \sum_{\Omega} E_{kin}(\Omega)$$

Why and How to keep synchronism?

A mechanical analogy… for 3 linked bodies



Electrical system



Mechanical system

N-bodies synchronization dedicated models

- Equipartition of the fluctuation on the iso-energy states [Kosterlitz-Thouless, 1973]
  - dimension of the lattice *vs.* dimension of the spin
  - ➔X-Y model in 2D is the marginal dimension with a weak order-disorder transition
  - ➔Soft modes (long-range) induce disordering (desynchronization)

➔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):

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

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

➔Synchronization is not inconditionnally stable!

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

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

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

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:

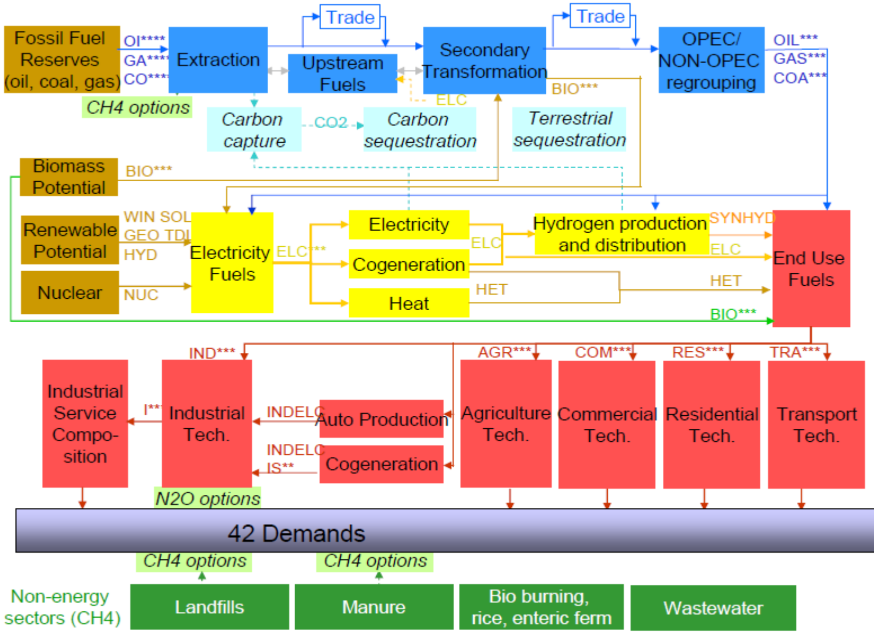
Some long-term planning exercises

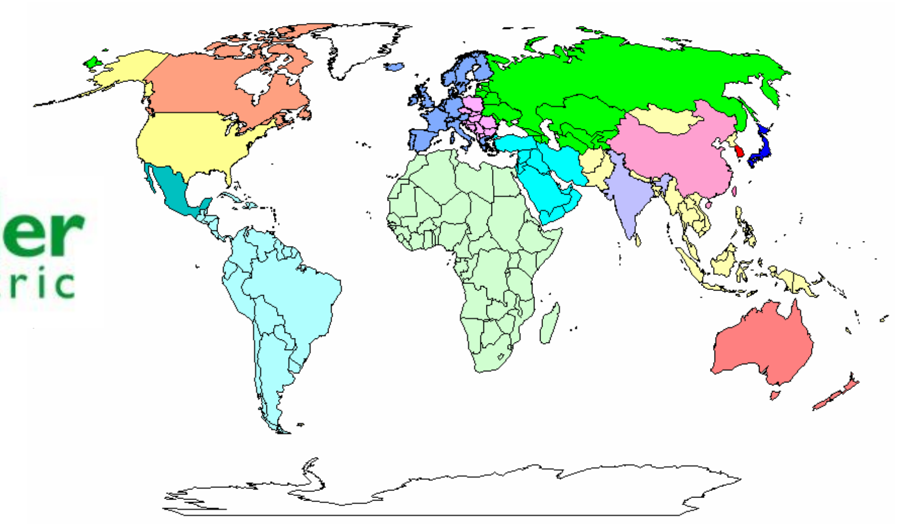
- Cimate-dedicated policies
  - Energy Efficiency vs. Clean generation
  - Carbon Pricing
  - Pledges and INDCs assessment
- Technical issues
  - Intermittency and non-dispatchable sources: time reconciliation
  - Synchronism issue: space aggregation
  - Reuniese and French cases

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





ADEME
Agence de l'Environnement et de la Maîtrise de l'Energie

EDF

GRTgaz

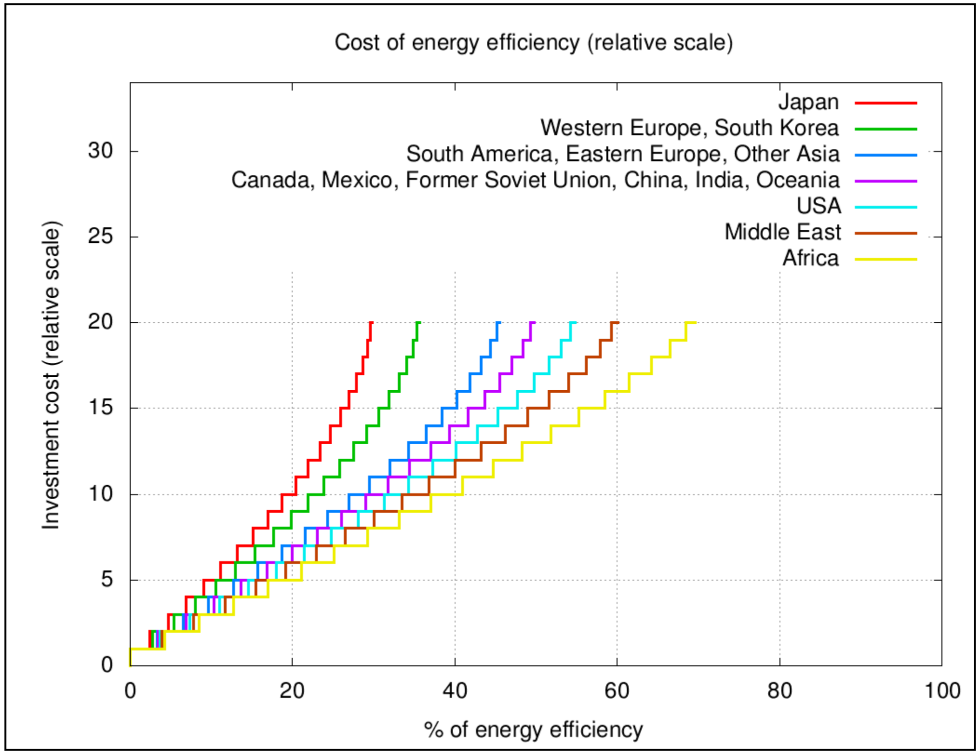
Schneider Electric

ParisTech
INSTITUT DES SCIENCES ET TECHNOLOGIES
PARIS INSTITUTE OF TECHNOLOGY

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*.]

Energy efficiency implementation costs



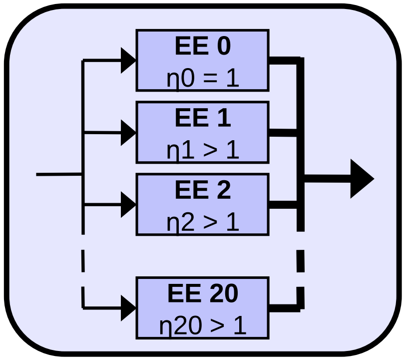
- Model refinement:
  - Provide the cost of the next EE step for an already achieved level (demand side)
- The model selects the rate of EE to implement at the demand side:
  - for each sector and
  - each region

  according to the competition with other abatement technologies (CCS…)

For each region
and each sector

$\eta 1, \eta 2, \ldots, \eta 20$
cost1, cost2,…, cost3

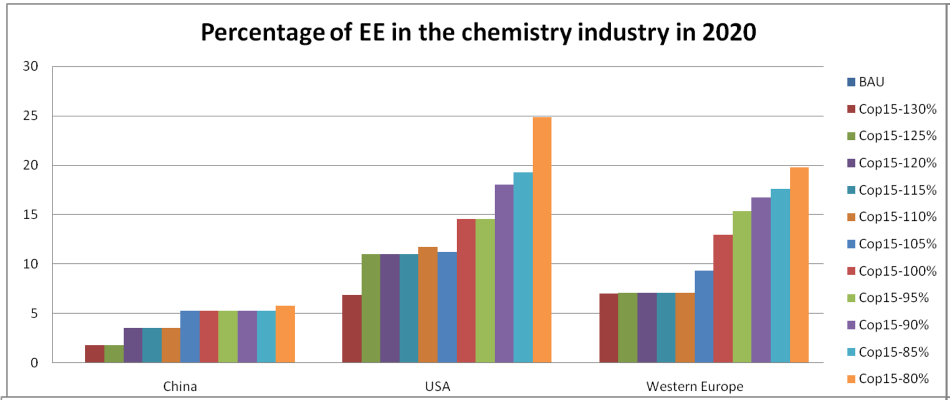
DS-EE technologies

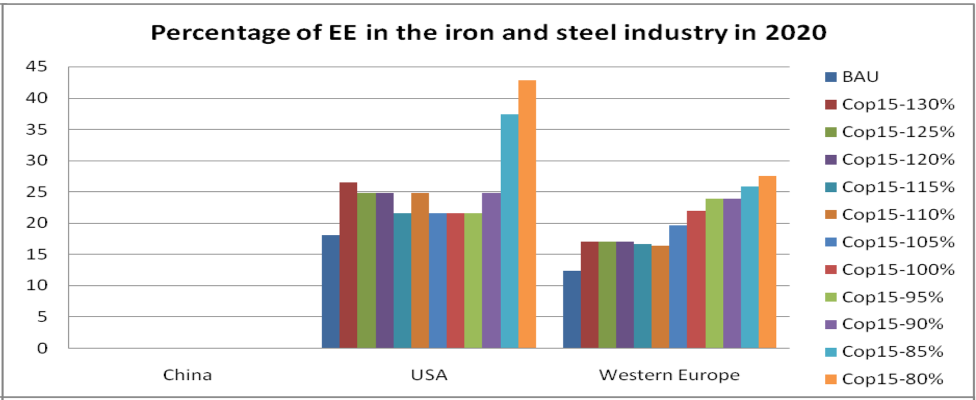


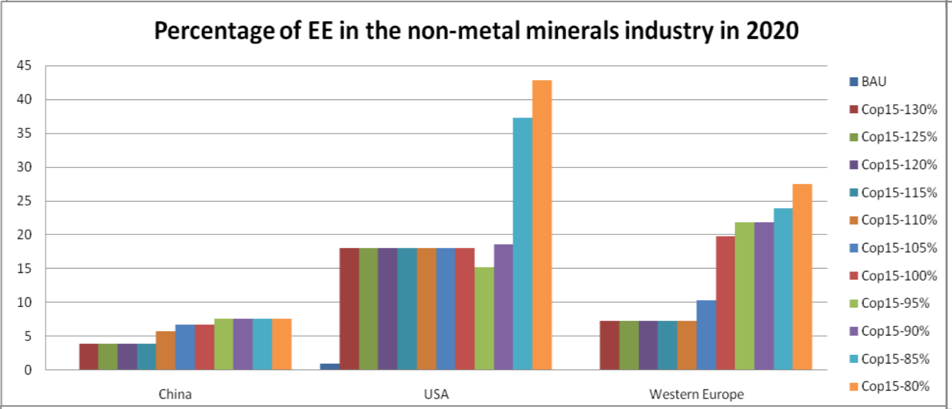
Climate scenarios for 2020

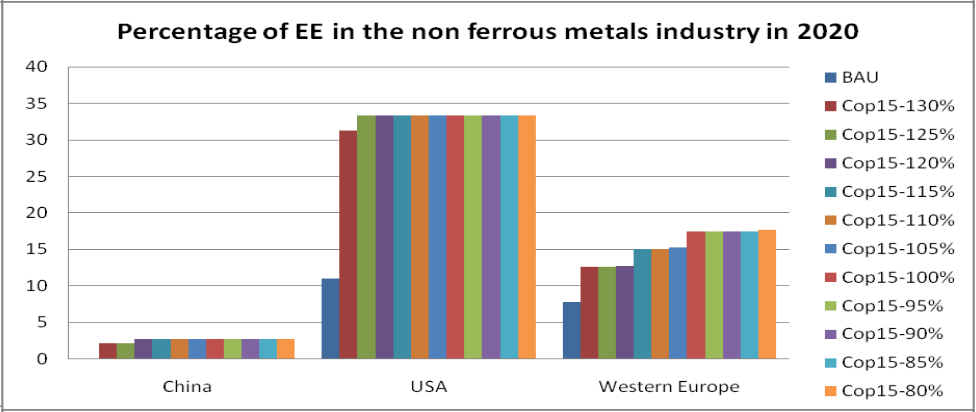
	Europe	USA	China
Business As Usual	No constraint		
COP15 – 80%	20% more constrained than COP15		
COP15 – 85%	15% more constrained than COP15		
COP15 – 90%	10% more constrained than COP15		
COP15 – 95%	5% more constrained than COP15		
COP15	20% on emissions (1990)	17% on emissions (2005)	40% on Carbon intensity (2005)
COP15 – 105%	5% less constrained than COP15		
COP15 – 110%	10% less constrained than COP15		
COP15 – 115%	15% less constrained than COP15		
COP15 – 120%	20% less constrained than COP15		
COP15 – 125%	25% less constrained than COP15		
COP15 – 130%	30% less constrained than COP15		

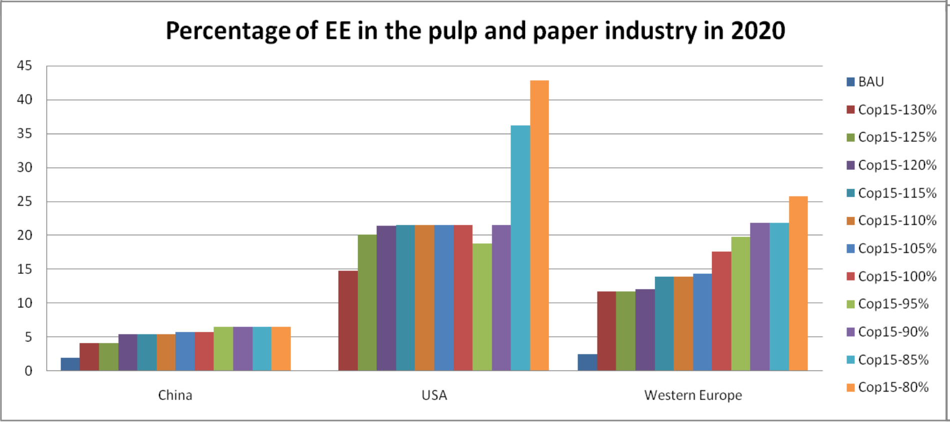
Energy Efficiency implementation in industry

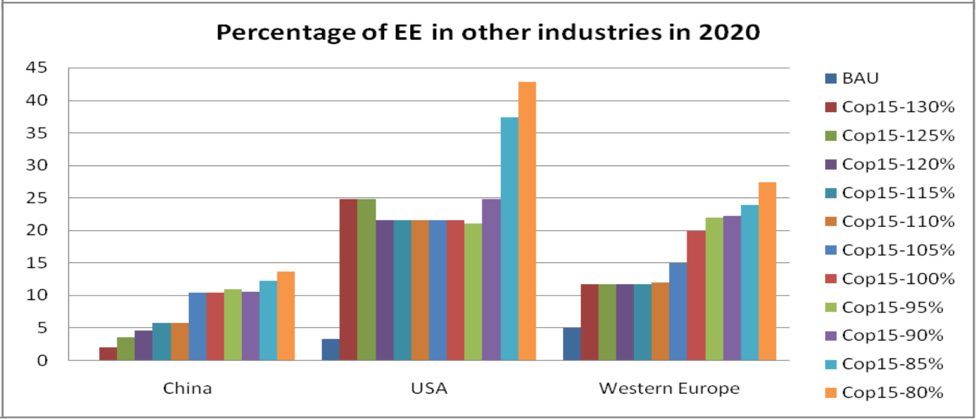

Percentage of EE in the chemistry industry in 2020


Percentage of EE in the iron and steel industry in 2020


Percentage of EE in the non-metal minerals industry in 2020

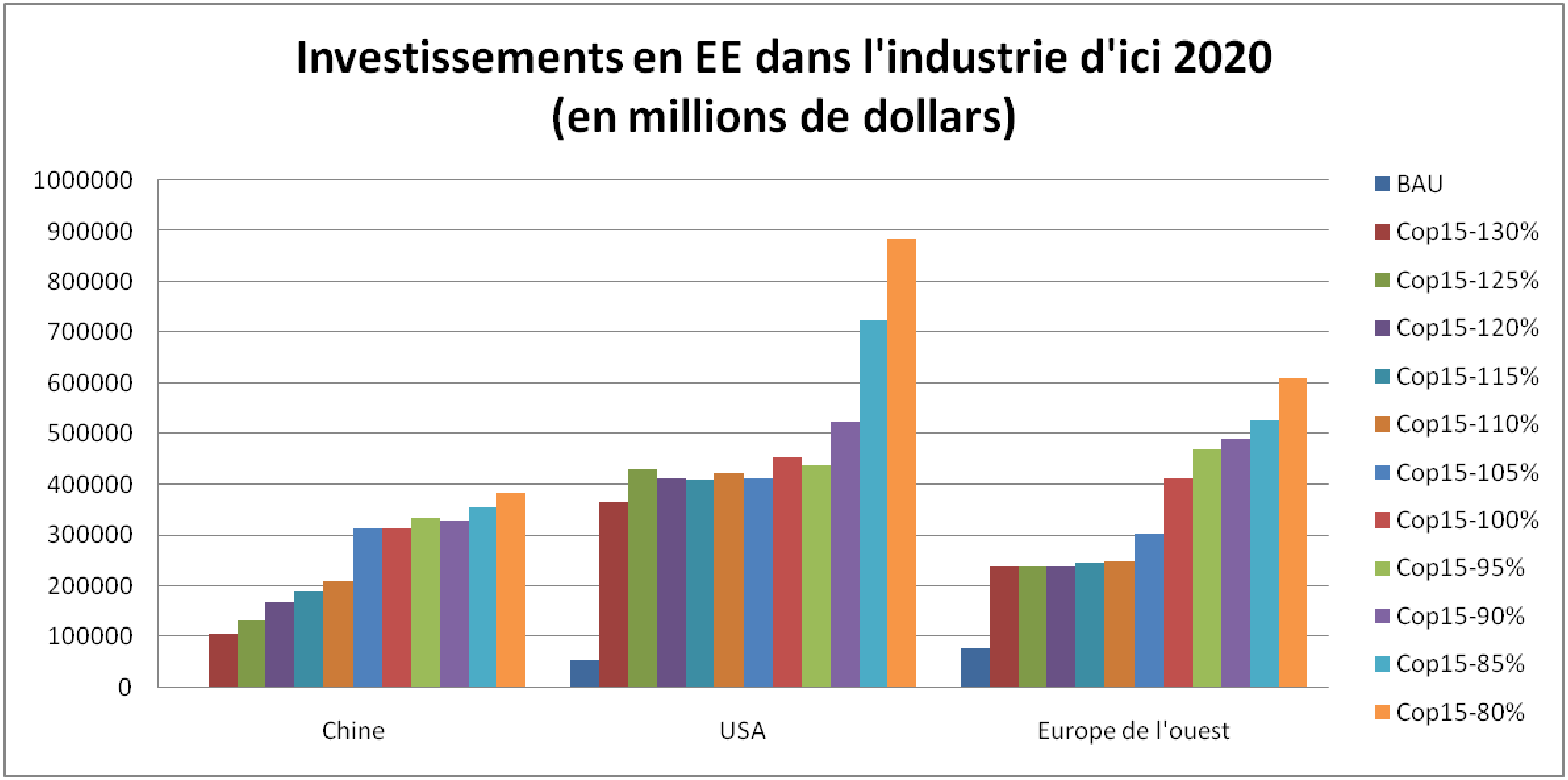

Percentage of EE in the non ferrous metals industry in 2020


Percentage of EE in the pulp and paper industry in 2020


Percentage of EE in other industries in 2020

Energy Efficiency market in industry

- No saturation for USA and Europe

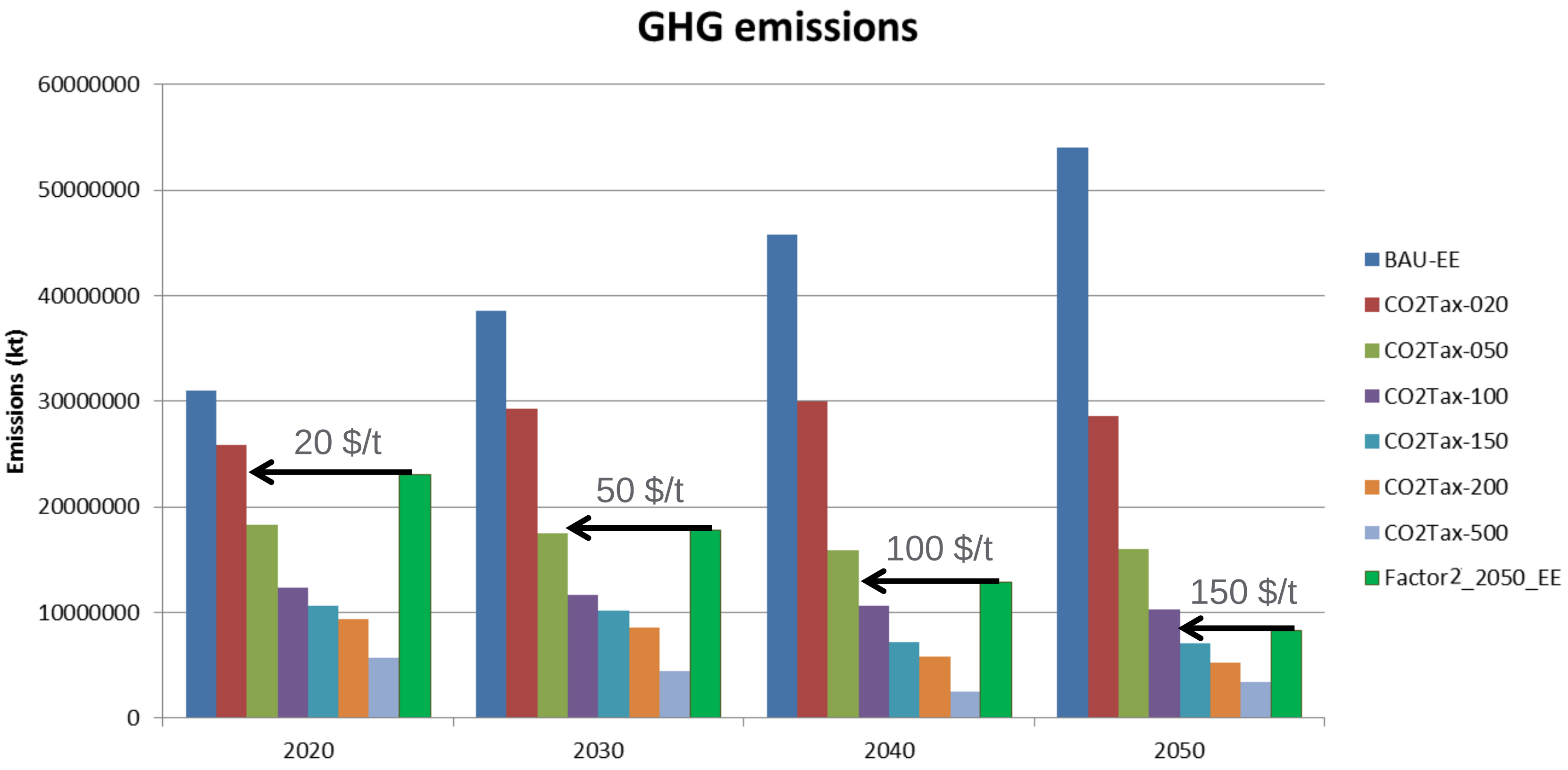


Carbon pricing...?

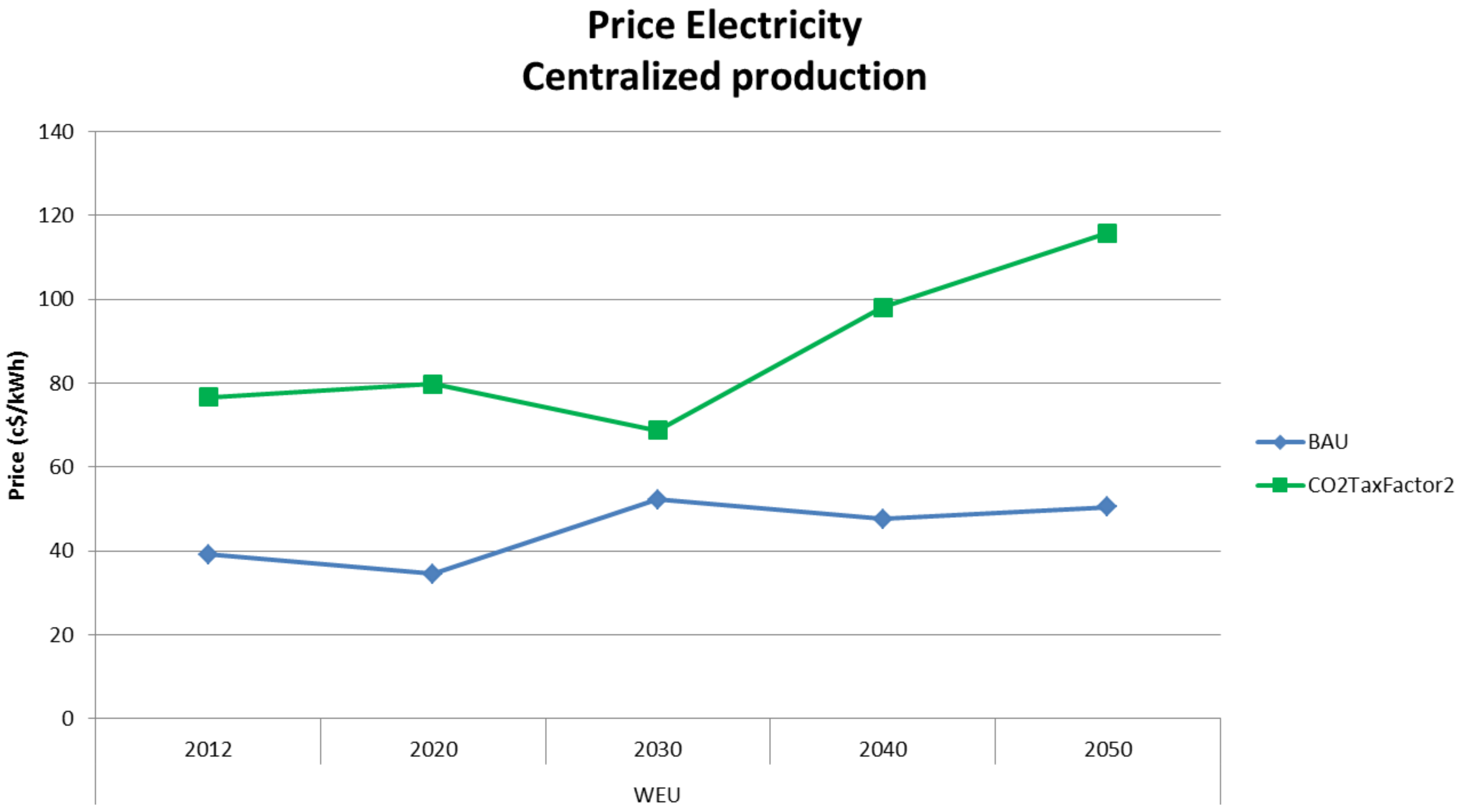
[N. Maïzi, A. Didelot, V. Mazauric, E. Assoumou, and S. Selosse, "Impacts of Fossil Fuels Extraction Costs and Carbon Pricing on Energy Efficiency Policies," in *International Energy Workshop (IEW 2016), Cork, Eire, 2016.*]

[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.*]

Which tax in order to reach ‘factor 2’?



Electricity prices



How much intermittency in the power mix

[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.*]

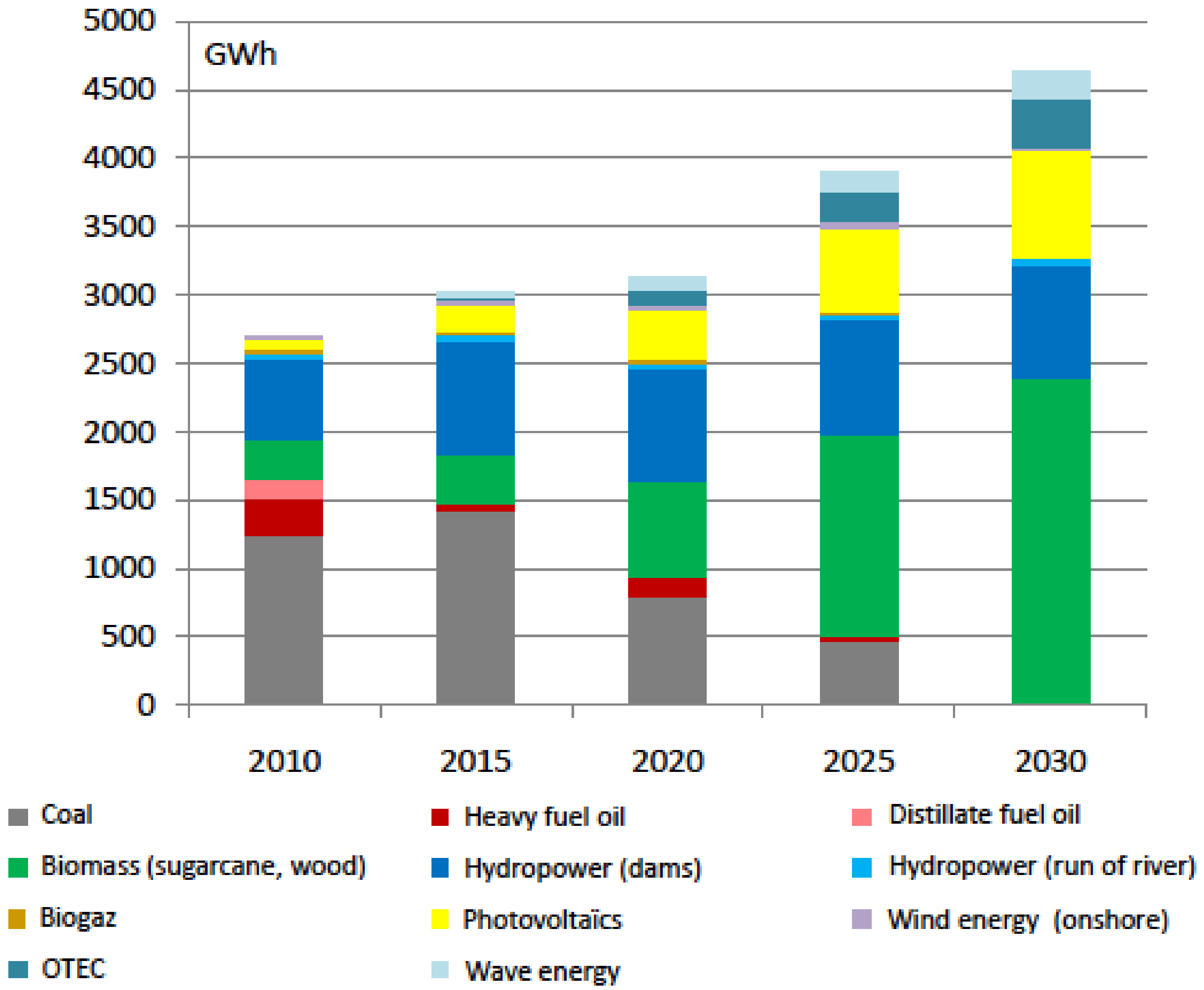
[S. Bouckaert, P. Wang, V. Mazauric, and N. Maïzi, "Expanding renewable energy by implementing Dynamic support through storage technologies," *Energy Procedia, vol. 61, pp. 2000-2003, 2014.*]

[N. Maïzi, V. Mazauric, E. Assoumou, S. Bouckaert, V. Krakpowski, X. Li, and P. Wang, "Maximaizing intermittency in 100% renewable and reliable power systems: A holistic approach applied to Reunion Island in 2030," *Applied Energy, 2017.*]

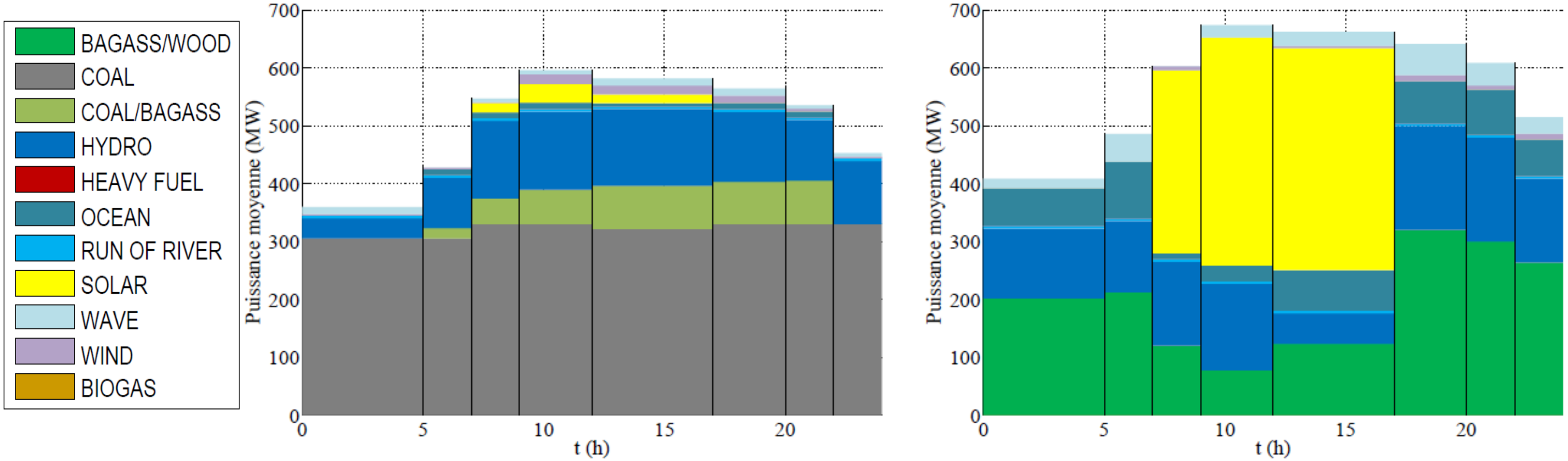
Interest of Reunion Island

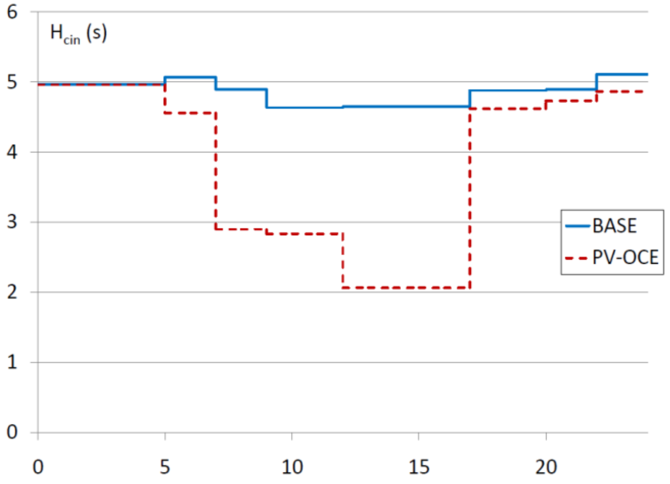
- Electricity generation:
  100% from renewables for 2030
- Available solutions:
  - Thermal power plants using bagass or wood
  - Intermittent renewable energy
  - Flexibility:
    - Demand Response
    - Storage

TIMES - Reunion 100% REN scenario



Electricity generation mix for a typical day during summer 2030



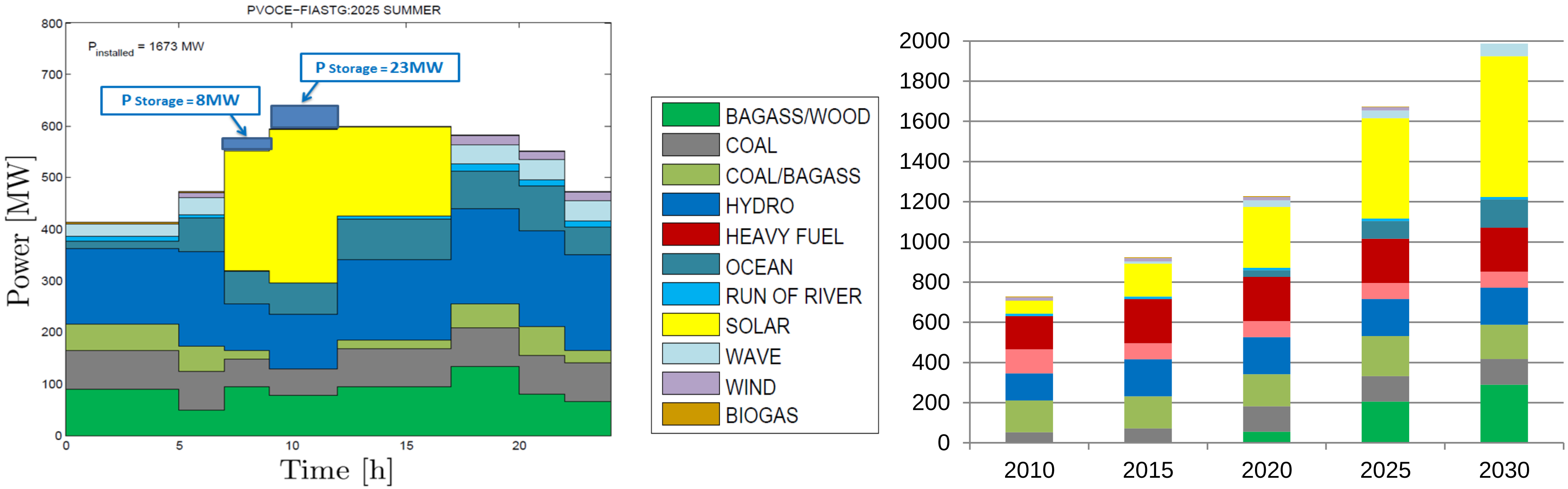


➔Ensure only system adequacy

➔How to derive reliable power systems within prospective studies?

[From :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.]

Dynamic storage technologies implementation



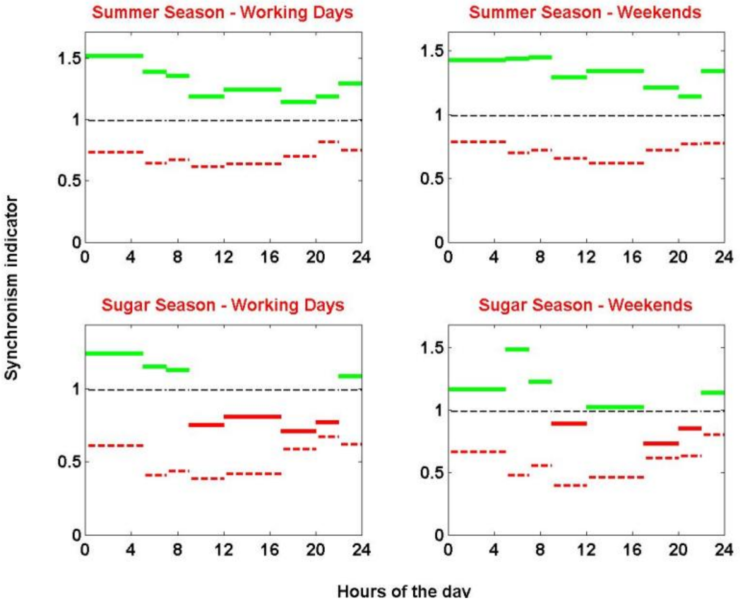
	PVOCE30	PVOCE-FIASTG
Installed Power (MW)	1576	1673
Storage Power (MW)	123	23 (=0.4 in 2020+22.6 in 2025)
Objective function (M euro)	1982 + Storage	2016

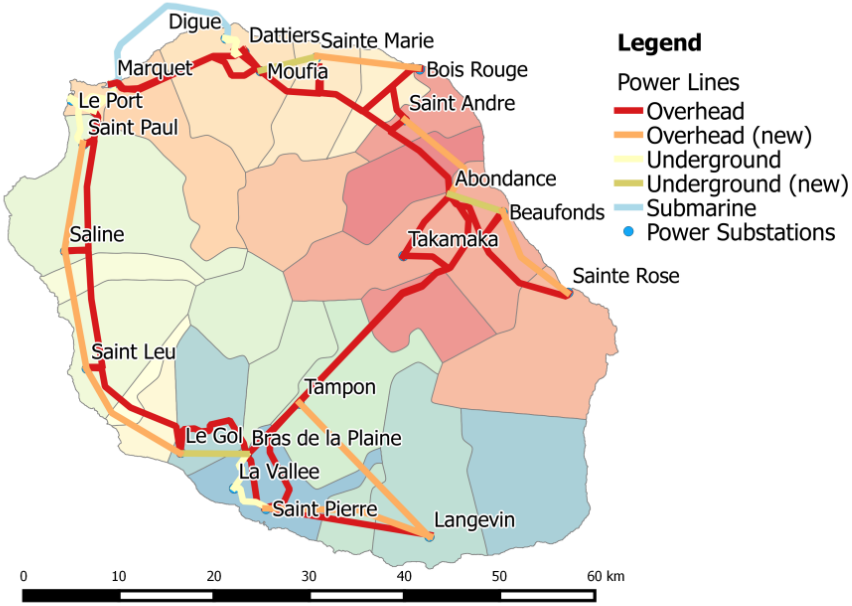
100% renewable energy scenario in 2030

Synchronism indicator:

- strengthened grid (solid lines)
- current grid (dashed lines)

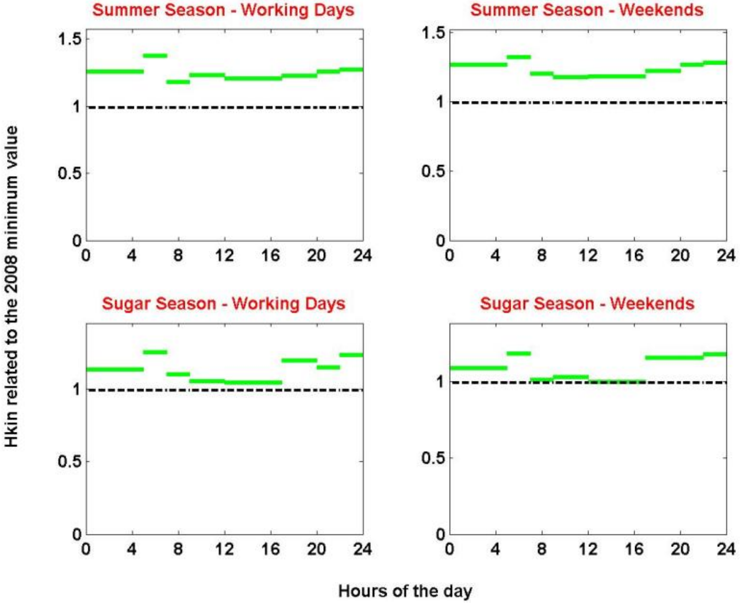
➔dispersed energy (summer) provides a more resilient grid





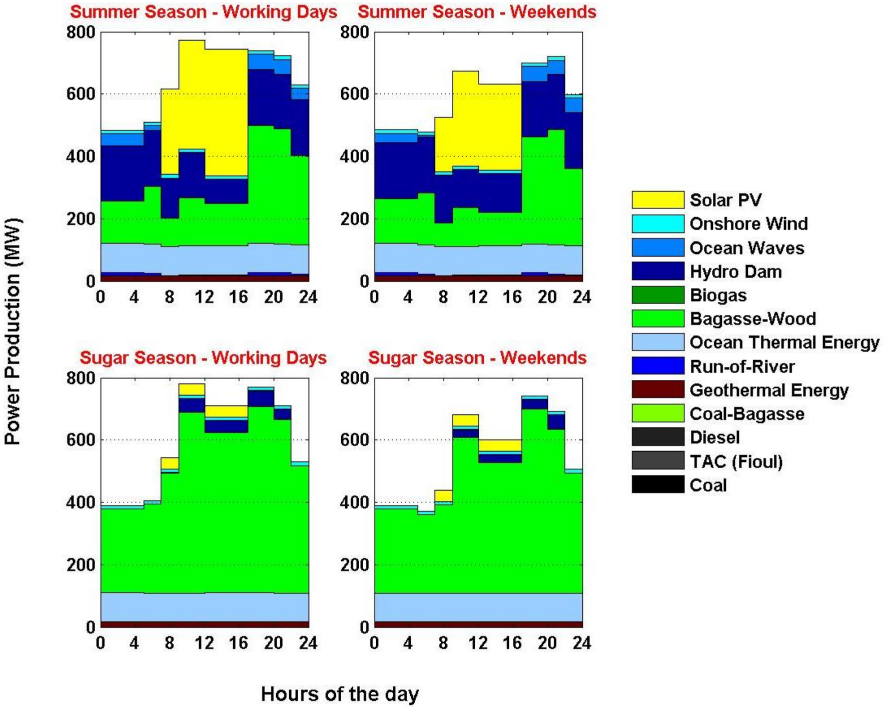
Kinetic indicator:

- 2030 *vs.* 2008 level

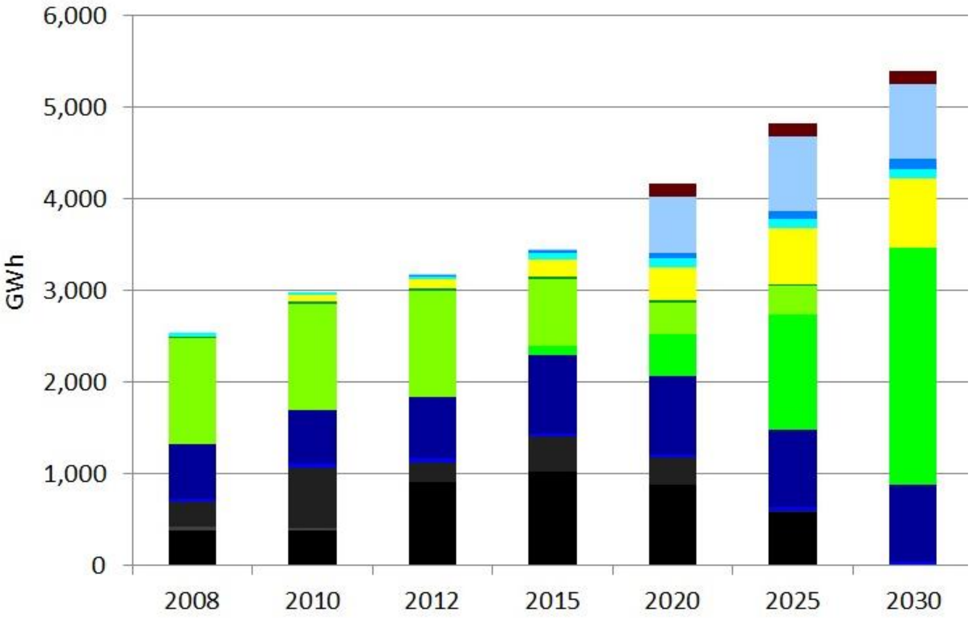


Power generation mix in 2030

Typical Day (2030)



Yearly generation transition



French case issues

Source : RTE

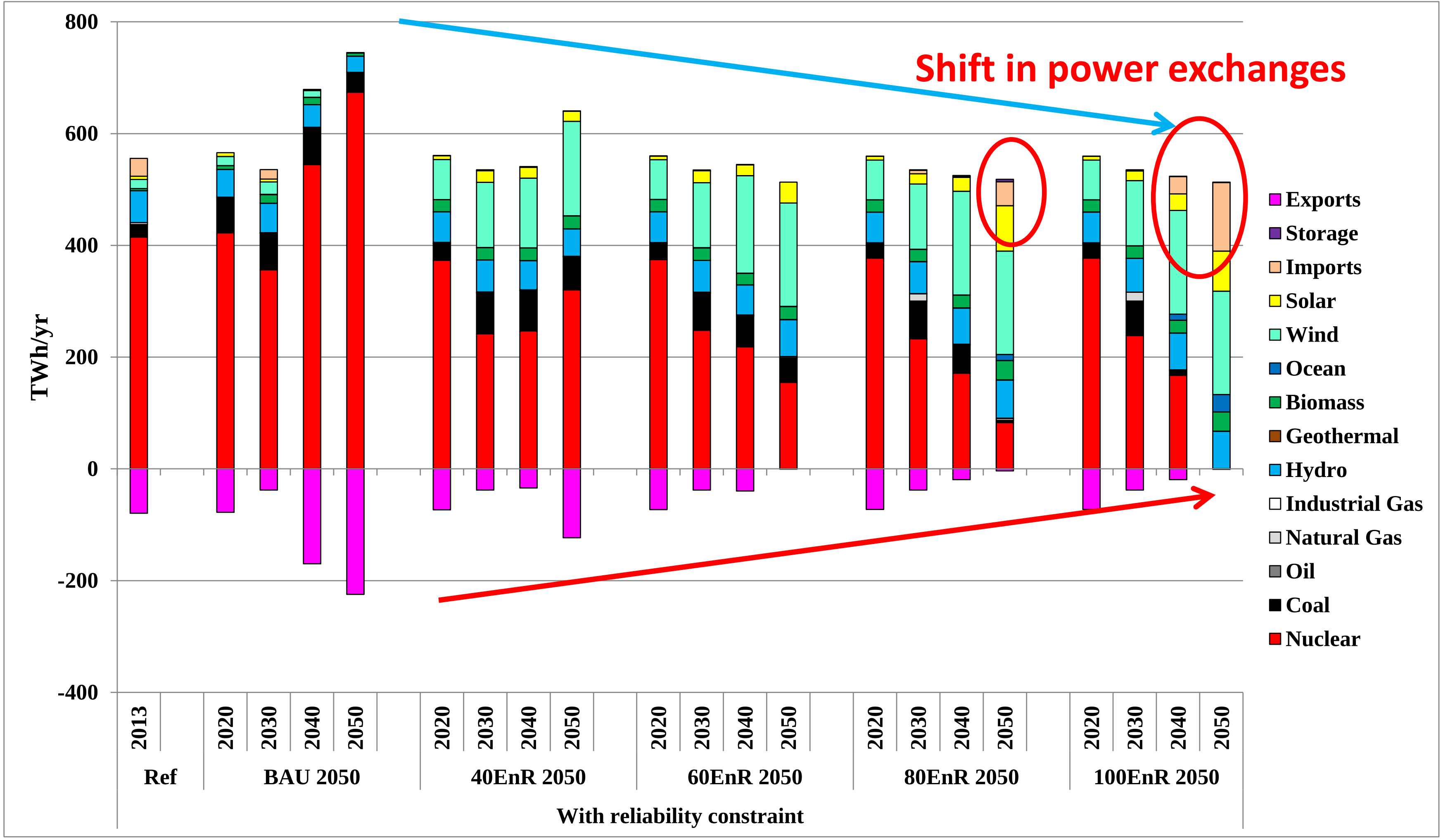
- *Nuclear phase out*
- Decarbonation of the power system with REN

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

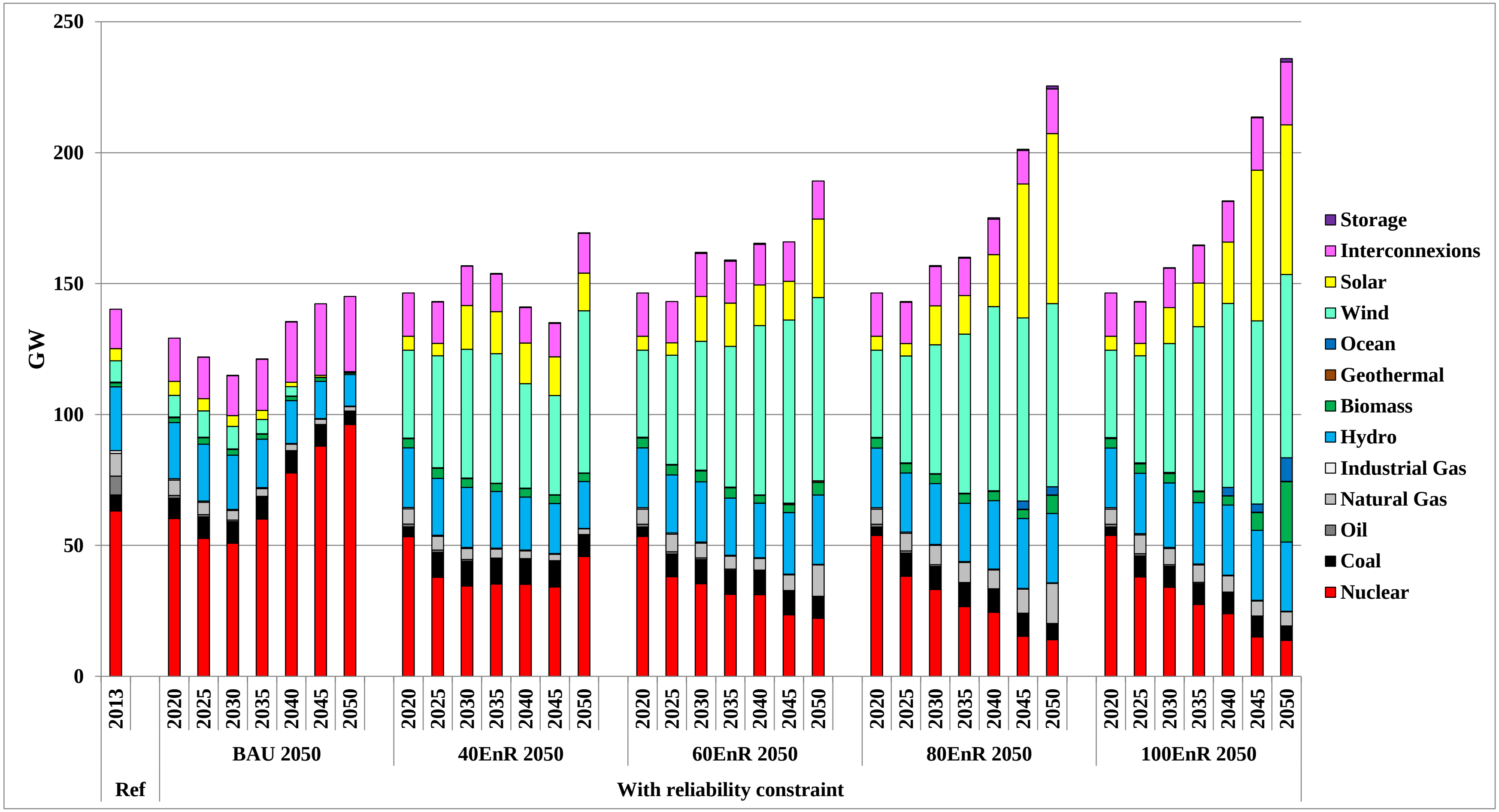
[V. Krakowski, E. Assoumou, V. Mazauric, N. Maïzi, “Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis”, *Applied Energy*, 2016, 171, pp. 501-522.]

[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.]

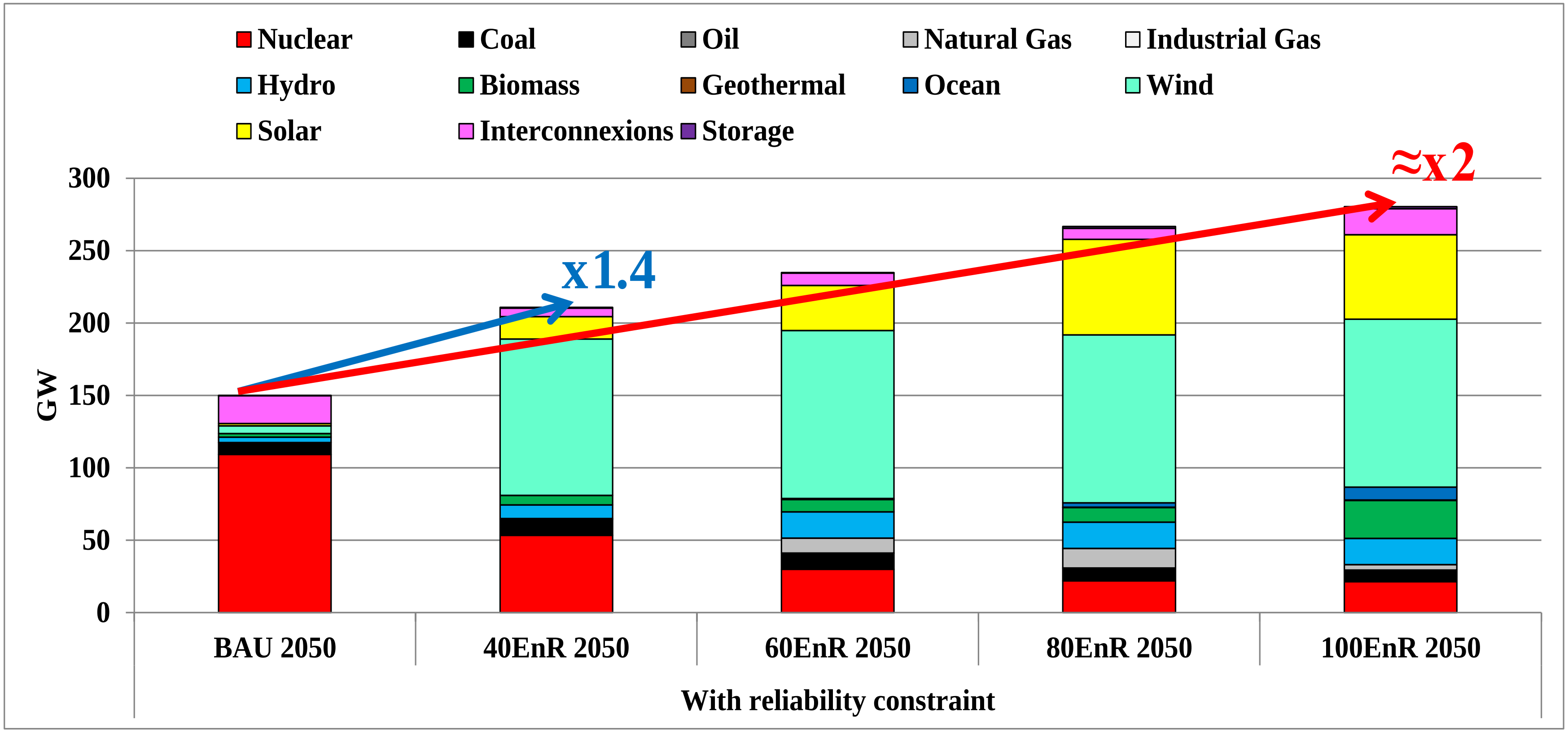
Yearly generation



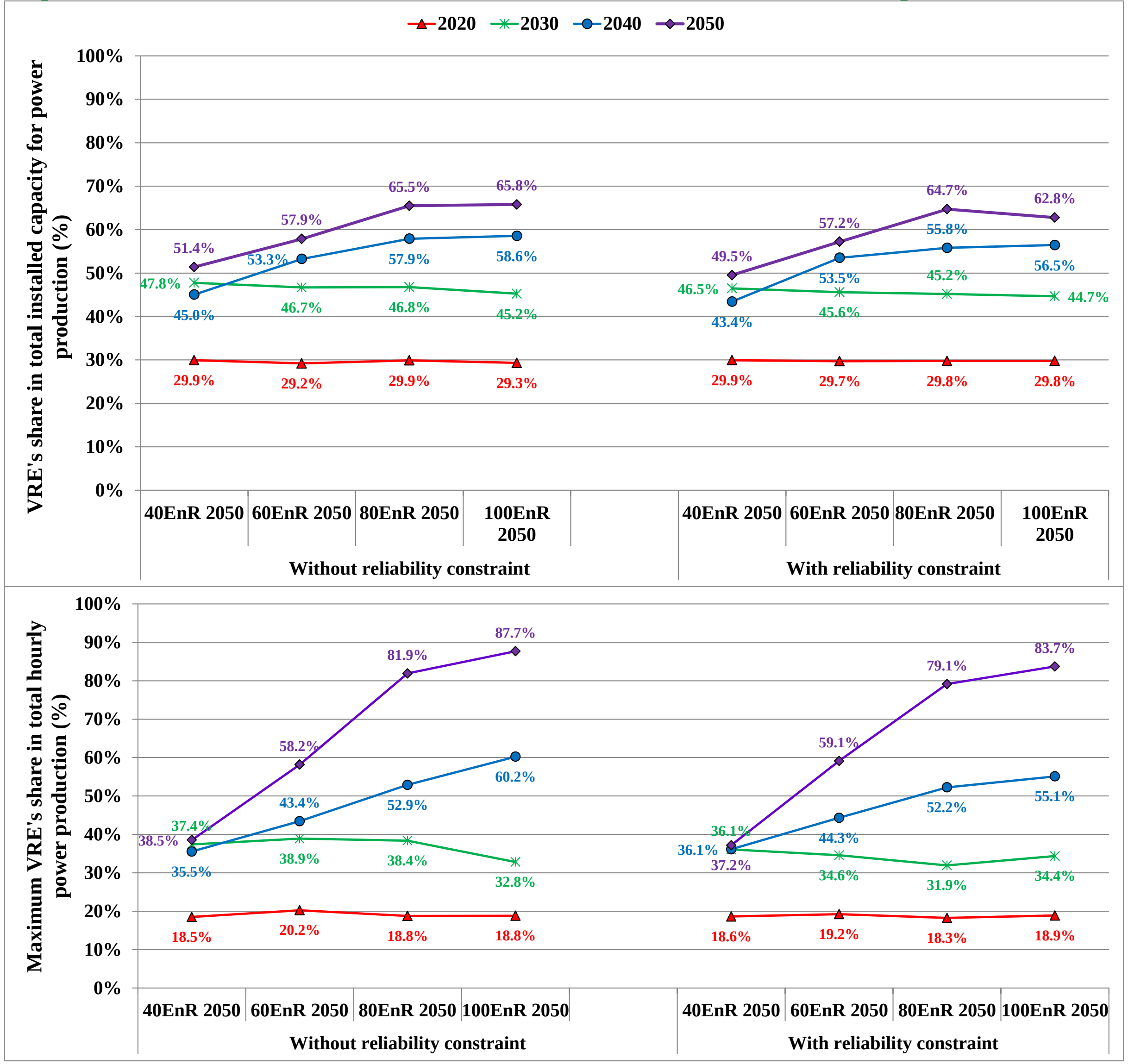
Installed capacity



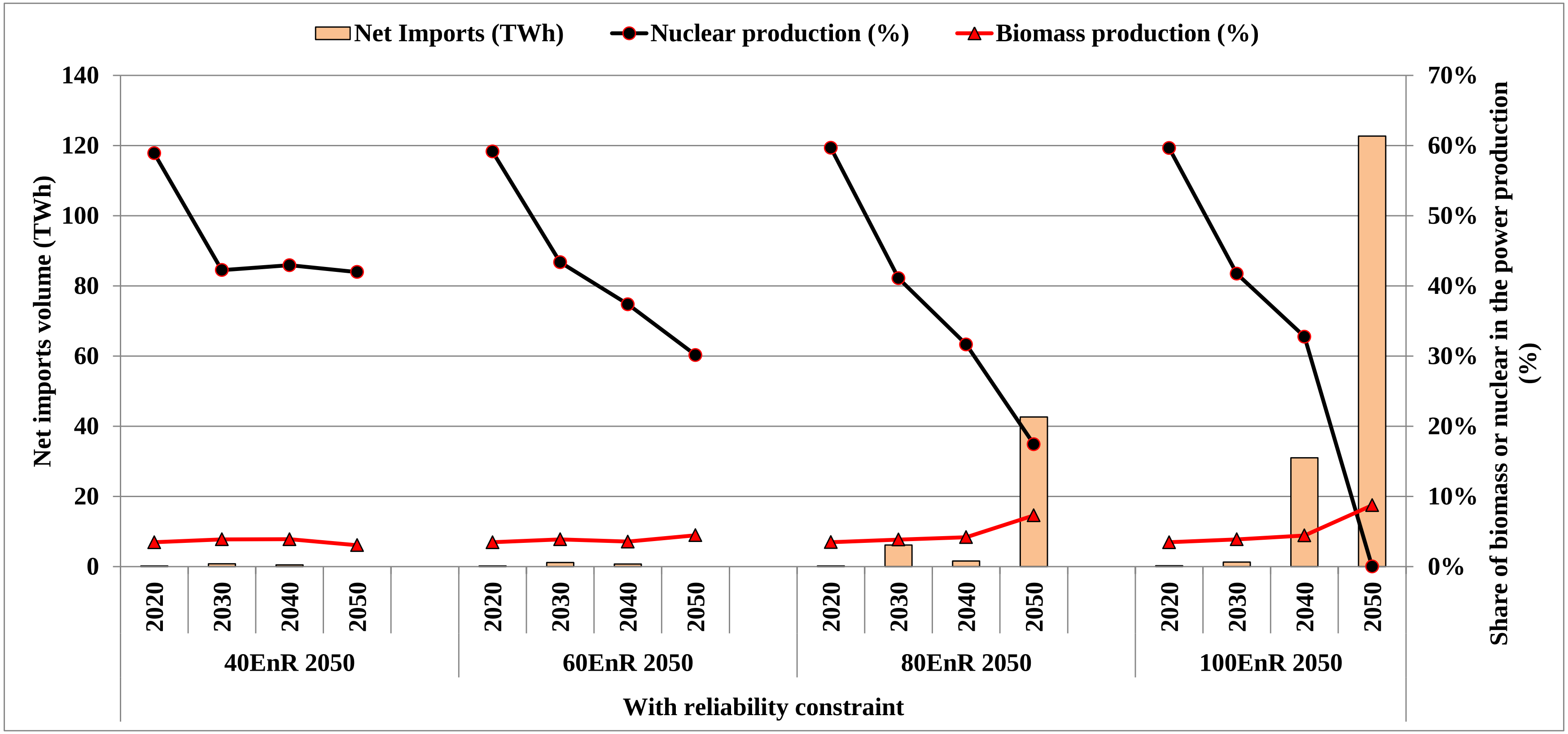
Installed capacity in 2050 (MW)



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

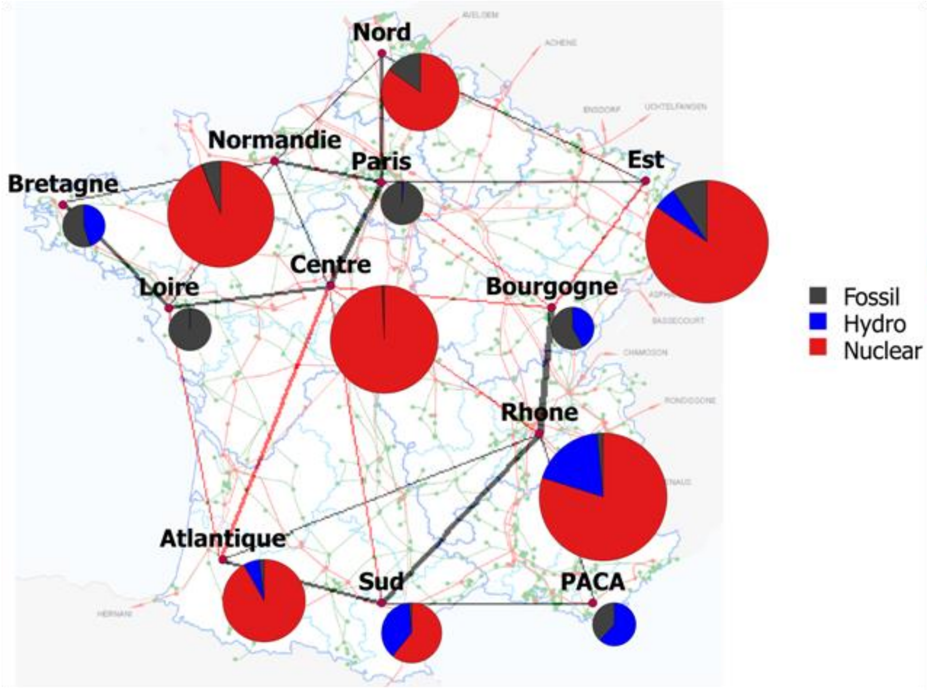


Sensitivity analysis to some critical issues

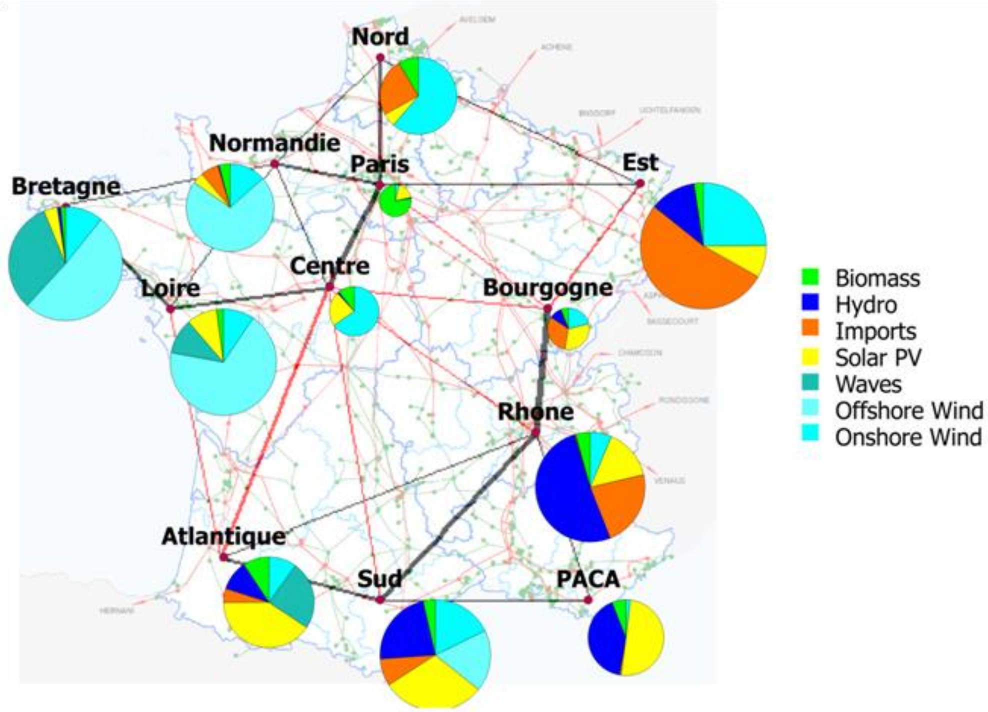


Regional mix (under progress)

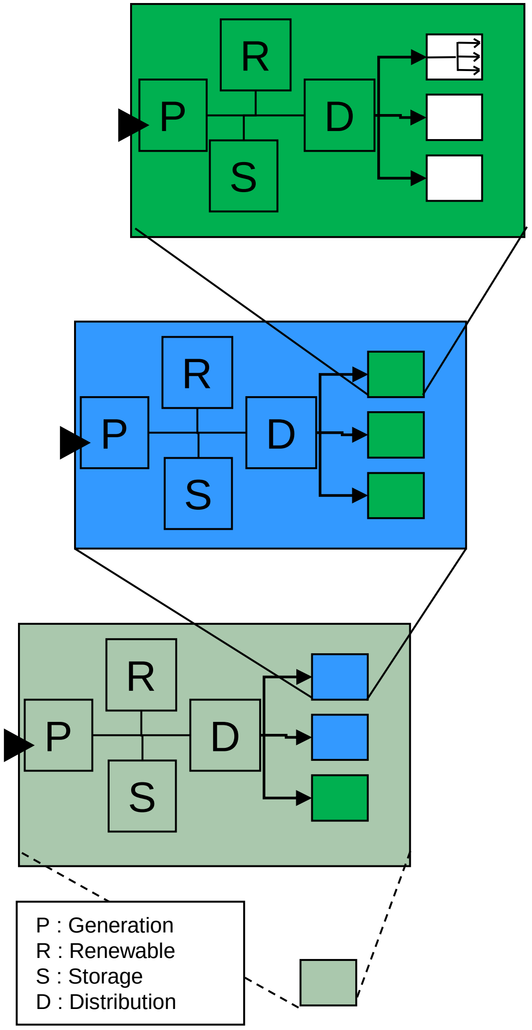
BAU generation
No fiability constraint



100% renewables
No fiability constraint



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 CO2 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

		centralized	decentralized
Relaxation time			
under	syncronism	Except "copper plate"	If well balanced
load or generation	kinetic reserve	few s	lower
fluctuation	magnetic linkage (transmission)	10 ms	lower
	elasticity of generation	few mn	no (AC/DC static converters)
	spinning reserve	few mn	lower
Losses			
	self-consumption	🟧	🟩
	auto-control	🟩	monitoring and data processing
	T&D losses	🟧	🟩
	reliability losses		???
Investment			
	sizing of capacity	global peak	Σ (local deficits)
	backup/storage	discard peak	balance intermittency
	demand response	discard peak	minimize local deficit
	generation & transmission	10.000 BillionUS$ (WEO, IEA 2003)	???
Systemic risk		weak but global	important but isolated
Emissions/Depletion			
	hydro	large	🟩
	renewables	farms	
	fossils	🟧	back-up
	nuclear	🟨	no (or small units)

Conclusion

- 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 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 (>80%) 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}