Bottom-up modeling of the energy system

Dedicating multiscale approaches to low carbon prospective studies using

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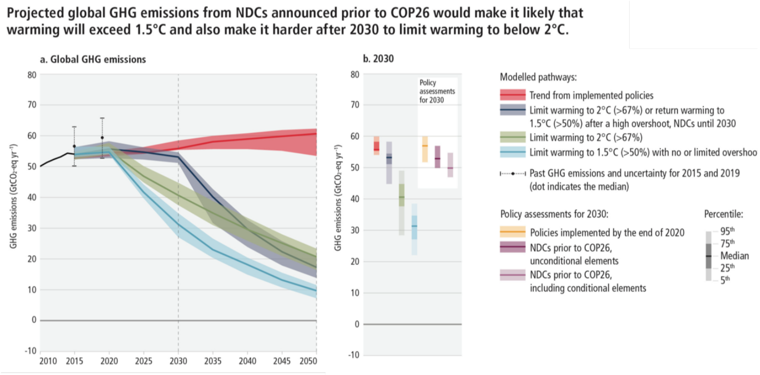
Mines Paris - PSL, PSL Research University

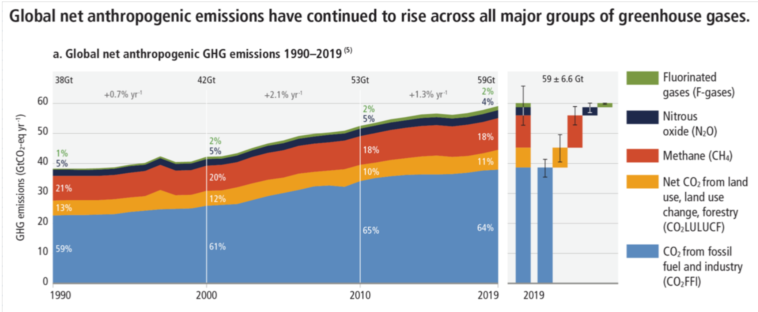
School on Energy, Mathematics and Theoretical challenges

The scale of the mitigation effort needed



Source : IPCC, WGIII, 2022: Summary for Policymakers

GHG balance



Source : IPCC, WGIII, 2022: Summary for Policymakers

- 2019 emissions 12% higher than in 2010 and 54% higher than in 1990.
- Emissions growth slowed from 2.1%/yr for 2000-2009 to 1.3%/yr for 2010-2019.
- Decarbonisation of energy is progressing far too slow at the global scale compared to what we see in 1.5°C and 2°C scenarios.
- Carbon emissions across the last decade are about the same size than the remaining carbon budget for keeping global warming to 1.5°C with a 50% probability.

Long term **pathways**

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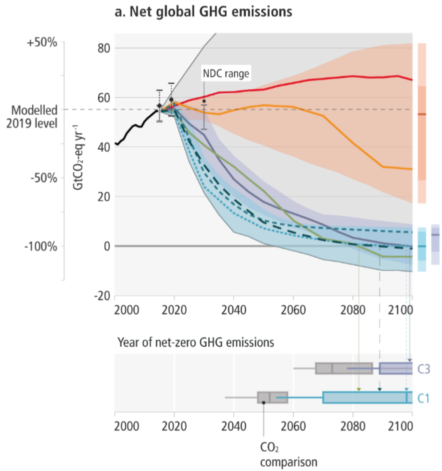
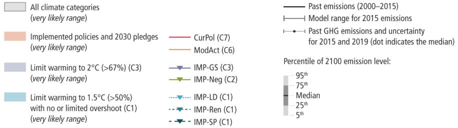
IPCC long term scenarios : what do they tell ?

Development of global GHG and CO2 emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO2 emissions reach net zero (lower sub-panels).





reference : IPCC, 2022: Summary for Policymakers

Conflicting learnings for a delicate consensus

[..] approval of the IPCC summary for policy-makers [...] expresses a range of divergent national interests (Aykut/Dahan 2014) :

- the AOSIS, Alliance of Small Island States plead for the introduction of a rhetoric of risk
- oil-producing countries argue for repeated mention of scientific uncertainties and other GHGs than CO_2
- developing countries want to mention the weight of past emissions
- Northern countries insist on future emissions
- ...

Where do they come from ? : 1200 scenarios

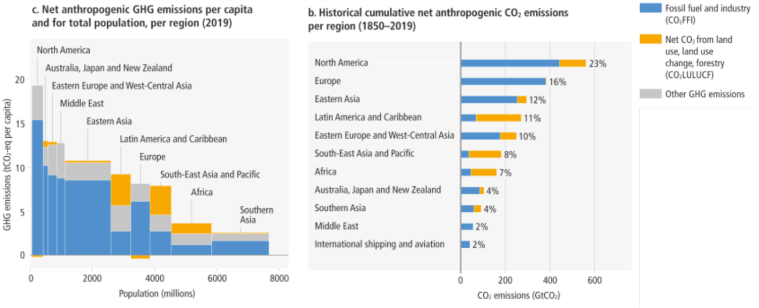
"Differences between pathways typically represent 3 choices that can steer the system in alternative directions through the selection of different 4 combinations of response options (high confidence). More than 2000 quantitative emissions 5 pathways were submitted to the AR6 scenarios database, of which more than 1200 pathways included 6 sufficient information for the associated warming to be assessed (consistent with AR6 WG I methods). 7 (Box TS.5) 3.2, 3.3."

(IPCC, 2022: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change)

Profusion of global trajectories that ultimately erase

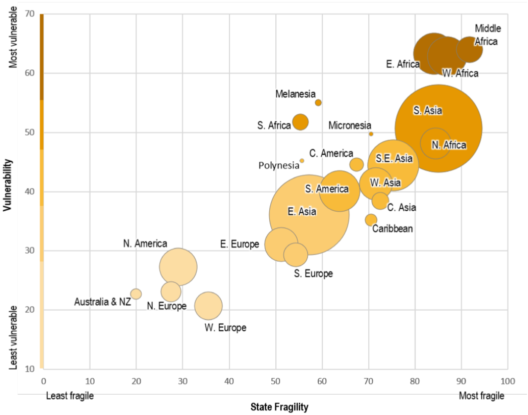
1. urgency and uncertainty : 1200 scenarios that erase many factors
2. global vision for local realities: methane from rice fields and the CO_2 of our transport

The responsibilities



Source : IPCC, WGIII, 2022: Summary for Policymakers

The regional impacts

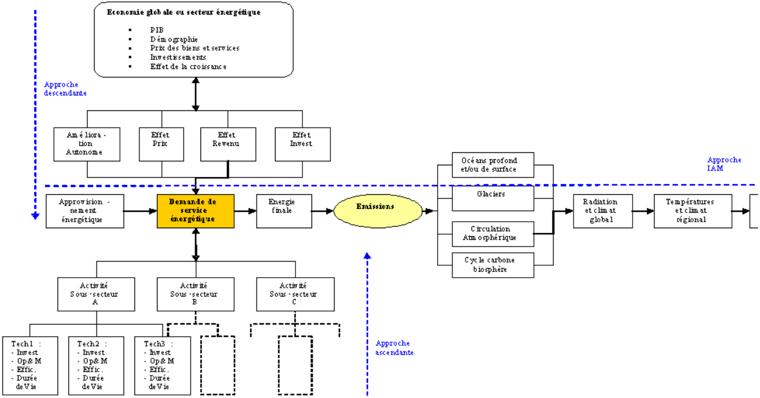


Source : IPCC, WGII, 2022: Summary for Policymakers

- 3.3 – 3.6 billion people live in hotspots of high vulnerability to climate change.

1200 scenarios that should be read

☞ according to the adopted predominance given to **economics, technology or climate**, the models that have been developed are based on



reference AIE et Parson & Fisher-Vanden & Assoumou (2005)

Pathways for the Future

☞ are misunderstood if interpreted with no indication about

- their **position regarding the future**
- the keys to connecting trajectories with reality : i.e. the ability to **open up the black boxes**

The Centre for Applied Mathematics of MINES ParisTech member of PSL research university and its Chair Modelling for sustainable development are part of the framework in which these questions are addressed.

MINES ParisTech

CMA Centre de Mathématiques Appliquées

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Position regarding the future

Whilst Prediction **imposes** the future,

Prospective

- **envisions** all the possible futures
- in order to **lighten** tomorrow's consequences of today's choices and decisions

In other words Prospective exercises enable to :

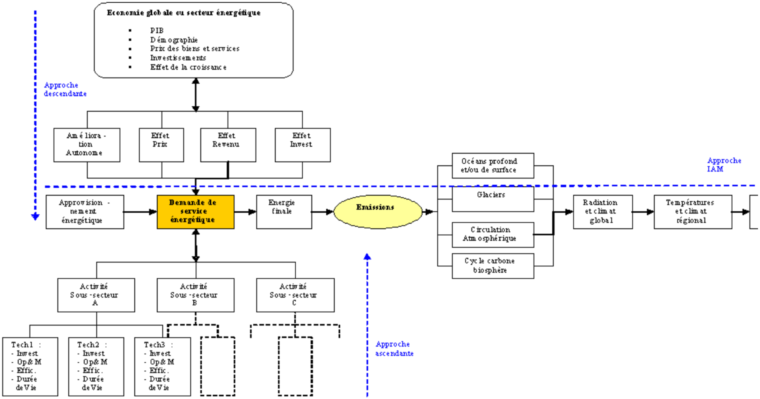
- **be prepared** to unexpected trends or events thanks to the assessment of a **diversity of imagined futures**
- i.e. **to build a prosthesis** for the stake-holders or decision-makers who desire a **calculated adventure**

Pierre Massé

☞ Tools are needed to think, debate, and to evaluate decisions and measures

Scenarios are meaningful

☞ according to the adopted predominance given to **economics, technology or climate**, the models that have generated are based on



Source AIE et Parson & Fisher-Vanden & Assoumou (2005)

Determinants of the move towards greenhouse effect models

A combination of the following preoccupations led to the modeling of issues related to the greenhouse effect:

1. The problem of **managing major technical systems** resulting from the application of operational research in the military field
2. The problem of **development** (in the sense of models of developing economies)
3. The discussion on the **theme of growth and its limits** (*Limits to growth*)
4. The **management of systems, technologies and finite resources** starting from the 1973 energy crisis
5. The question of **global pollution and greenhouse gases**

The class of techno-economical models

TECHNO-ECONOMICAL MODELS

TECHNICAL	ECONOMIC
energy sector disaggregated	energy sector aggregated
deviations permitted regarding historical trends	no possible deviation regarding historical trends
energy = function (efficiency, usage) energy units	energy = function (GDP, price, inflation) monetary units

The question debated in the 1930s was

the reconstruction of economic activity for an infinite timespan

Two types of approach developed in parallel came together

1. The infinite horizon growth model developed by **Ramsey** (1927) to answer the question:
   ☞ *"How much of its income should a nation save ?"*
2. The formalism of the activity analysis (describing the processes of "who consumes" or "produces" goods) developed by **von Neumann** (1930) then **Sraffa** to propose
   ☞ *a reconstruction of the economic sphere*
   This involved establishing **balanced prices for goods and quantities exchanged**

"A model of general equilibrium" von Neumann (1937) revolutionized mathematical economics

Theoretical framework of prospectif models

Put very simply, the key principles are:

1. **Optimal growth models**

2. **Activity analysis**

☞ based on an **optimal paradigm**

Optimal paradigm: the planner

$$\min_{x \in X} f(x)$$

x decision variable

X feasible set of solutions

f objective function

Based on an optimality paradigm

derived from **von Neumann** (1930) and **Sraffa**

☞ *How much should a nation save ?*

The objective

establish a production plan (programme) $x_1, \dots, x_n$ *in order to minimize the production cost taking into account the potentiels of the production factors and driven by a demand*

The plan is formulated as follows

$$\min_{x_j} z = \sum_{j=1}^{n} c_j x_j$$

$$\sum_{j=1}^{n} a_{ij} x_j \leqslant b_i \quad i = 1, \dots, m \qquad x_j \geqslant 0 \quad j = 1, \dots, n$$

$$\sum_{i,j} a_{ij} x_j \geqslant D$$

TIMES

A technical linear optimization model, **open-source** developed in the framework of **ETSAP**: Energy Technology Systems Analysis Program initiated by the IEA (in 1980)

- demand driven
- on a long term horizon: (50/100 years)
- in order to achieve **a technico-economic optimum** minimizing the overall actualized cost of the reference energy system

1. whose flows are balanced
2. satisfying a set of relevant technical constraints (peak reserve for the power system,. . .)

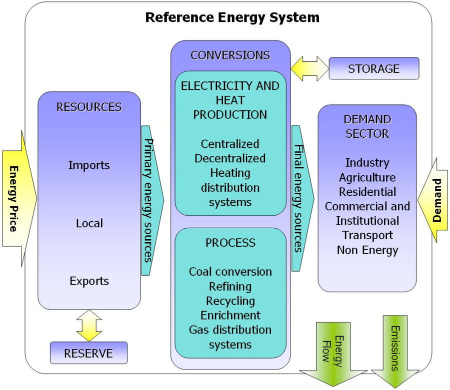


Figure: The Integrated MarkAl (market allocation)-EFOM Reference Energy System

TIMES as a Prospective tool

"What we have the right to ask a conceptual model is that is seize on the strategic relationships that control the phenomenon it describes and that it thereby permit us to manipulate, i.e., **think about the situation**"

Source: R. Dorfman, P. A. Samuelson,R. M. Solow

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The use of scenarios: prospective versus prediction

Energy planning modelling through TIMES enables to:

- **envision** all the possible futures
- in order to **lighten** tomorrow's consequences of today's choices and decisions

- Instead of using **scenarios kept in a stock**
- each question requires **a flow of dedicated scenarios**, to assess a future energy systems

Desirable, Plausible, Sustainable

Solutions to mitigate GHG in the energy sector

We witnessed a thematic renewal that has evolved over the last decade

1. opening up Europe's electricity and gas markets.
2. industrial ecology, energy efficiency, the green economy, green growth, degrowth and carbon finance, greater energy efficiency
3. first-, second- or third-generation biofuels, biomass, solar, wind and marine power (waves, marine turbines, etc.), geothermal energy, etc.
4. technological solutions : storage facilities (step, batteries, flywheel etc.)., flexibility (aggregation, virtual power plants, smart energy, smart grids, smart cities, smart buildings, etc.).

Multi-scale integration : mandatory

In order to identify long-term strategies relevant to all types of climate constraints (e.g. climate-related, financial, legal, political, technical) we propose to **reconcile and connect different scales (temporal, spatial, social)** :

1. **Time reconciliation** The impact of phenomena with different dynamics (several decades versus seconds)
2. **Space aggregation** The political implications that necessarily take place at several levels, from global to local
3. **Financial scale** where we evaluate how carbon finance tools (especially taxes and carbon market) could contribute to both reduce the volume of carbon dioxyde emissions and encourage the use of renewable sources along with energy efficiency policies.
4. **Societal scales** The central role of people (for whom the future must be acceptable and desirable, i.e. compatible with aspirations and behavior)

Spatial scale: regional issues

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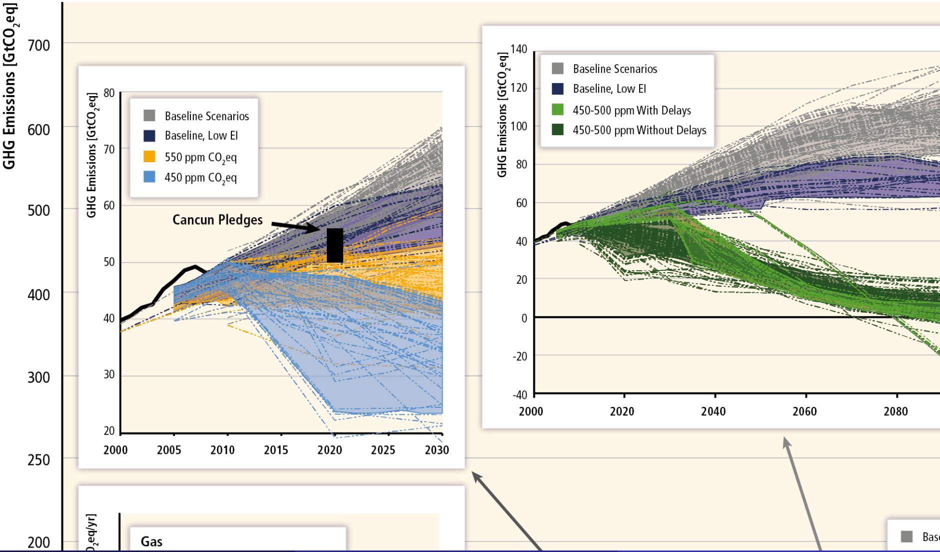
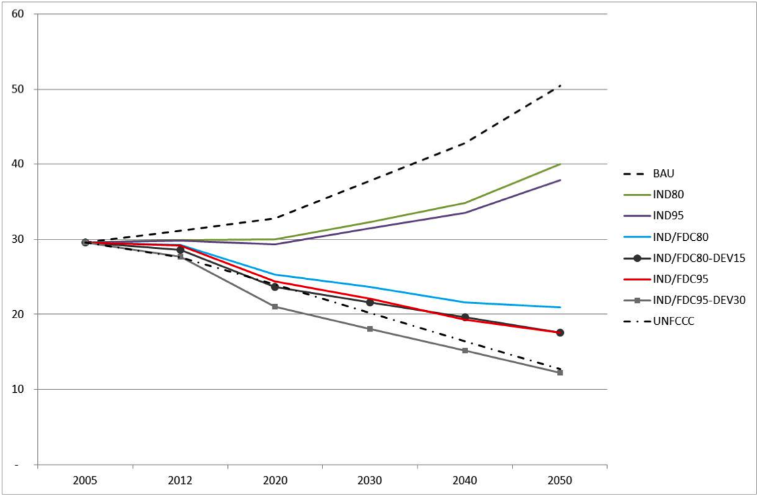
Back to IPCC : opening the black boxes



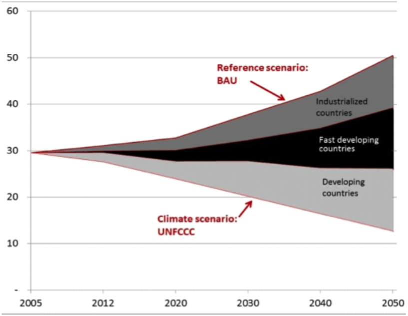
Focusing on energy scenarios towards 2050

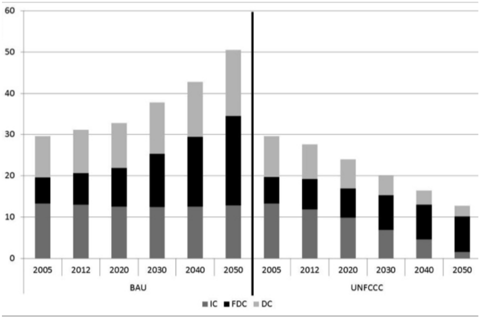
S. Selosse, N. Maïzi, What commitments for the future climate regime: Long-term decoding using TIAM-FR, IEW Beijing 2014.



Top Down options to reach the 2°C target

S. Selosse, N. Maïzi, What commitments for the future climate regime: Long-term decoding using TIAM-FR, IEW Beijing 2014.

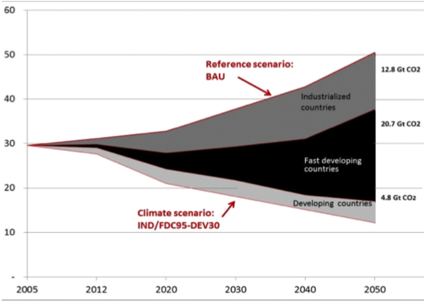


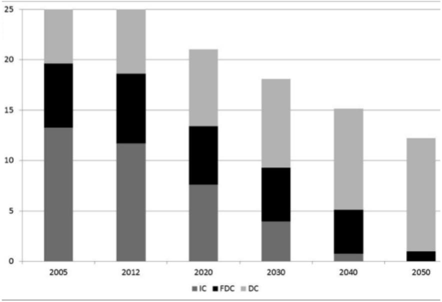


Burden for DC: they have to mitigate up to 84% compare to BAU

Pledges options to reach the 2°C

S. Selosse, N. Maïzi, What commitments for the future climate regime: Long-term decoding using TIAM-FR, IEW Beijing 2014.

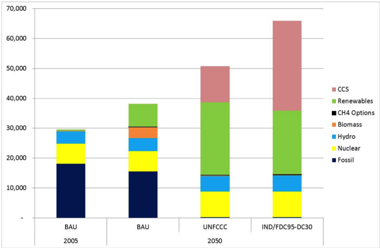


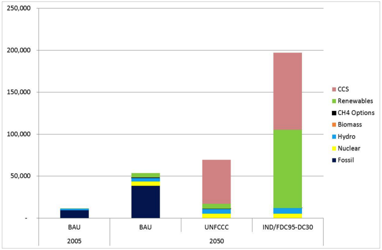


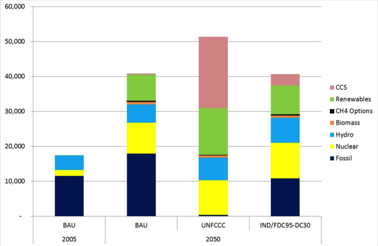
Burden for DC: they have to mitigate up to 30% compare to BAU

Realism for regional technological options

Regional view of the power mix from left to right IC and FDC, bottom DC







[S. Selosse , O. Ricci, Achieving negative emissions in the power sector: New insights from the TIAM-FR model, in proc. Climatic Change, 2014]

Time reconciliation and space agregation to shed light on low carbon power sytems

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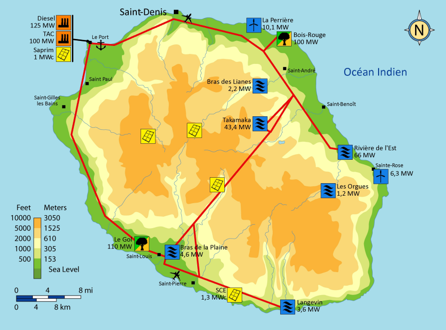
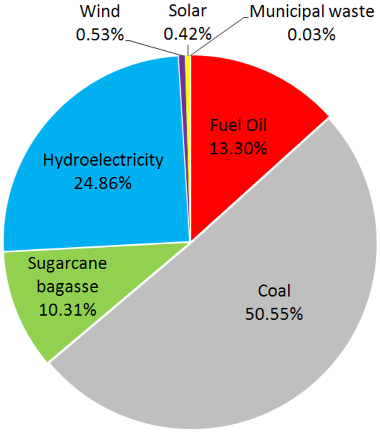
Focusing on the Reunion Island



power production: 100% renewable in 2030

1. Blessed with high renewable energy potentials
2. Small, weakly-meshed and remoted power system
3. Binding target in 2030: 100% renewable sources in power generation
4. Maximum : 30% RE **intermittency**

The electricity sector in 2008



Source : BPPI - EDF SEI 2009

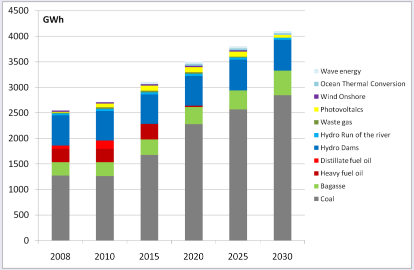
Electricity production: 2 546 GWh

Installed capacities

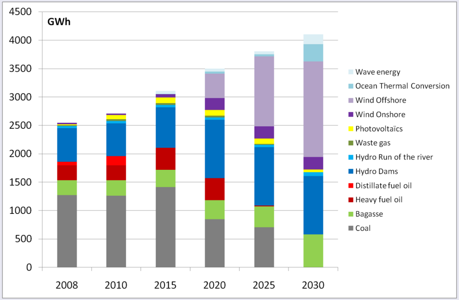
- **Thermal units** (76%):
  - 476 MW
  - Fuels: coal, fuel oil, sugarcane bagasse
- **Hydroelectricity** (20%):
  - Dams: 109,4 MW
  - Run-of-the-river: 11,6 MW
- **Others** (4%):
  - Wind: 16,8 MW
  - Solar PV: 10 MW
  - Municipal Waste: 2 MW

Assessment of future power systems

BAU Scenario : production (GWh)



100% Renewable Energy in 2030, production (GWh)



- Ensure only system adequacy
- Need to consider transient stability physical phenomena i.e. **dynamical issues**

☞ This study proposes an approach combining these dynamics issues to assess future power mixes where

A reliability criteria

is established to handle the dynamic management (frequency and voltage controls)

- depending on:
  - the level of reliability required,
  - the dynamic properties of capacities,
  - the load profile
  - the grid properties
- avoiding *time-consuming* methods relying on Kirchhoff laws.

Reliability: Ability of a Power System after a Transient Period to lock back into Steady-State conditions, maintaining Synchronism.

Deriving reliability indicators (Patent FR 11 61087)

☞ **The higher the reserves, the more reliable the system is:**

- **magnetic reserve** : transmission maintenance ;
- **kinetic reserve** : frequency maintenance.

Reliability criteria

- The reserves are associated to two indicators $H_{cin} = \frac{E_{cin}}{S}$ and $H_{mag} = \frac{\tilde{F}}{S}$
- They refer to **dynamic properties** of the installed capacities, each contributing to the reserves level in a specific way

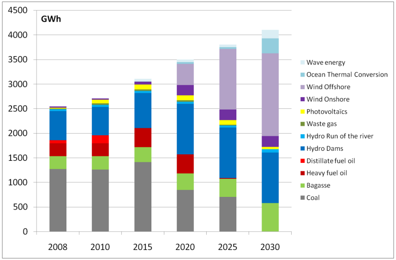
The level of reliability is characterized by H:

the time you have to recover the stability of the system after a load fluctuation (equivalent to the whole system capacity) by monitoring its reserves.

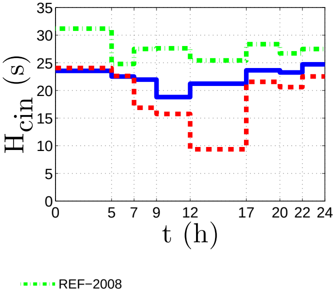
Is 30% the maximum share ?

Electricity production mix in 2030

100% RE scenario



of a typical day during summer



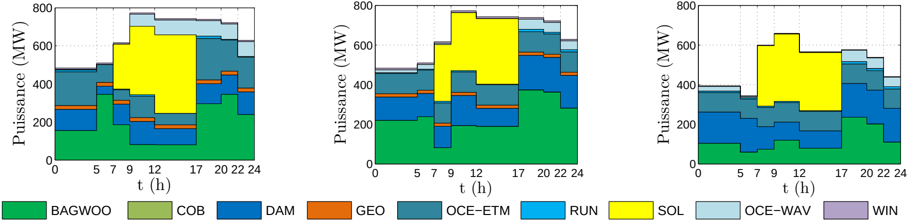
- 100 % EnR : limitation of 30 % of instantaneous power production issued from intermittent sources
- PV-OCE : no constraint on intermittency
- REF-2008 : kinetic reserve level in 2008

Demand Side Management and Storage

DSM = postponing demand from peak to off-peak periods + EE

Electricity production mix of a typical day during summer in 2030

Without reliability constraint | $\forall t : H_{cin,t} \geqslant \min(H_{cin,2008})$ | Reliability + DSM + Storage (24MW)



- ***share of intermittent sources $\geqslant$ 50%***
- ***$\nearrow$ total installed capacities of 9.4 %***

- ***share of intermittent sources $\geqslant$ 50%***
- ***$\searrow$ total installed capacities of 6 %***

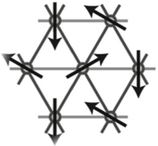
From time reconciliation to space aggregation

☞ So far, the assumption that synchronism is inconditionally achieved, whatever the regime and the fluctuation, enabled to implicitely add E_{cin}

But, even if the reserves indicators are high, **synchronism is the necessary condition** ensuring that the system is able to withstand a load fluctuation :
☞ this requires namely the **equirepartition of magnetic energy**.

The critical behavior is captured thanks to a dedicated lattice model

2d-DoF (DoF physical) objects (here **the rotors of the generators**) are coupled within a 2D lattice **the grid**

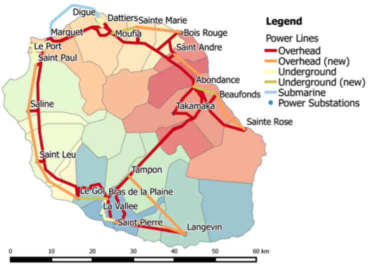


From phase transition theory it comes that fluctuation on the iso-energy states [Kosterlitz-Thouless, 1973] is not inconditionally **synchronized** (ordered) for this lattice (2d-DoF/2D) and may experience a disordering process under long-range soft modes.

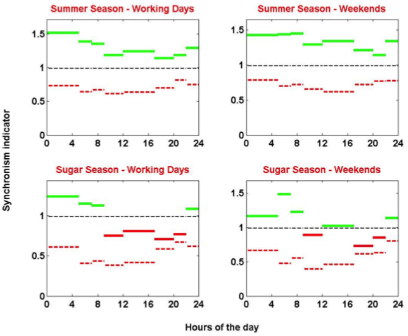
Reunion 100 % RE in 2030

☞ Scenario where the reserves indicators are high

Strengthened Reunion grid



Synchronism indicator



current (dashed) and strengthened grid (solid)

☞ dispersed energy (summer) provides a more resilient grid

Summary and perspectives

We have developed a unique framework to successfully handle:

- Space-agregation
- Time-reconciliation

At the upper scale:

☞ synchronism of the whole power system may be discussed through the Kuramoto's model; while

☞ kinetic energy balances the load fluctuations.

This approach is dedicated to assess the technical feasibility of future power mix through:

- discuss energy-efficient and environmental-friendly issues;
- take into account intrinsic qualities of the implemented infrastructures.
- Preliminary studies exhibit share of intermittency higher than 30% without jeopardize power management.

Societal scale: behavior

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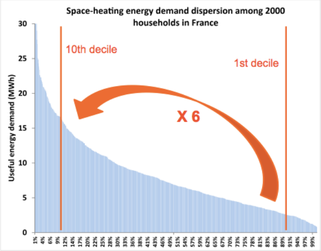
Households heterogeneity explains behavior

J.-M. Cayla, N. Maïzi, C. Marchand, "The Role of Income in Energy Consumption Behaviour: Evidence from French Households data", Energy Policy, Volume 39, Issue 12, December 2011, Pages 7874-7883.

☞ Importance of households behavior in energy consumption (2009 survey on 2000 French households related to housing, climate, household characteristics and their space-heating practices in addition to their energy bill:)

variables linked to housing characteristics represent around 66% of explained dispersion (half of it) in space-heating energy demand whereas variables linked to inhabitants represent about 33%. (Cayla 2010).

- Great dispersion between households: **factor 6 between extreme deciles** depending on
  - Thermal quality of housing
  - Space living area
  - Type of heating system (boiler, heat pumps?)
  - Climatic variable
  - Household behavior...



Reference: Cayla (2011)

TIMES-Households model: integrating individual behavior

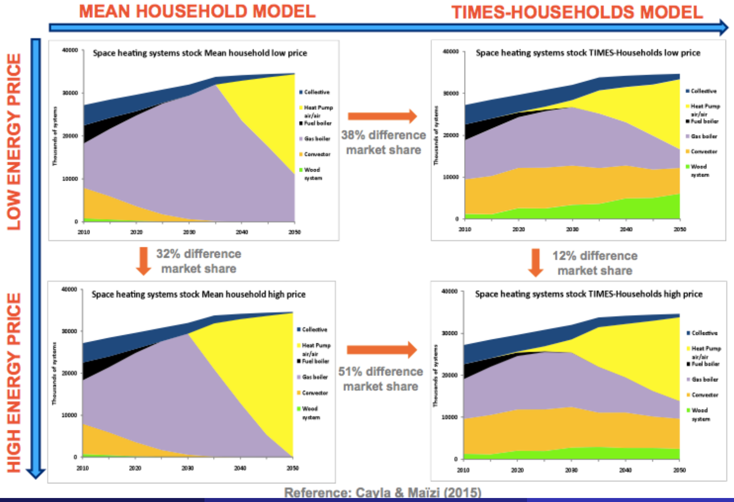
180 segments to encapsulate heterogeneity and behavior in energy models were defined according to

- Access to available technologies
  - Size of car depends on household size
  - Access to collective transports (subway, bus) depends on location
  - Solar water heating systems are available only for houses
  - Thermal insulation are available only for owners
- Level of energy services consumed
  - Space heating need depends on thermal insulation, space living area, income
  - Water heating need depends on household size
  - Number of trips depends on activity status
  - Length of trips depends on location
- Preferences for equipments
  - Required rate of return depends on income and type of equipment
  - Maximum amount of investment in equipments depends on income

[J.-M. Cayla and N. Maïzi. Integrating behavior and heterogeneity into the TIMES-households model. Applied Energy (2015) vol. 139 pp 56-67.]

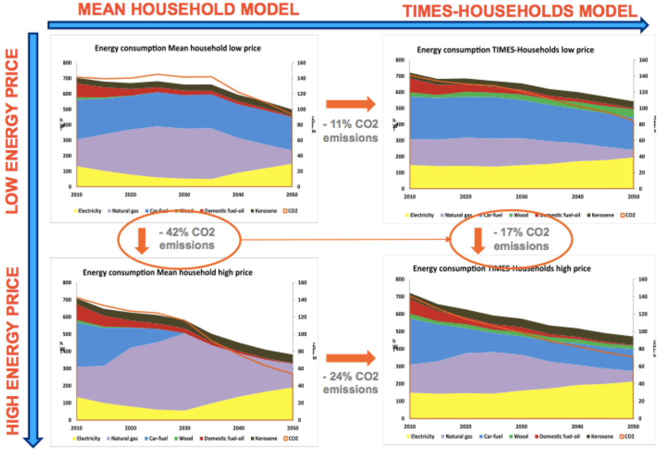
Technology diffusion in residential sector

Model provides more realistic technology diffusion patterns & answers to energy price variations
[J.-M. Cayla and N. Maïzi. Integrating behavior and heterogeneity into the TIMES-households model. Applied Energy (2015) vol. 139 pp 56-67.]



Energy and CO_2 emissions for residential/transports sectors

Implications in terms of Technology and policy recommendations when energy models are over-simplified may be dramatic



Source: Cayla & Maïzi (2015)

Conclusion for behavior issues

- Household behavior explains a large part of energy consumption
- Technological change may surely not be sufficient to reach ambitious (but needed ?) CO2 emissions reduction pathways
- There is a need to consider, understand and include household behavior in long-term energy models
- Considering households heterogeneity is a required first step in order to correctly catch household behavior as it greatly varies accross households
- Modeling household behavior would help to better understand and design adapted policy measures: improve economic efficiency and acceptability, solve equity issues
- There is a need to keep improving behavioural realism and its impacts on energy consumption in long-term energy models

[J.-M. Cayla and N. Maïzi. Integrating behavior and heterogeneity into the TIMES-households model. Applied Energy (2015) vol. 139 pp 56-67.]

Societal scale: degrowth paradigm

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- NOT GDP degrowth per se
- A project of transition toward a society of « frugal abundance » (S.Latouche)
- A « matrix » for multiple alternatives

Source: « Degrowth, a vocabulary for a new era » Routledge 2014

Ambition:

A voluntary , democratic, socially sustainable, equitable, smooth downscaling of production and consumption for high consumption countries, to an environmentally sustainable level

Degrowth concept issues

☞ GDP degrowth is a plausible consequence of Degrowth

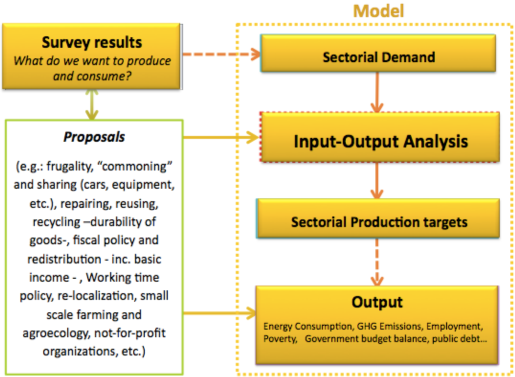
- Can it happen in a socially and environmentally sustainable way?
- Under which conditions? (any institutional or structural obstacles?)
- Which concrete proposals could enable a sustainable Degrowth?
- Welfare state in a degrown economy?

☞ What can prospective modeling tell us?

[F. Briens, N. Maïzi, Coping with the complexity of socio-ecological systems : Investigating the Degrowth Paradigm through prospective Modeling, ÖkologischesWirtschaften 3.2014 (29)]

Back to model: in a nutshell

- **MODESTES** (MOdèle Dynamique d'analyse Entrées-Sorties pour l'exploration de Transitions Economiques et Sociales) Input-Output Dynamic Simulation Model (based on STELLA)
- Based on public data (French National Accounts (Insee), Eurostat, WIOD , etc.)
- Focus on structural relationships, long term concern (rather than conjonctural issues)



[F. Briens, La décroissance au prisme de la modélisation prospective : exploration macroéconomique d'une alternative paradigmatique, PhD thesis, December 2015]

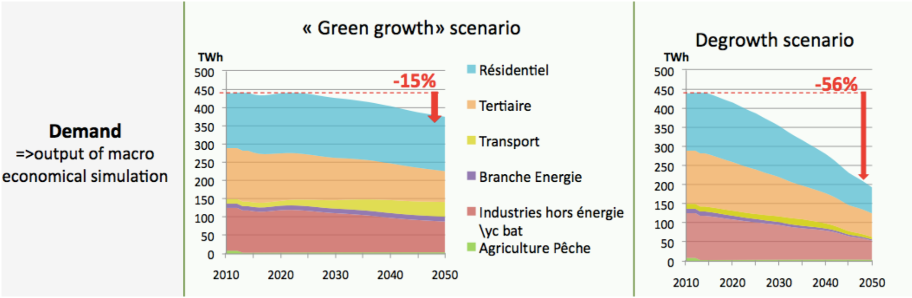
Survey result

One example of a scenario built after an interview:

- Changes in consumption of various goods services
- Switch to more vegan food & 100% organic farming by 2050
- Changes in mobility and modal shares
- Relocalization
- Changes in cohabitation behaviors
- Decrease in Working time (35-> 24h by 2050)
- Slow down in efficiency improvement rates until 2040
- 100% Renewable Energy by 2050 (with reduced network stability) Etc.

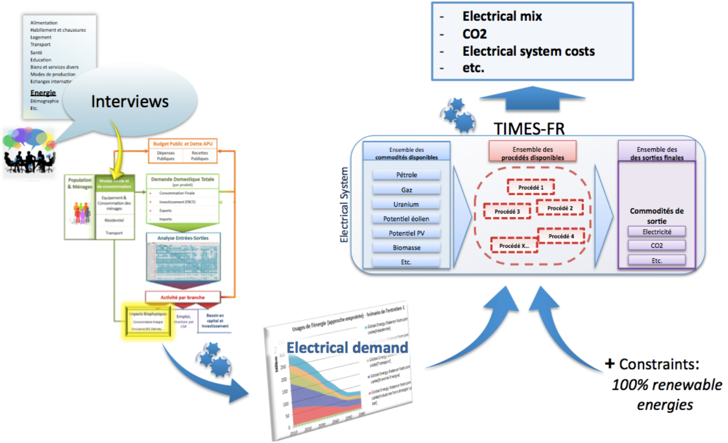
[F. Briens, PhD thesis, Dec 2015]

Scenario results for France



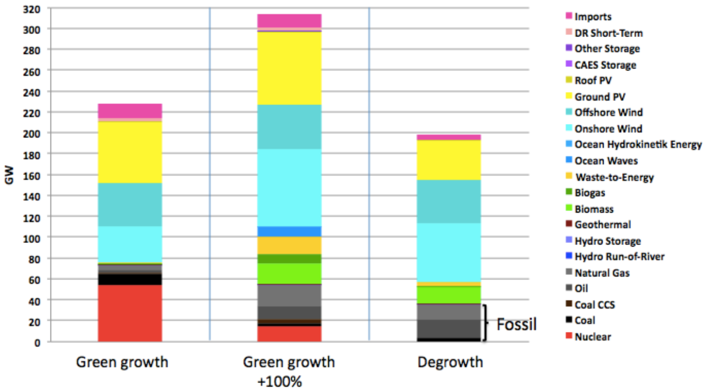
[F. Briens, PhD thesis, Dec 2015]

Linking degrowth and energy



[F. Briens, PhD thesis, Dec 2015]

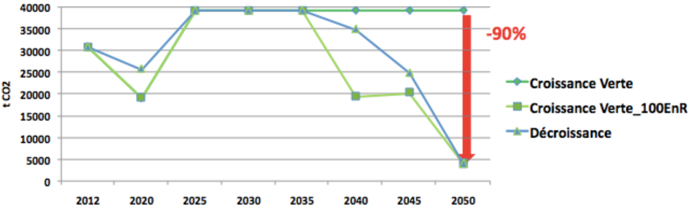
New capacities investments for the power system



Gaz and Coal are mandatory to phase-out from nuclear.

[F. Briens, PhD thesis, Dec 2015]

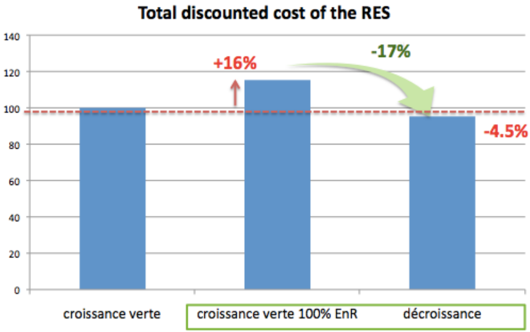
CO_2 emissions of the power system



[F. Briens, PhD thesis, Dec 2015]

Discounted cost of the power system

This questions the discussion about climate change financing.



A powerful tool for collective understanding and deliberation

Good potential of Degrowth pathways? but not there yet!
[F. Briens, PhD thesis, Dec 2015]

Conclusive remarks

Chaire ParisTech Modélisation prospective
au service du développement durable

Bottom-up long-term investment planning model

enable to identify long-term strategies relevant to all types of climate constraints (e.g. climate-related, financial, legal, political, technical)

- tackle **complex systems** associated more specifically with climate-related issues (technologies, carbon, energy, water, rarefaction of primary resources and functional materials);
- investigate the maturity of **electricity and carbon markets**;
- deal with the challenges of **deploying electrical systems** that integrate technologies linked to renewable energies and smart grids;
- and consider the **central role of people** for whom the future must be acceptable and desirable, i.e. compatible with aspirations and behaviours.

Prospective exercises

based on a methodology

- enabling the evaluation of the quality of service provided to the user
- measuring marginal cost of abatements
- integrating externalities
- assessing sectorial competitions
- dealing with the role of people

is the Condition of the elaboration of the desirable energy transition (the one we wish to elaborate)

either wise **ALL** transitions are possible.

Travaillons donc à bien penser, c'est le principe de la politique. Pascal

More on ....

http://www.modelisation-prospective.org/en

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