4th October 2024

Eoles, an open-source energy model for studying low-carbon scenarios – Application to the *négaWatt* scenario

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Outline

1. The *négaWatt* scenario
2. The EOLES-elec model
3. EOLES-elec compared to other open-source energy system optimization models
4. Results
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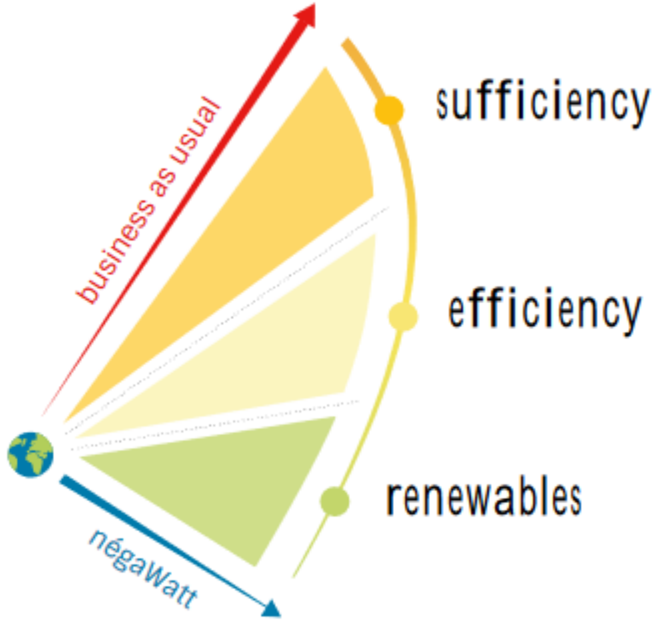
    2. Results with the original *négaWatt* energy mix
    3. Identification of "missing" storage
    4. Four variants to attain zero lost load
5. Computational cost
6. Conclusion & discussion

1. Brief description of the *négaWatt* scenario

- **Prioritising essential needs** in individual and collective energy uses, through **sufficiency** (e.g. suppressing wasteful uses, reducing packaging, etc.).
- **Reducing the amount of energy** required to cover each need through **energy efficiency** (e.g. insulating buildings, improving the performance of appliances and vehicles, etc.).
- **Developing renewable energies**, as they are the most environmentally-friendly sources and never run out (they are based on energy flows, rather than finite resources such as coal, oil, fossil gas and uranium).

The négaWatt scenario is not utopian, and does not require radical **technological, economic or societal breakthroughs.** Significant changes are required, but they will not be implemented abruptly.



The négaWatt© approach

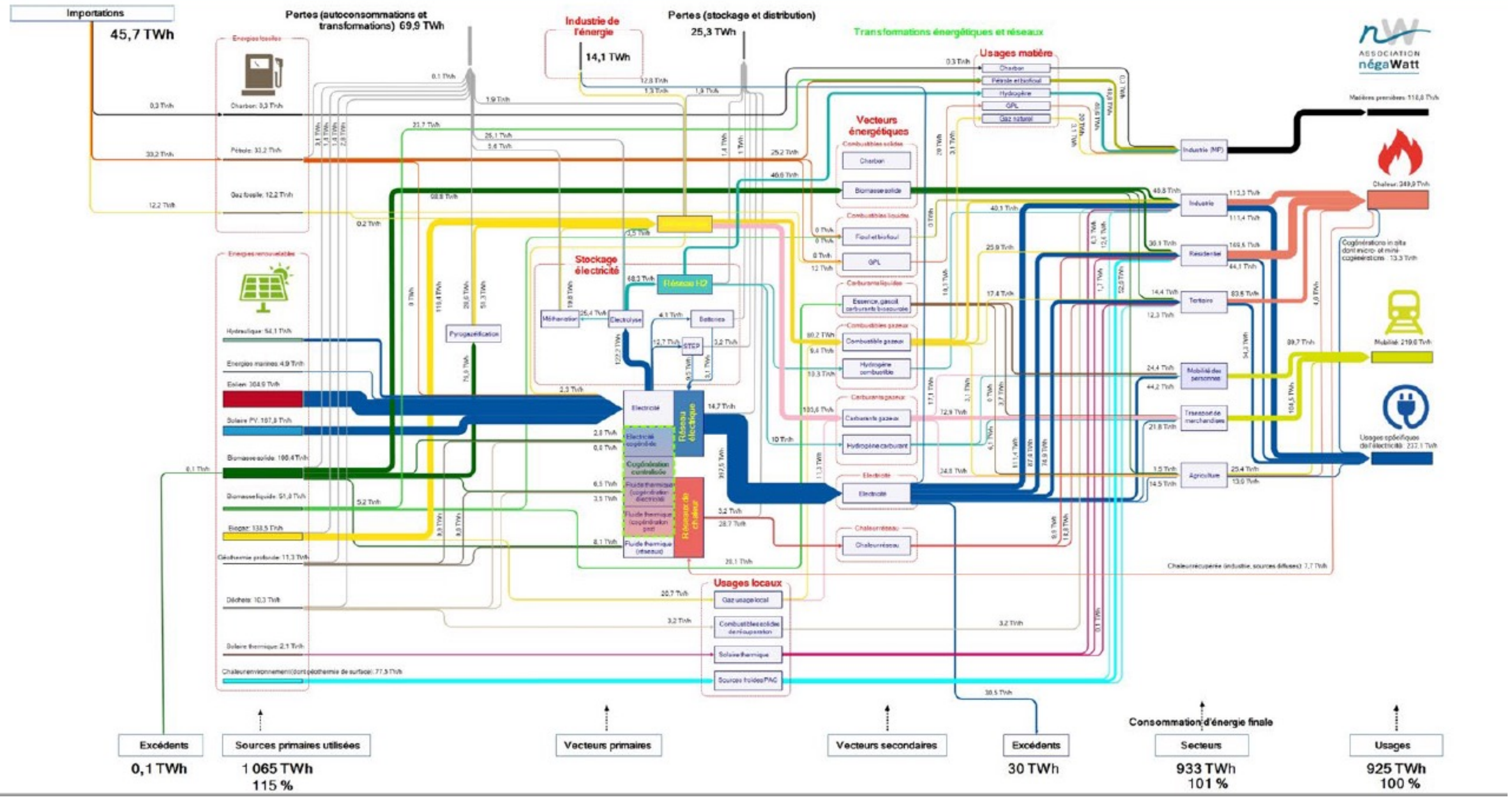
Going further

Resources on the négaWatt scenario are available on the following webpages:

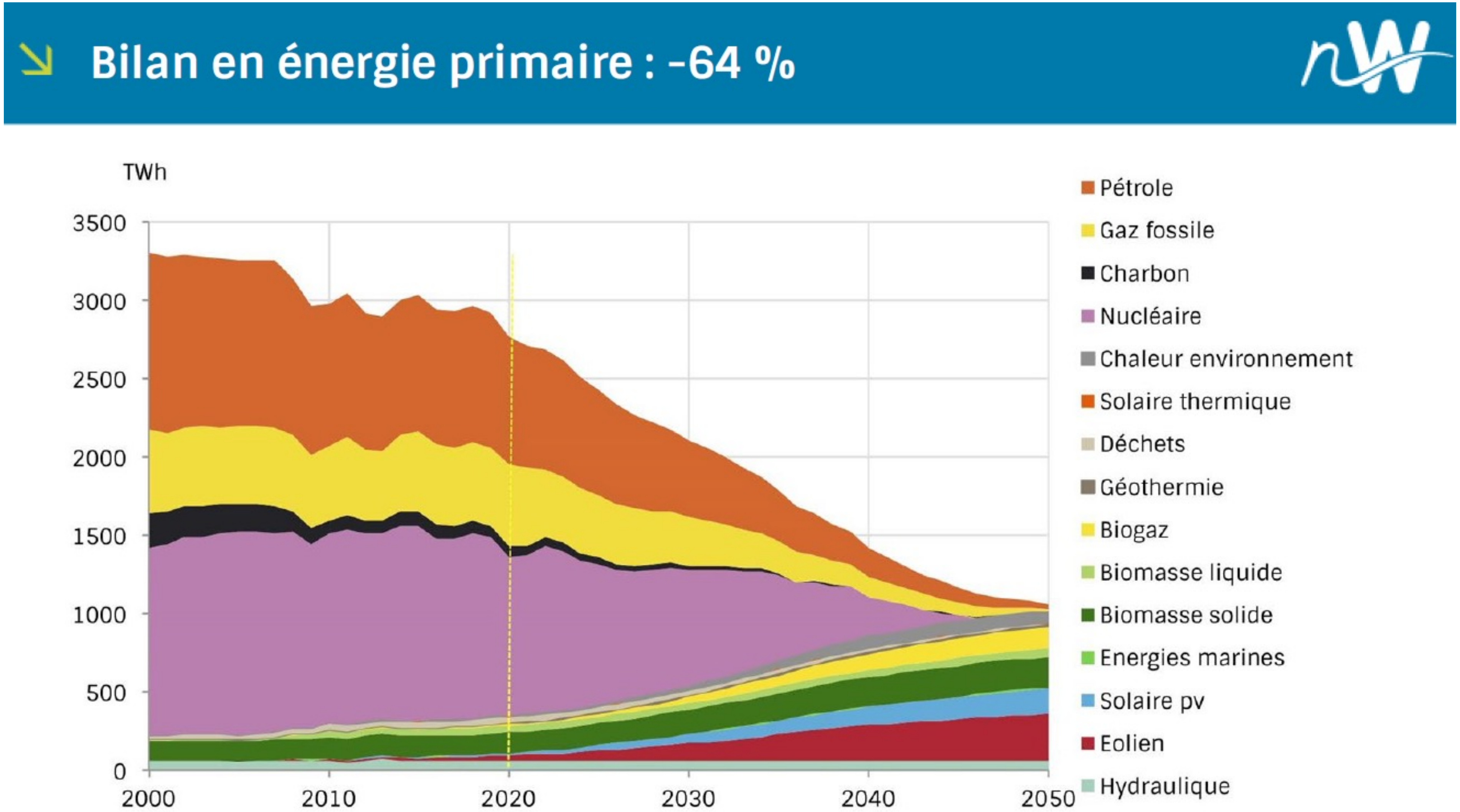
In English: www.negawatt.org/en
- An executive summary of the 2017–2050 négaWatt scenario
- A video explaining the role of energy sufficiency in a 100% renewable scenario
- A document presenting the concept of energy sufficiency

In French: www.negawatt.org/scenario-negaWatt-2017
- An in-depth presentation of the négaWatt scenario
- Dynamic graphs: www.negawatt.org/scenario
- A selection of videos

Bilan énergie France 2050

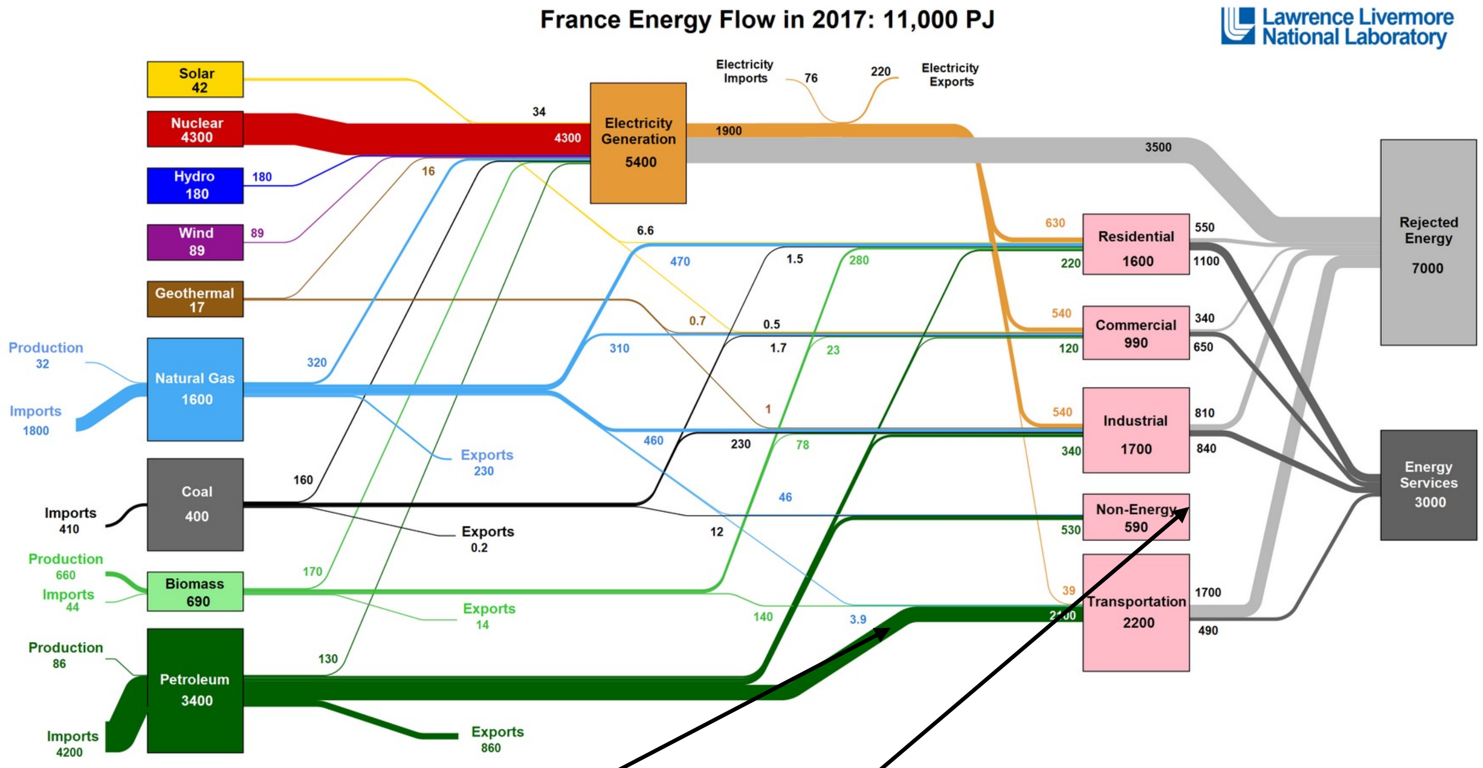


By 2050, final energy halved, primary energy divided by 3



Bilan en énergie primaire : -64 %

Ambitious? Yes but 2/3 of energy is currently wasted!



Source: LLNL 2021. Data is based on IEAs Detailed World Energy Balances (2019 Edition). If this information, or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the U.S. Department of Energy, under whose auspices this work was performed. All quantities are rounded to 2 significant digits and annual flows of less than 0.10 PJ are not included. Total energy supply (top of chart) and energy resource statistics (left-side boxes) represent national energy use which is the sum of production and imports minus exports. Totals may not equal sum of flows due to independent rounding, stock changes, statistical difference and reporting inconsistencies. Further information can be accessed at https://flowcharts.llnl.gov. LLNL-MI-410527

ENERGY 2017 FRANCE

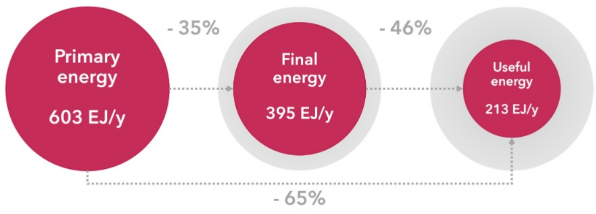


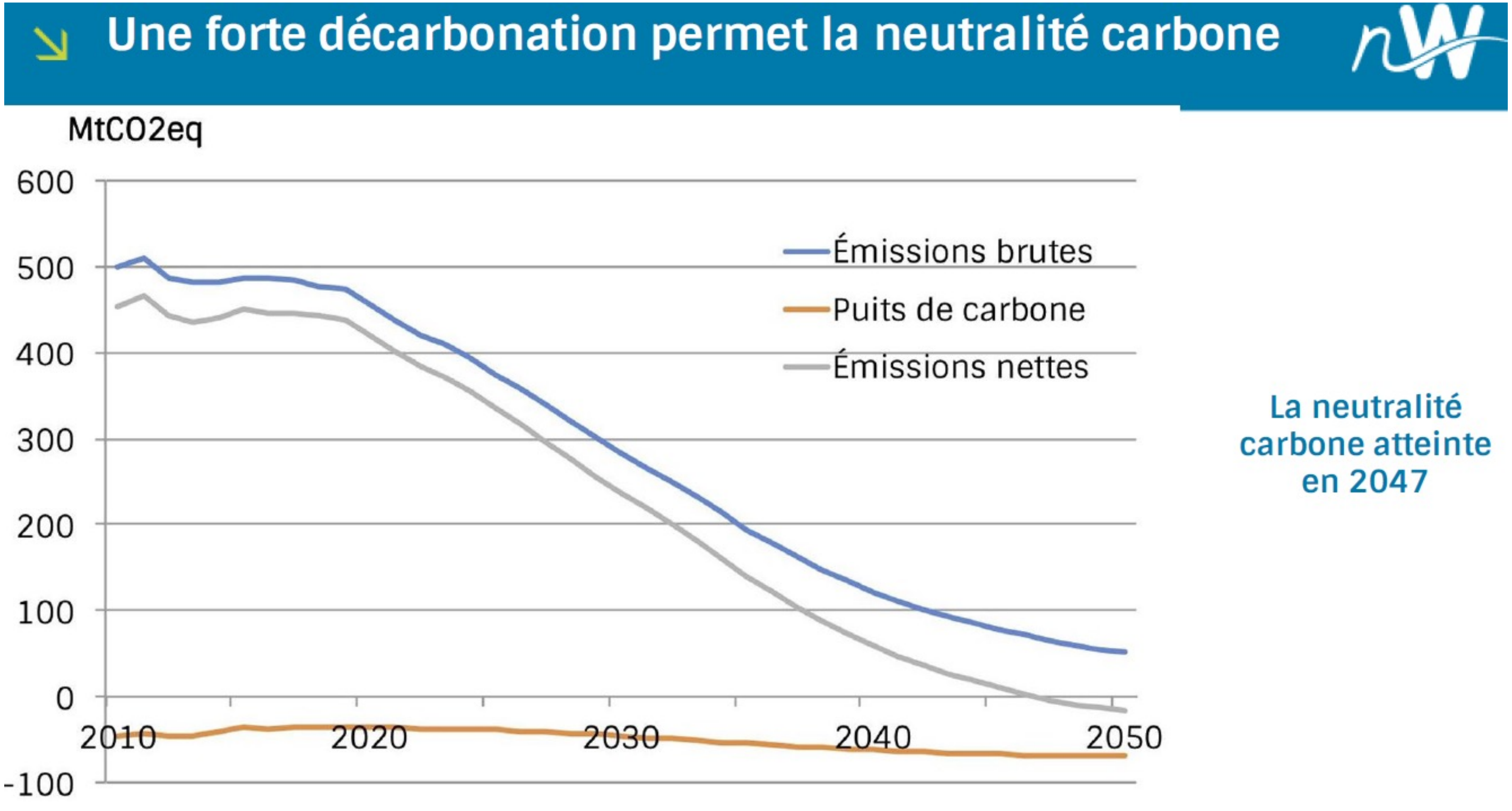
Figure 6. World primary, final and useful energy consumption in 2014[14]

← World, 2014

Source : Zenon Research, 2023. Beyond primary energy

https://assets-global.website-files.com/62b9fb2aad2275b3dcfe568b/64a6e7c8bf3662ad7a43a57f_Rapport_Efficacite%CC%81_Energe%CC%81tique_V3.pdf

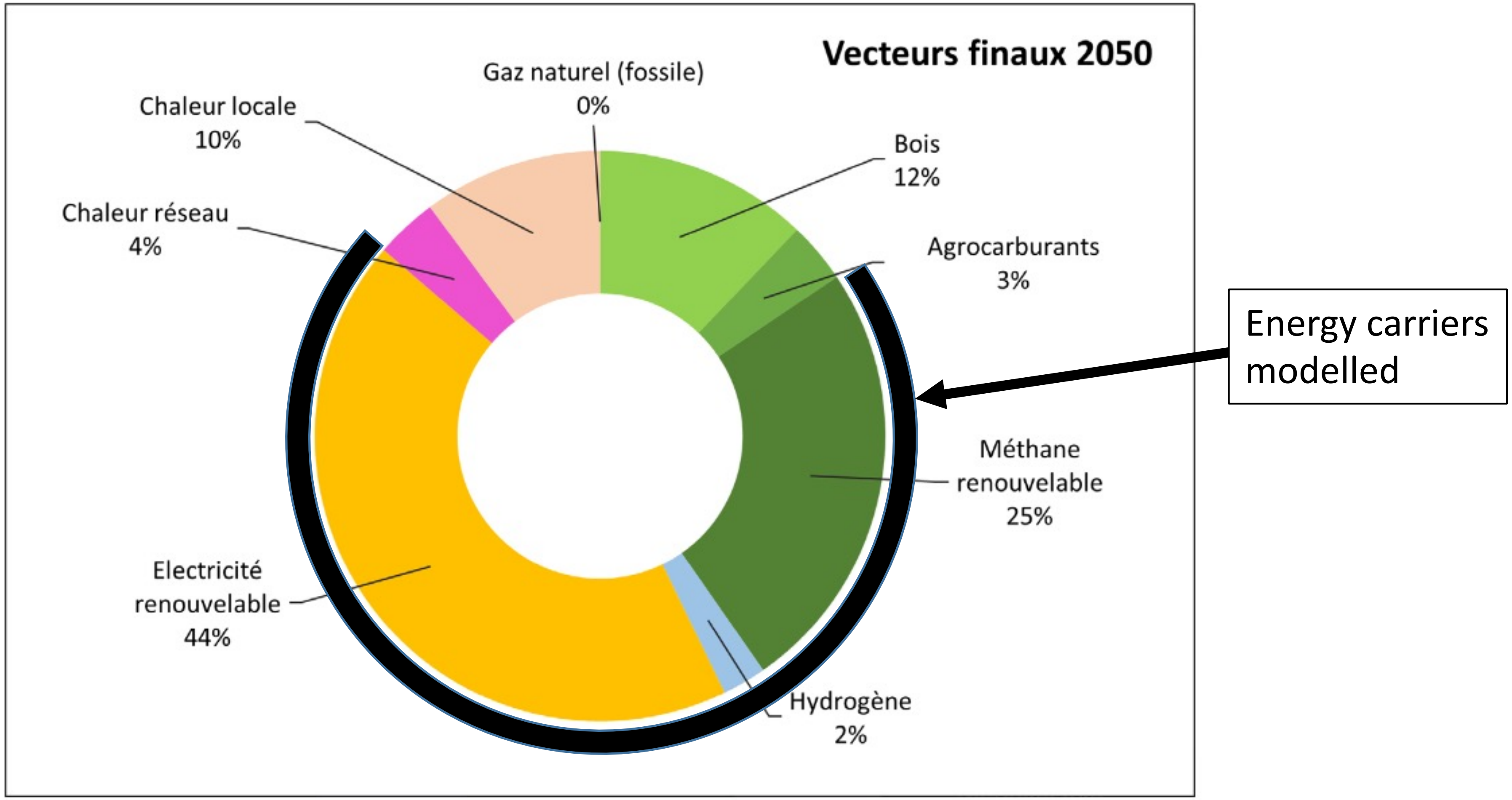
Climate neutrality by 2047 (territorial emissions) & 2050 (footprint)



Une forte décarbonation permet la neutralité carbone

La neutralité carbone atteinte en 2047

We model the supply of electricity, hydrogen, methane and (partly) heat networks



Energy carriers modelled

Figure 41 - Répartition des vecteurs finaux d'énergie (hors matières premières) en 2050 selon le scénario négaWatt

In transportation, oil is phased out thanks to:

- sufficiency
- efficiency
- fuel switch

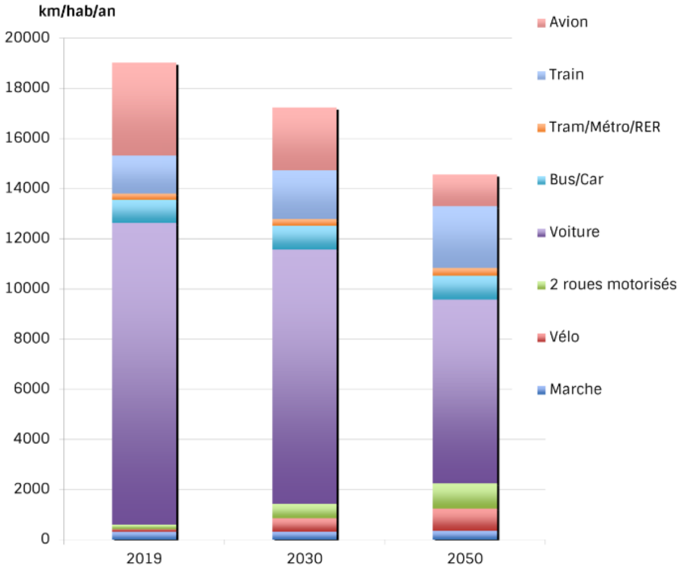


Figure 11 - Nombre de km/habitant/an par mode de déplacement dans le scénario négaWatt, en 2019, 2030 et 2050

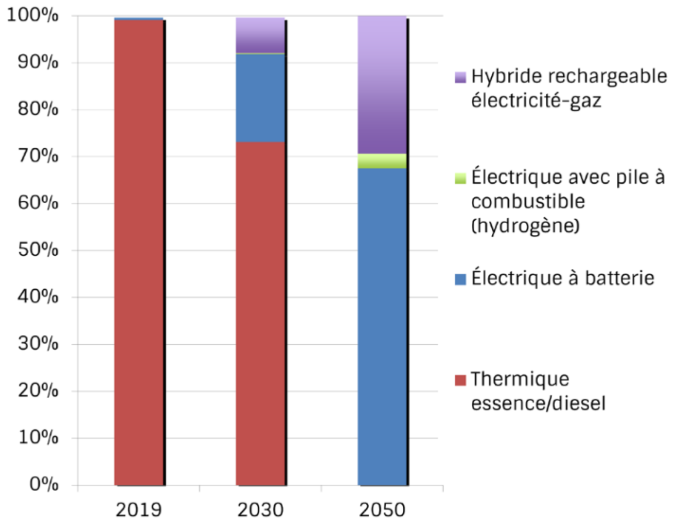


Figure 13 - Répartition des motorisations pour les véhicules particuliers (en % des véhicules.km) dans le scénario négaWatt en 2019, 2030 et 2050

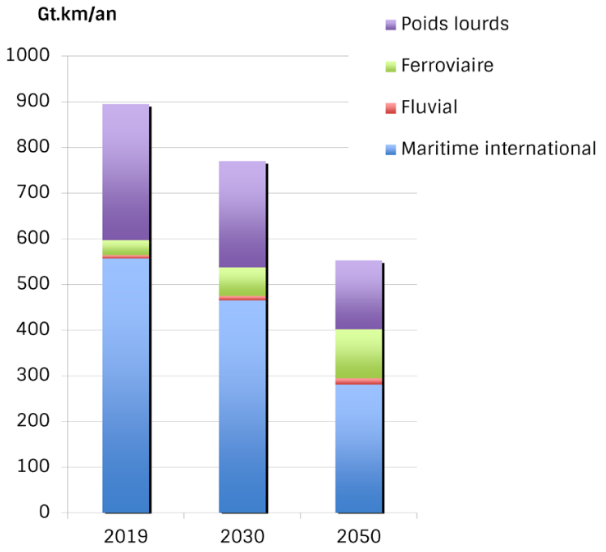


Figure 12 - Nombre de tonnes.km transportées dans le scénario négaWatt (en Gt.km) en 2019, 2030 et 2050

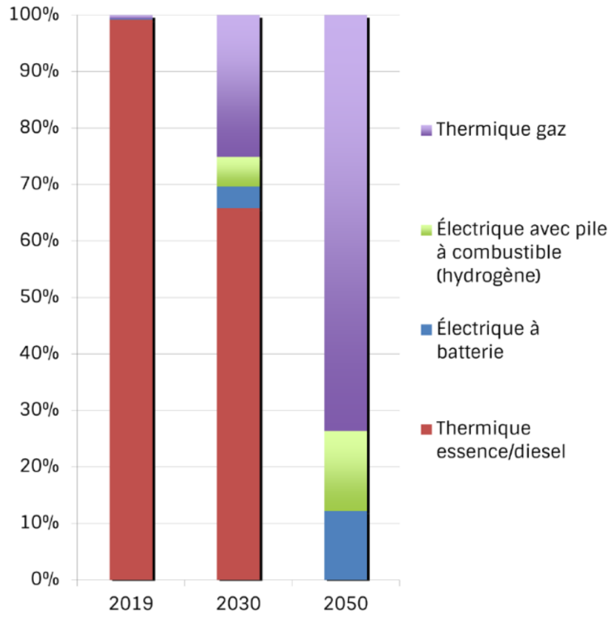
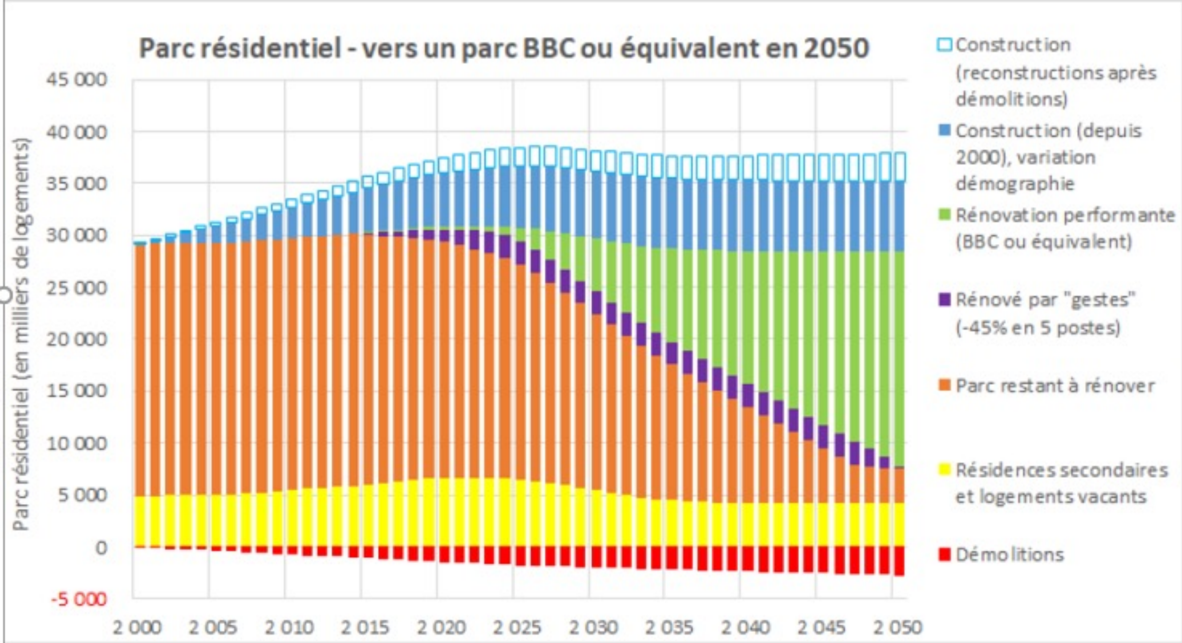


Figure 15 - Répartition des motorisations pour les poids lourds (en % des tonnes.km transportées) dans le scénario négaWatt en 2019, 2030 et 2050

Space heating: insulation and partial fuel switch



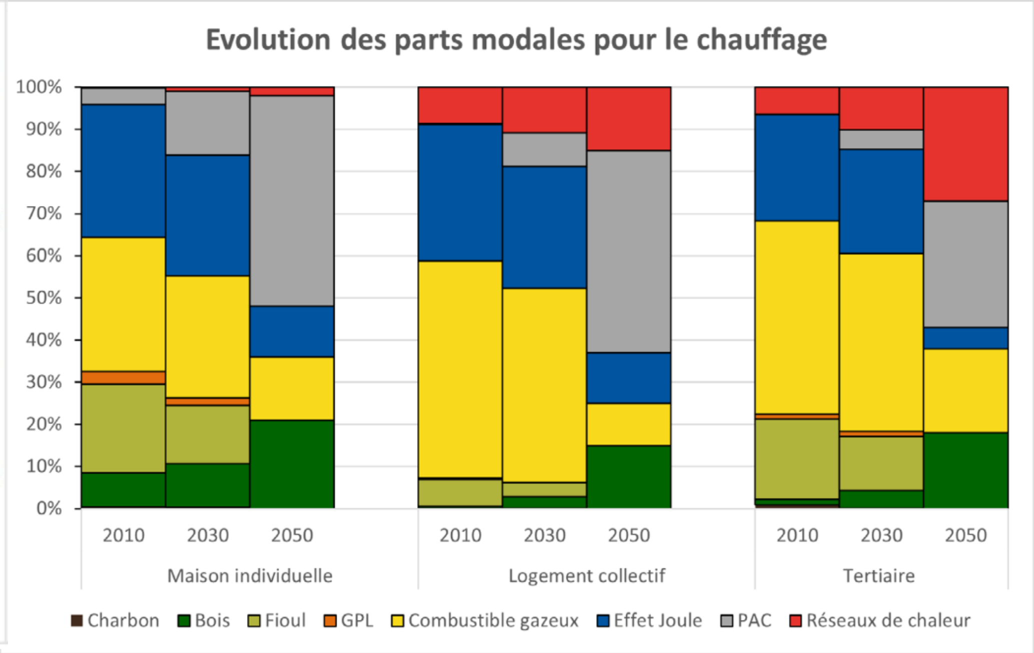
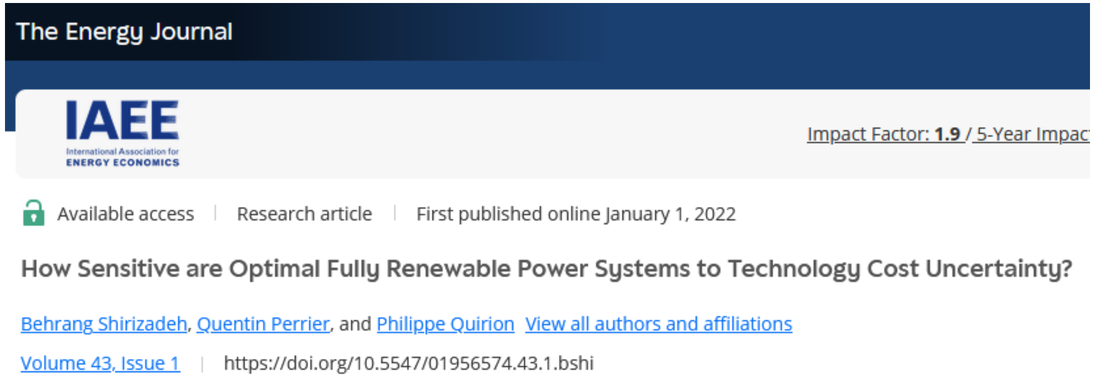


Figure 9 - Répartitions des parts modales des énergies utilisées pour le chauffage, dans le scénario négaWatt

Les graphiques détaillent la répartition des systèmes (et non les consommations d'énergie) pour les maisons individuelles, les logements collectifs et les bâtiments tertiaires en 2010, 2030 et 2050.

2. The EOLES-elec model



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IAEE International Association for ENERGY ECONOMICS

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How Sensitive are Optimal Fully Renewable Power Systems to Technology Cost Uncertainty?

Behrang Shirizadeh, Quentin Perrier, and Philippe Quirion View all authors and affiliations

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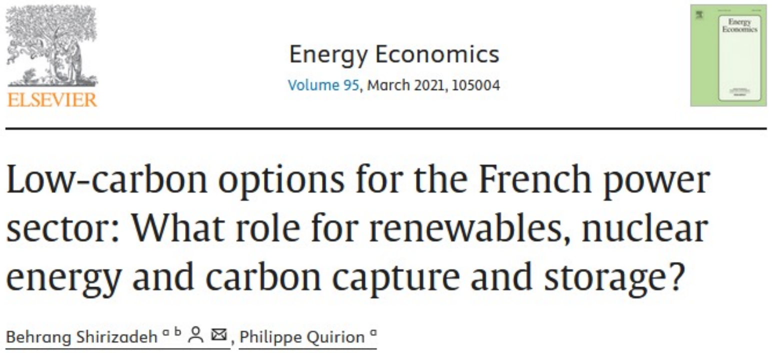


Energy Economics

Volume 95, March 2021, 105004

Low-carbon options for the French power sector: What role for renewables, nuclear energy and carbon capture and storage?

Behrang Shirizadeh [a, b], Philippe Quirion [a]

Energy

Volume 255, 15 September 2022, 124503

The importance of renewable gas in achieving carbon-neutrality: Insights from an energy system optimization model

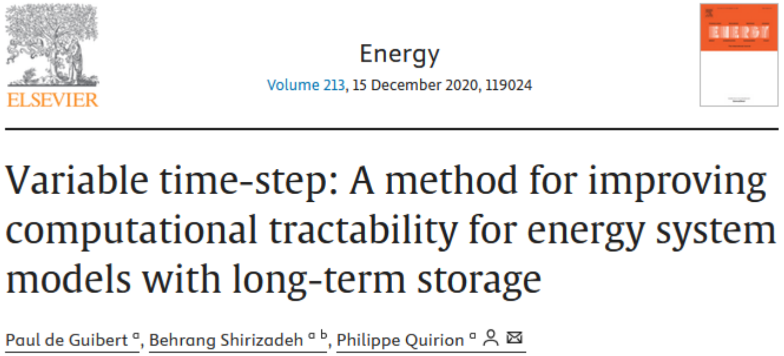
Behrang Shirizadeh [a, b], Philippe Quirion [a]

Energy Policy

Volume 181, October 2023, 113702

Long-term optimization of the hydrogen-electricity nexus in France: Green, blue, or pink hydrogen?

Behrang Shirizadeh [a, b], Philippe Quirion [a]

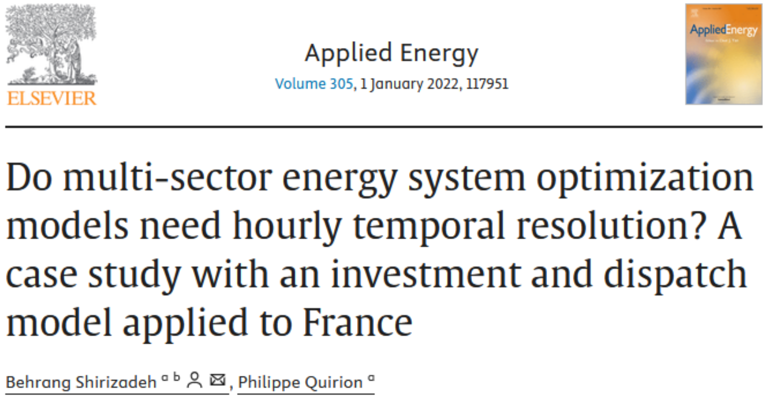


Energy

Volume 213, 15 December 2020, 119024

Variable time-step: A method for improving computational tractability for energy system models with long-term storage

Paul de Guibert [a], Behrang Shirizadeh [a, b], Philippe Quirion [a]



Applied Energy

Volume 305, 1 January 2022, 117951

Do multi-sector energy system optimization models need hourly temporal resolution? A case study with an investment and dispatch model applied to France

Behrang Shirizadeh [a, b], Philippe Quirion [a]

ENVIRONMENTAL RESEARCH
LETTERS

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How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector

Célia Escribe[5,6,1,4], Lucas Vivier[5,6,1,2], Louis-Gaëtan Giraudet[1,2] and Philippe Quirion[1,3]

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Environmental Research Letters, Volume 19, Number 5

Simultaneous optimization of dispatch and investment

$$\min_{Q_i, E_{i,t}} C(Q_i, E_{i,t}) = \sum_i fc_i Q_i + \sum_i \sum_t vc_i E_{i,t}$$

s.t. $\sum_i E_{i,t} \geq d_t$

$Q_i \geq E_{i,t}$

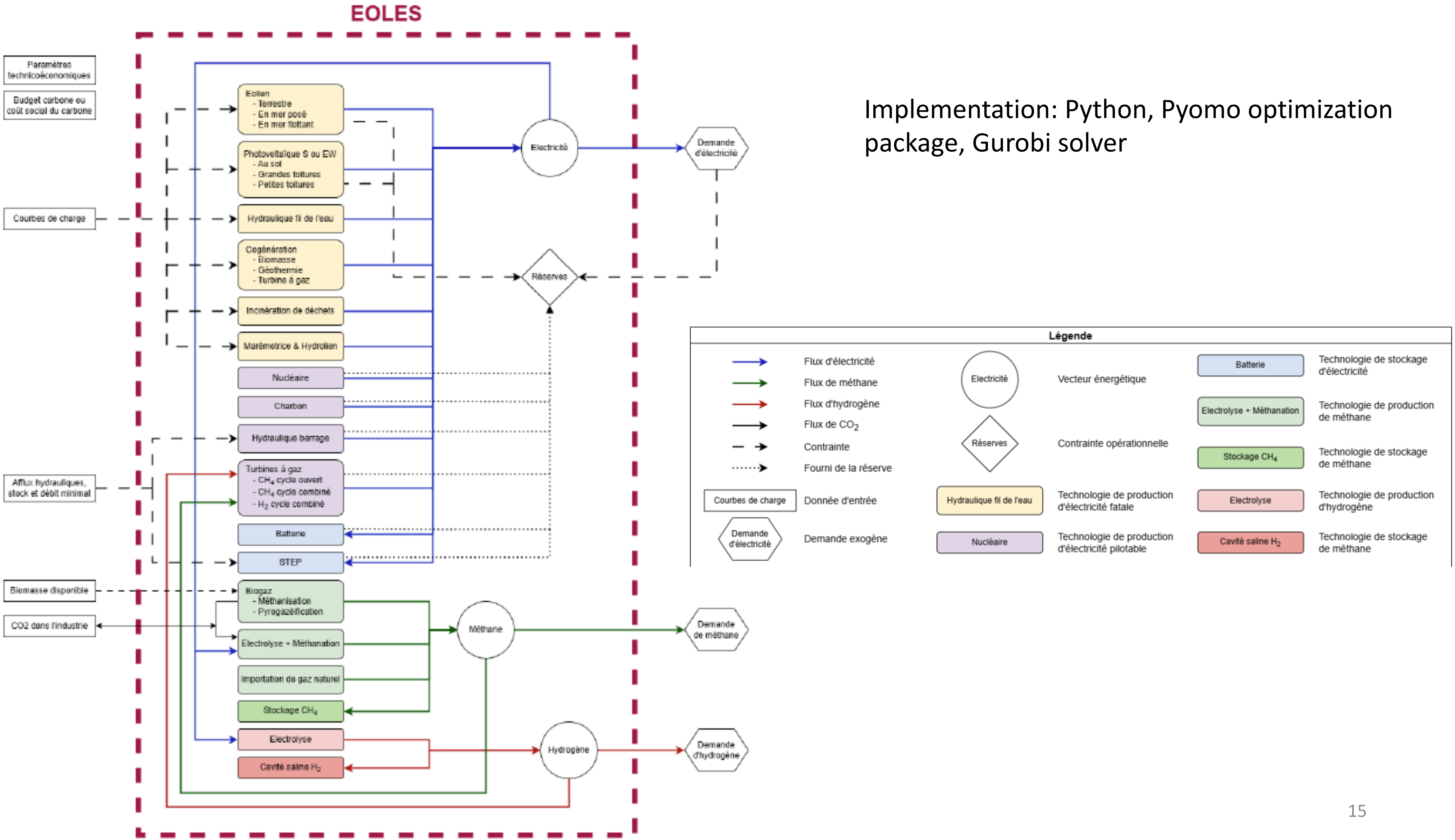
Primary and secondary reserves

Q_i = installed available capacity of technology i
$E_{i,t}$ = energy generation of technology i at hour t (can be negative for storage)
d_t = energy demand at hour t

fc_i = annualized fixed cost

vc_i = variable cost

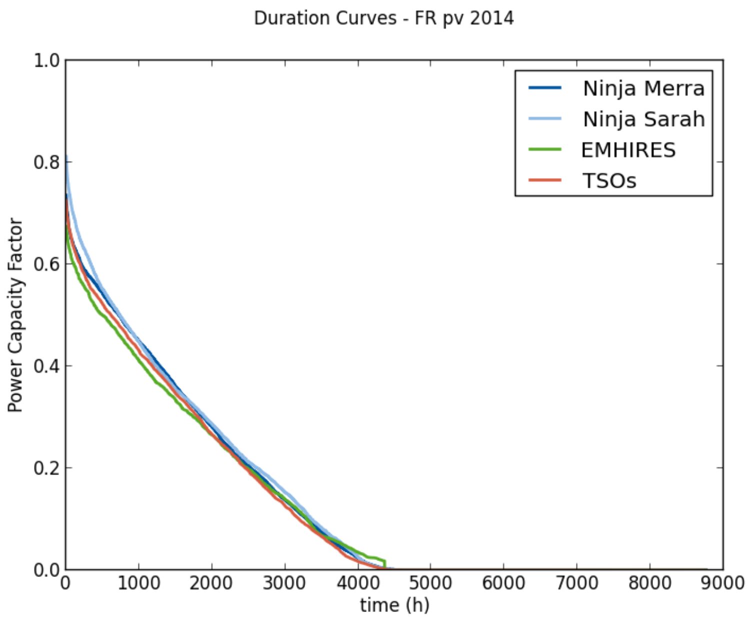
Implementation: Python, Pyomo optimization package, Gurobi solver

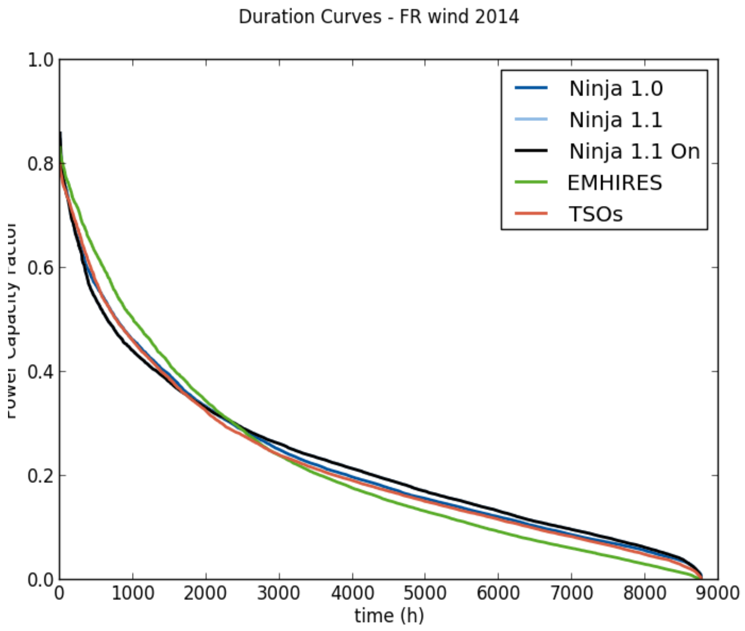


Main input data and assumptions

- Single node (continental France), no interconnection
- Inelastic demand
- Linear programming
- Full information
- Cost of capital: 4%/year
- Hourly wind and PV capacity factors: NASA MERRA-2
- Hydro: coupling with Orchidee forced by SAFRAN data (Baratgin, 2024)
- Costs & energy losses: RTE, *Futurs énergétiques 2050*, except:
  - Onshore wind : Ademe (2019)
  - Hydropower, CHP: JRC (2014, 2017)
  - Renewable gas: Ademe, JRC

Onshore wind and PV capacity factors





- Renewables.ninja
  - MERRA-2 & bias correction: Pfenninger and Staffell, *Energy*, 2016
  - Corrélation with RTE observations : 0.98 (onshore wind) & 0.97 (PV)
  - Source: Moraes et al., *Applied Energy*, 2018
- Implementation
  - Windpower curve: Vestas v110 (for onshore)
  - 19 years of hourly data (2000-2018)
  - Locations for offshore wind: projected and existing sites
  - Locations for onshore wind & PV : one site per *département*, proportional to capacity in 2017
  - Wind yearly capacity factor adjusted to *négaWatt* assumptions: 30%, 40% (fixed offshore), 45% (floating offshore)

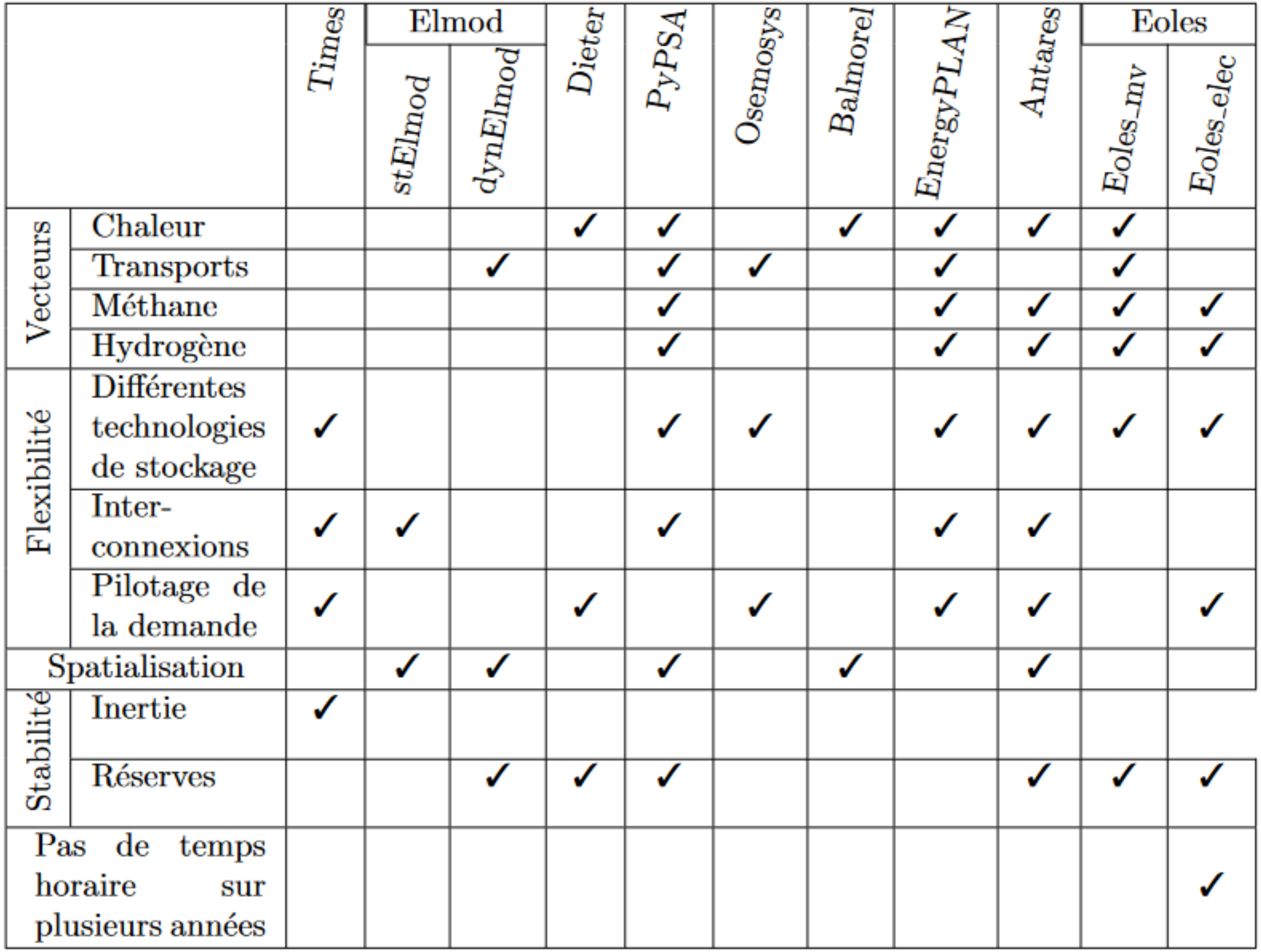
Consistency between thermo-sensitive demand, wind, PV and hydro

- Same time period (hourly, 2000-2018)
- Wind & PV: MERRA-2
- Hydro: SAFRAN
- Heating needs:
  - Total power consumption for heating: négaWatt
  - Daily profile: linear function (heating degree-days) beyond a threshold varying by *région* (Staffell et al., 2023)
  - Intra-day profile: Staffell et al. (2023)
- Cooling needs:
  - Temperature: MERRA-2 (Staffell et al., 2023)
  - Daily profile: linear function (heating degree-days) beyond a threshold, 700 MW/°C (RTE, 2020, 2024)
  - Intra-day profile: RTE (2015)

Other constraints

- Primary reserves: as today
- Secondary reserves: ENTSO-E (increases with demand, PV & wind)
- Load shifting:
  - up to 6h,
  - 7 GWh ($1.89 * 10^{-5}$ GWh per GWh of yearly demand; RTE 2022)
- CO_2 availability constraints for power-to-methane
- Biomass availability constraints
- Maximum capacities: *négaWatt* scenario

3. EOLES-elec compared to other open-source energy system optimization models



		Times	Elmod		*Dieter*	*PyPSA*	*Osemosys*	*Balmorel*	*EnergyPLAN*	*Antares*	Eoles	
			stElmod	*dynElmod*							*Eoles_mv*	*Eoles_elec*
Vecteurs	Chaleur				✓	✓		✓	✓	✓	✓	
	Transports			✓		✓	✓		✓		✓	
	Méthane					✓			✓	✓	✓	✓
	Hydrogène					✓			✓	✓	✓	✓
Flexibilité	Différentes technologies de stockage	✓				✓	✓		✓	✓	✓	✓
	Inter-connexions	✓	✓			✓			✓	✓		
	Pilotage de la demande	✓			✓		✓		✓	✓		✓
Spatialisation			✓	✓		✓		✓		✓		
Stabilité	Inertie	✓										
	Réserves			✓	✓	✓				✓	✓	✓
Pas de temps horaire sur plusieurs années												✓

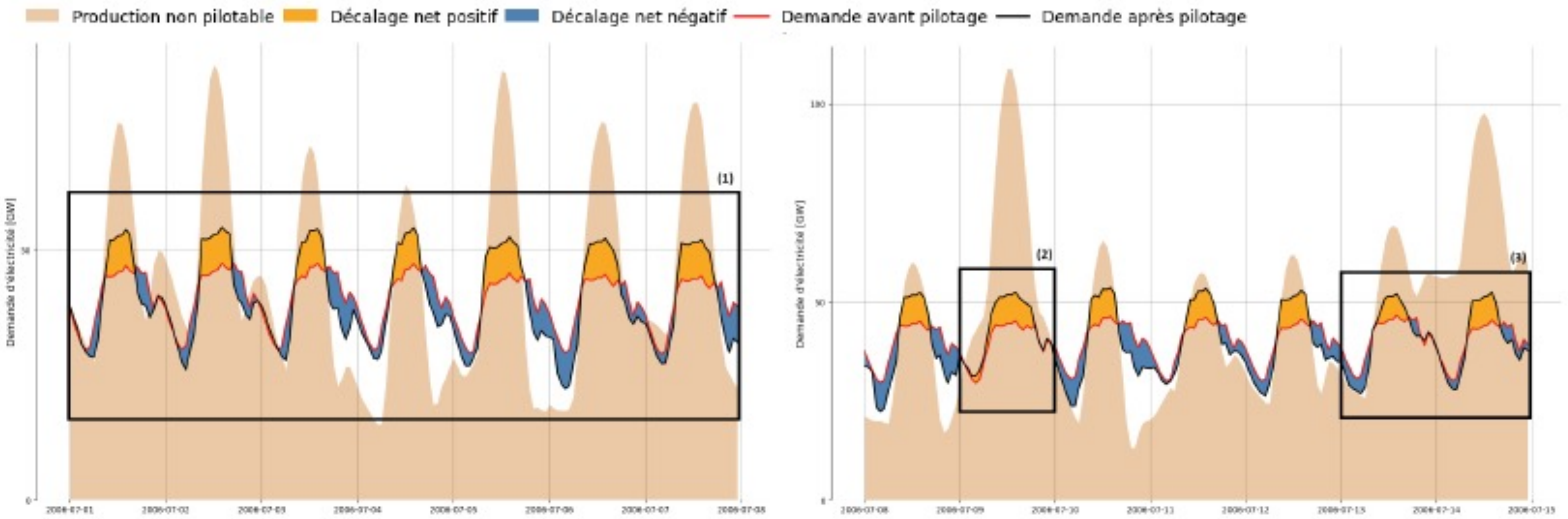
Tableau 1: Comparaison des fonctionnalités des différents modèles utilisés dans les études sur les mix énergétiques en Europe. La version de Times mentionnée est celle de Seck et al. (2020).

4. Results

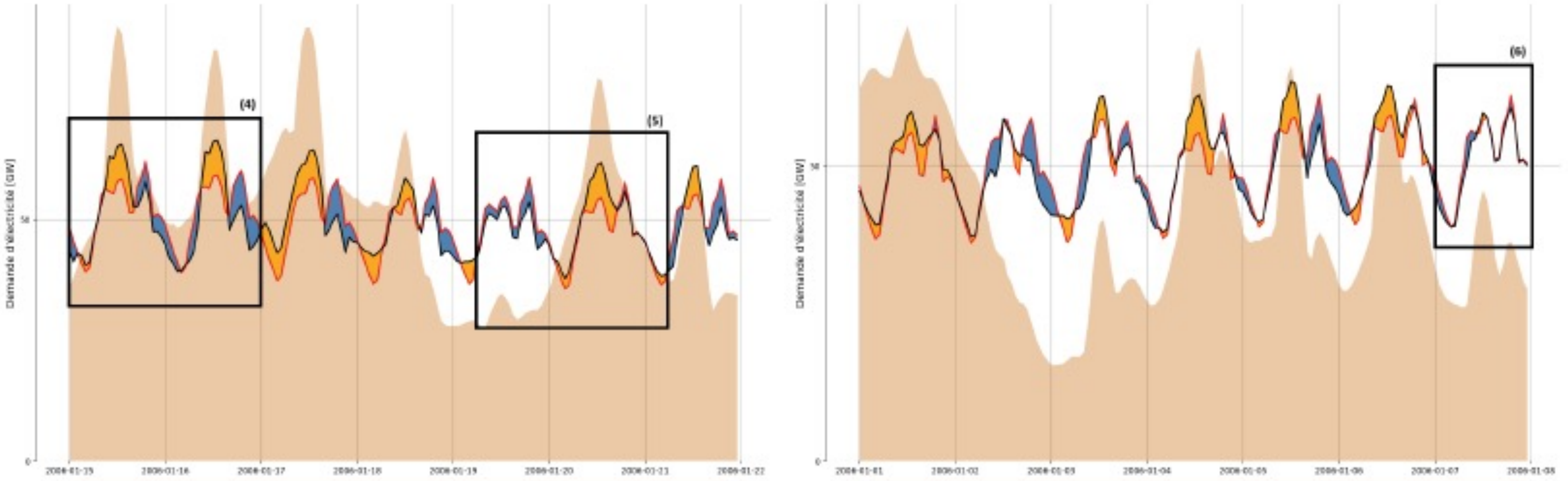
Methodology

- Demand not met at every hour → EOLES cannot run
- Inclusion of a “dummy” dispatchable technology (very costly → last resort)
- Used only 3.2h/yr. in average
- → the négaWatt scenario almost complies with the failure criterion of the Energy Code (3h/yr. in average) even without interconnections
- Adding PHS as in RTE 2022 (8.5 GW instead of 6.2) is not enough
- Comparison of four realistic variants, meeting demand every hour
  - More batteries
  - More hydrogen turbines
  - More natural gas turbines
  - Optimal mix of the three above

Load shifting



(a) Pilotage de la demande sur deux semaines typiques d'été : l'utilisation est très régulière (1), même lorsque la production est plus haute que la demande sur l'ensemble de la journée (2)(3).

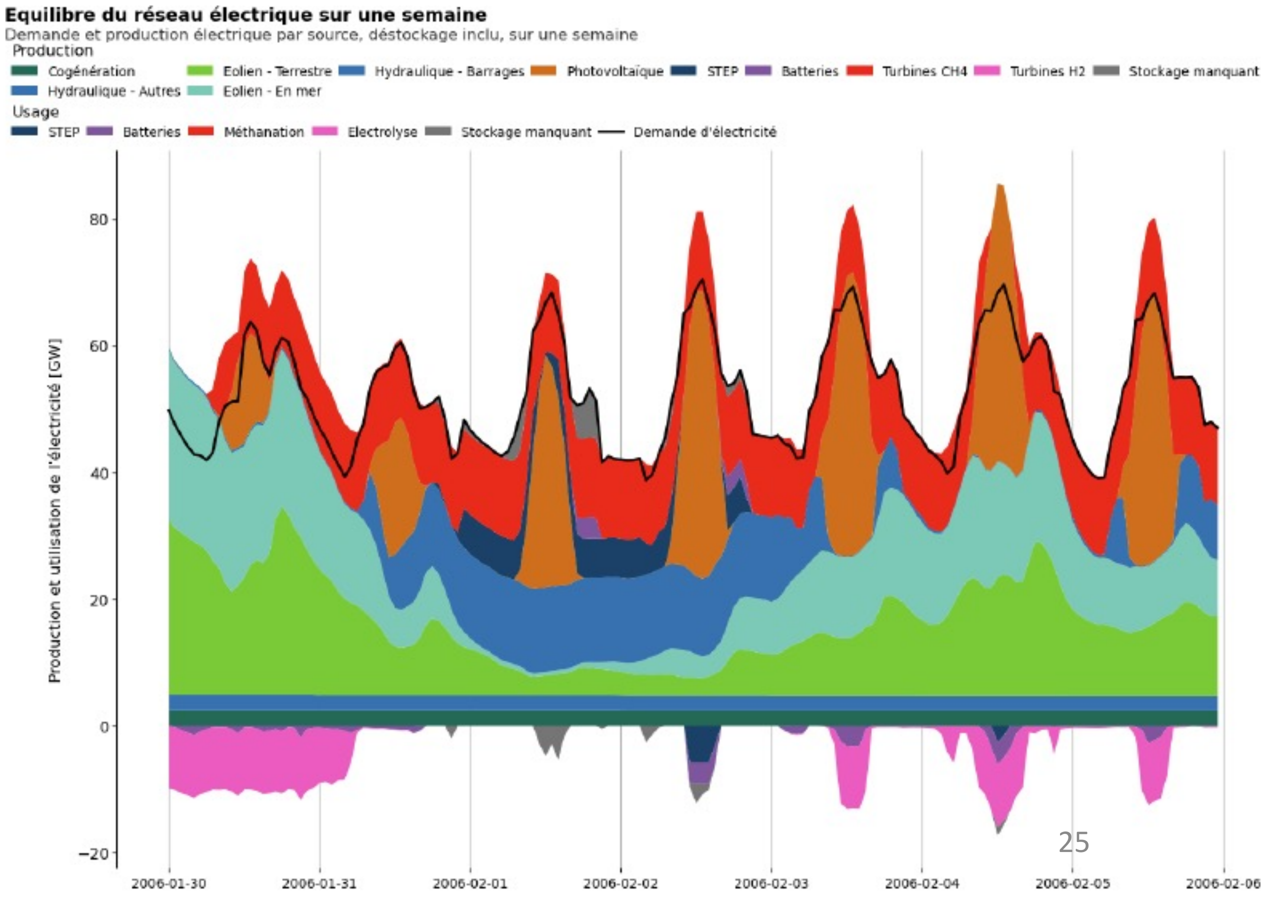


(b) Pilotage de la demande sur deux semaines typiques d'hiver : la demande est également souvent décalée vers le pic de production photovoltaïque (4), mais peut aussi être décalée d'un jour à l'autre (5) ou être peu pilotée (6).

Results with the “dummy” dispatchable technology

- Lack of dispatchable power: 7.8 GW
- Lack of reserves: 5.4 GW
- Total: 13.2 GW (+37% wrt. *négaWatt* scenario)

Week with the largest use of the dummy tech. (Jan–Feb 2006) →



Comparison of 4 realistic variants, meeting demand every hour

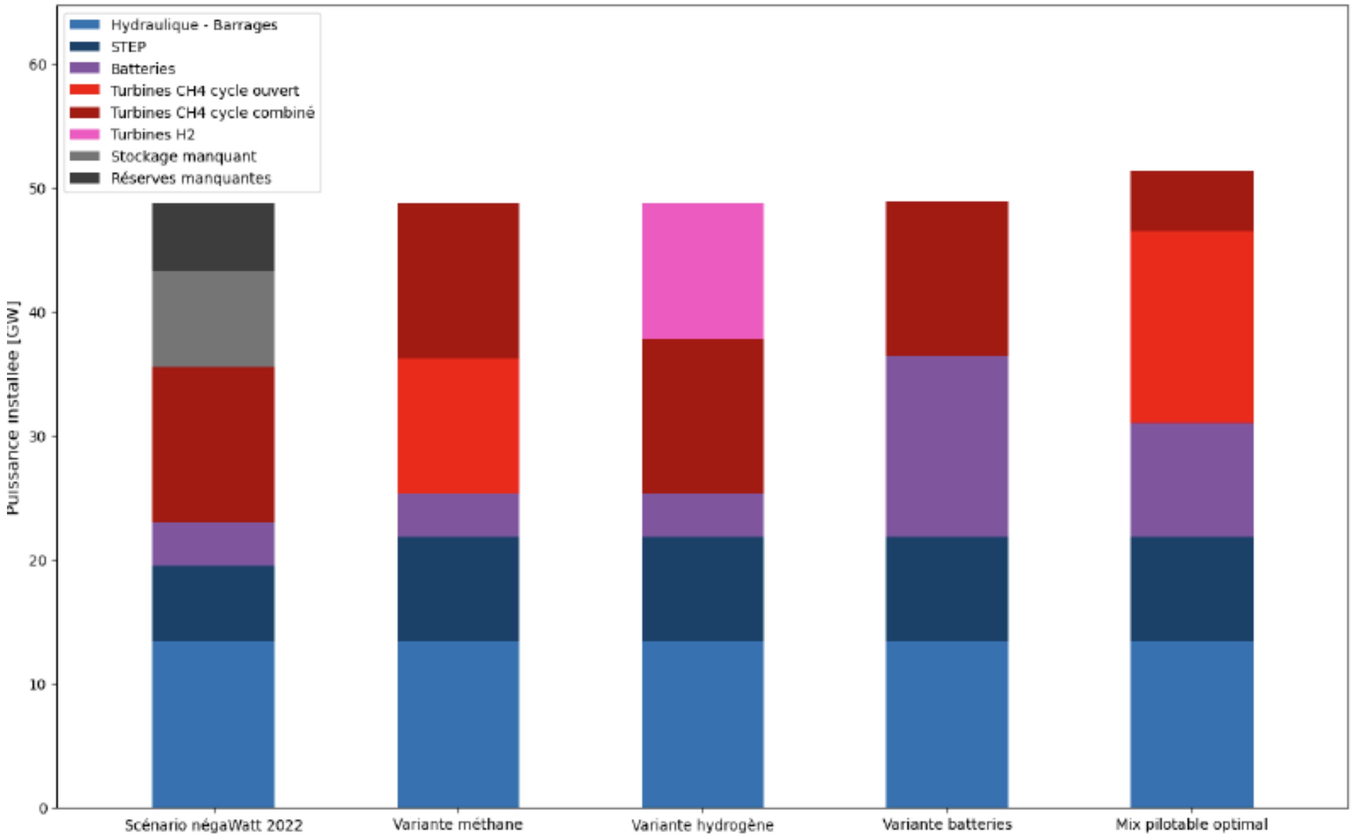
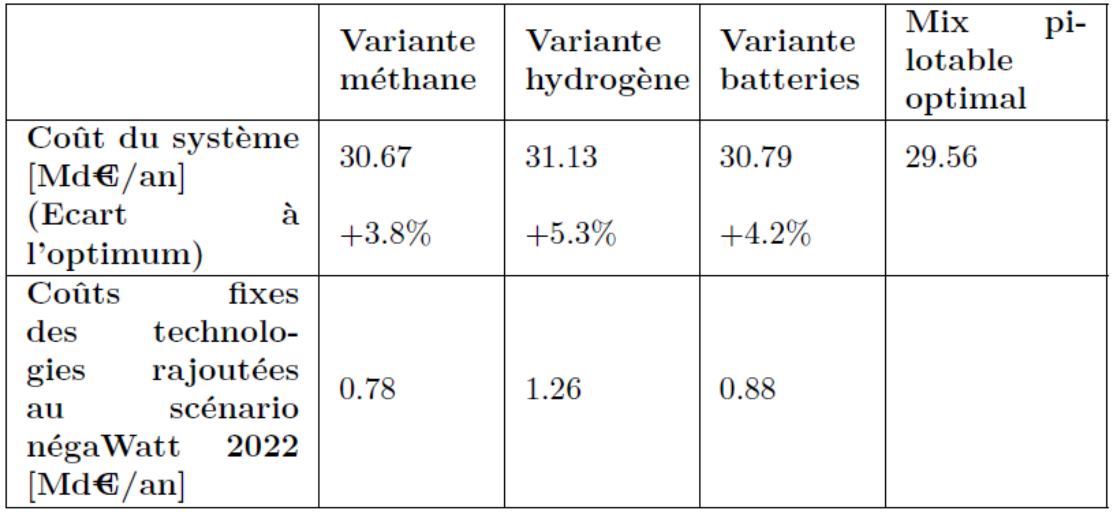


Figure 4: Comparaison de la partie pilotable des différents mix énergétiques



	Variante méthane	Variante hydrogène	Variante batteries	Mix pilotable optimal
Coût du système [Md€/an] (Ecart à l'optimum)	30.67 +3.8%	31.13 +5.3%	30.79 +4.2%	29.56
Coûts fixes des technologies rajoutées au scénario négaWatt 2022 [Md€/an]	0.78	1.26	0.88	

Tableau 4: Comparaison des coûts des différentes variantes entre elles et avec le mix pilotable optimal

Optimal mix:
112 GW of PV vs. 138 GW in the *négaWatt* scenario
Reserves: ½ Batteries & PHS
→ 5.5 bn. €/yr. saved

Methane variant: +2 TWh of pyrogasefication

5. Algorithm choice and computational speed

Interior point : much faster for sparse and degenerate problems, but midface solution
Vs.
Simplex : provides a basic solution, better for dense problems

Gurobi choses interior point for our problem

A crossover step after the interior point method allows to recover a basic solution …

	Barrier (Interior point)	+ crossover
Solution	Midface	Basic
Approximate computational time for 5 year at hourly resolution	700s	1600s
Approximate computational time for 19 years at hourly resolution	2-3 hours (~25 MegaBytes, 3 cores, Intel Xeon Gold 6130 CPU @ 2.10GHz)	> 6 days

… but it is not worth the cost !

6. Conclusion and discussion

- The *négaWatt* scenario ensures security of supply, as defined by the Energy Code
- PV could be reduced from 138 to 112 GW
- Is it worth adding 13 GW of dispatchable power to avoid 3h/yr. of failure without interconnections?
  - In my opinion: no
- Limits
  - Final electricity demand of the *négaWatt* scenario: realistic?
    - Detailed bottom-up modelling
    - But electrification lower than in other scenarios
    - Difficult to forecast power consumption from air conditioning
  - No modelling of inertia
    - But “20 to 30% of wind and photovoltaic capacity inverters with grid-forming capabilities are sufficient to maintain frequency stability” (RTE 2020)
  - No modelling of the electricity transportation and distribution grids
  - No modelling of interconnection (would allow installing less capacities or electrify more)

Thanks for your attention

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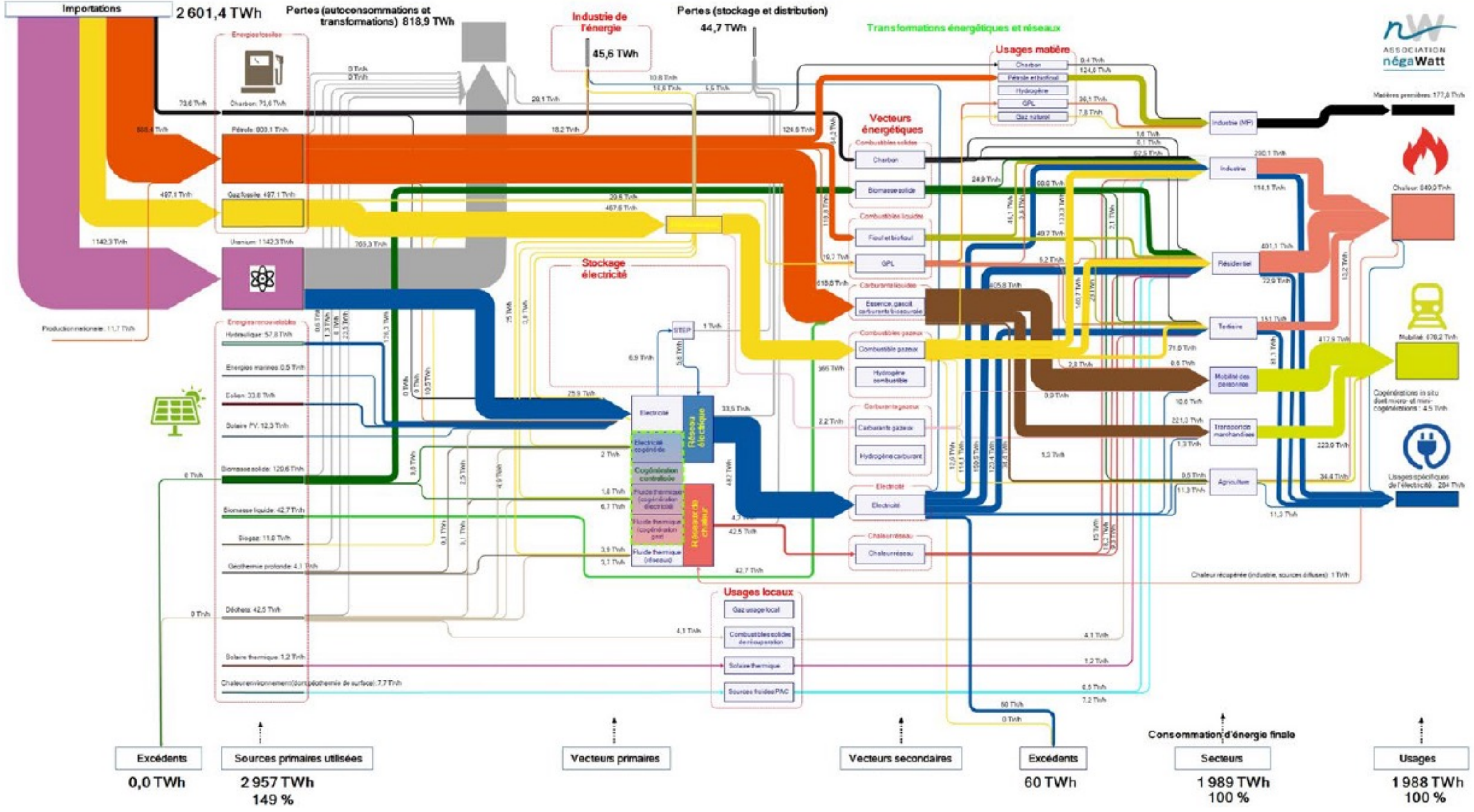
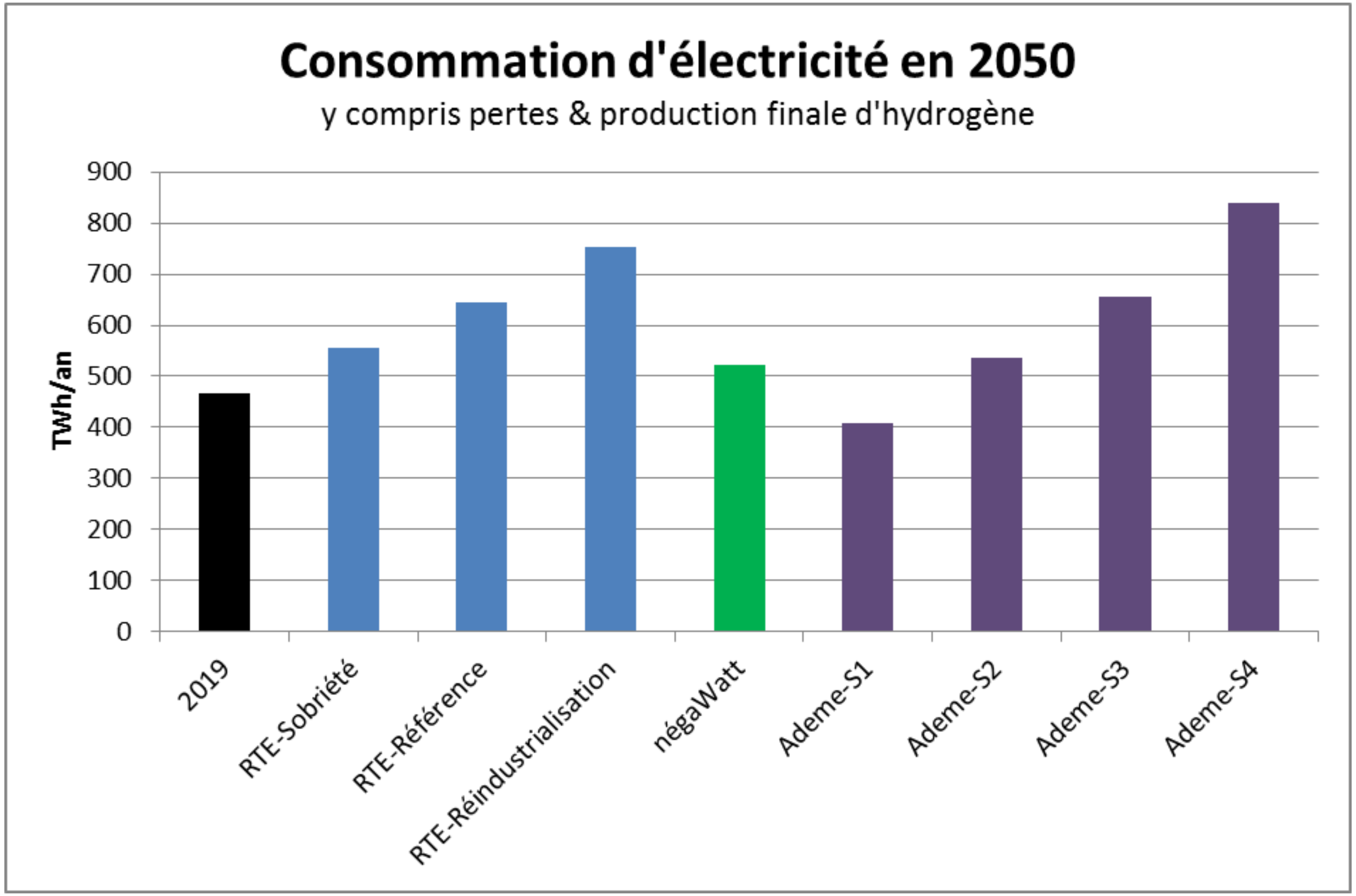
https://www.negawatt.org/en
https://www.centre-cired.fr/the-eoles-family-of-models
https://github.com/CIRED/EOLES
https://www.centre-cired.fr/philippe-quirion/

Reserve

Bilan énergie France 2019





Consommation d'électricité en 2050

y compris pertes & production finale d'hydrogène

Catégories modélisées	Sous-catégories
Réfrigérateurs	Combinés & 2 portes - 1 porte - Américain
Congélateurs	Congélateurs coffres - Congélateurs armoires
Lave-linge	
Sèche-linge	
Lave-vaisselle	Modèles standards - Petits modèles (45 cm)
Aspirateurs	Aspirateurs traîneaux - Aspirateurs balais Aspirateurs robots
Fours	Fours encastrés - Fours de cuisinières Mini-fours
Micro-ondes	
Plaques de cuisson	Plaques indépendantes - Plaques de cuisinières
Petits appareils de cuisine	Cafetières & bouilloires - Cuiseurs spéciaux Hottes
Téléviseurs	TV principales - TV secondaires
Ordinateurs	Fixes & moniteurs - Portables
Box & décodeurs	Box internet - Box TV - Autres décodeurs
Consoles de jeux	
Ventilations	VMC simple flux - VMC double flux
Circulateurs de chaudière	
Sources d'éclairage	Ampoules - Spots - Ampoules décoratives

Tableau 2 - Les 17 catégories d'appareils électriques modélisées dans le scénario négaWatt

Entre 2015 et 2050, la durée de vie moyenne de la plupart des appareils électroménagers et électroniques augmente de plusieurs années, et la consommation d'électricité de l'ensemble des appareils résidentiels et tertiaires installés en France est réduite de 38 %.

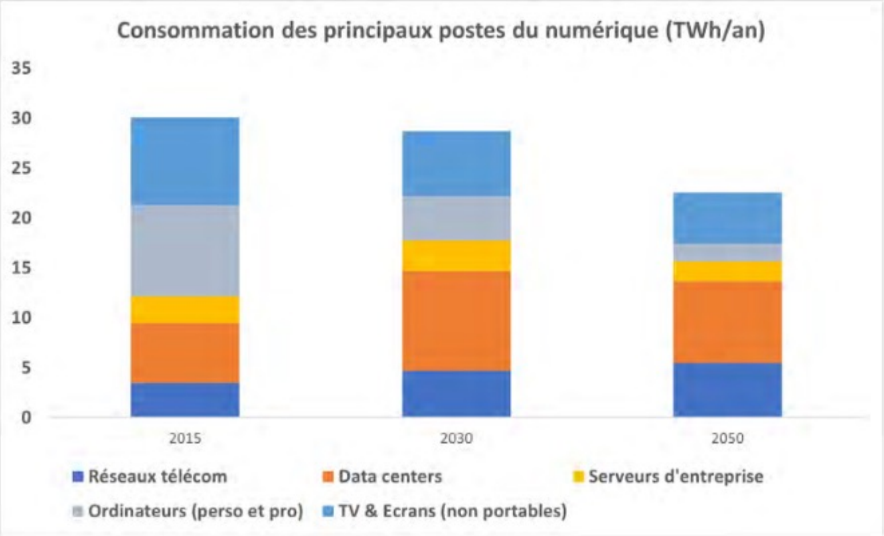
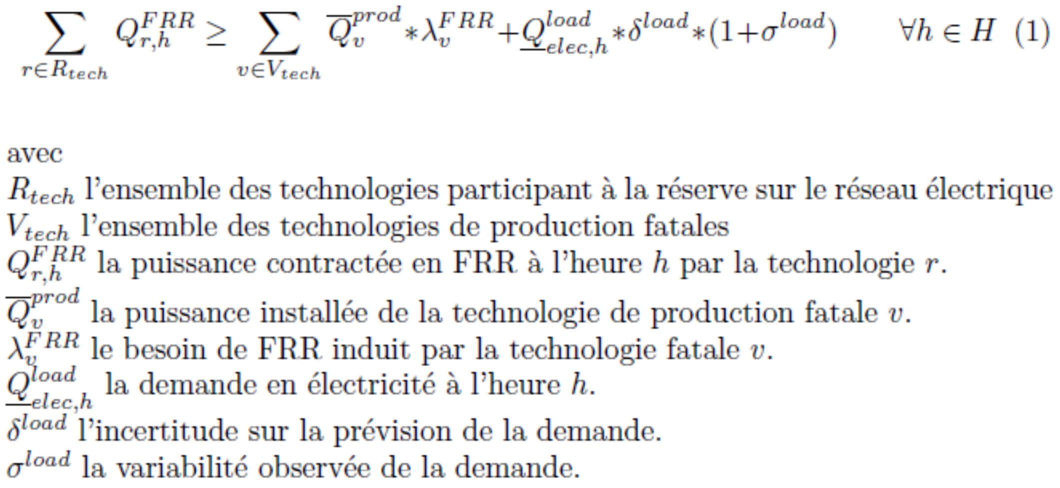


Figure 16 - Consommation des principaux postes du numérique[33] *dans le scénario négaWatt en 2015, 2030 et 2050*

Secondary reserves (FRR)



$$\sum_{r \in R_{tech}} Q^{FRR}_{r,h} \geq \sum_{v \in V_{tech}} \overline{Q}^{prod}_{v} * \lambda^{FRR}_{v} + \underline{Q}^{load}_{elec,h} * \delta^{load} * (1 + \sigma^{load}) \qquad \forall h \in H \quad (1)$$

avec

R_{tech} l'ensemble des technologies participant à la réserve sur le réseau électrique

V_{tech} l'ensemble des technologies de production fatales

$Q^{FRR}_{r,h}$ la puissance contractée en FRR à l'heure h par la technologie r.

$\overline{Q}^{prod}_{v}$ la puissance installée de la technologie de production fatale v.

λ^{FRR}_{v} le besoin de FRR induit par la technologie fatale v.

$\underline{Q}^{load}_{elec,h}$ la demande en électricité à l'heure h.

δ^{load} l'incertitude sur la prévision de la demande.

σ^{load} la variabilité observée de la demande.