Boundary conditions for energy transition scenarios

Technical file #3 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

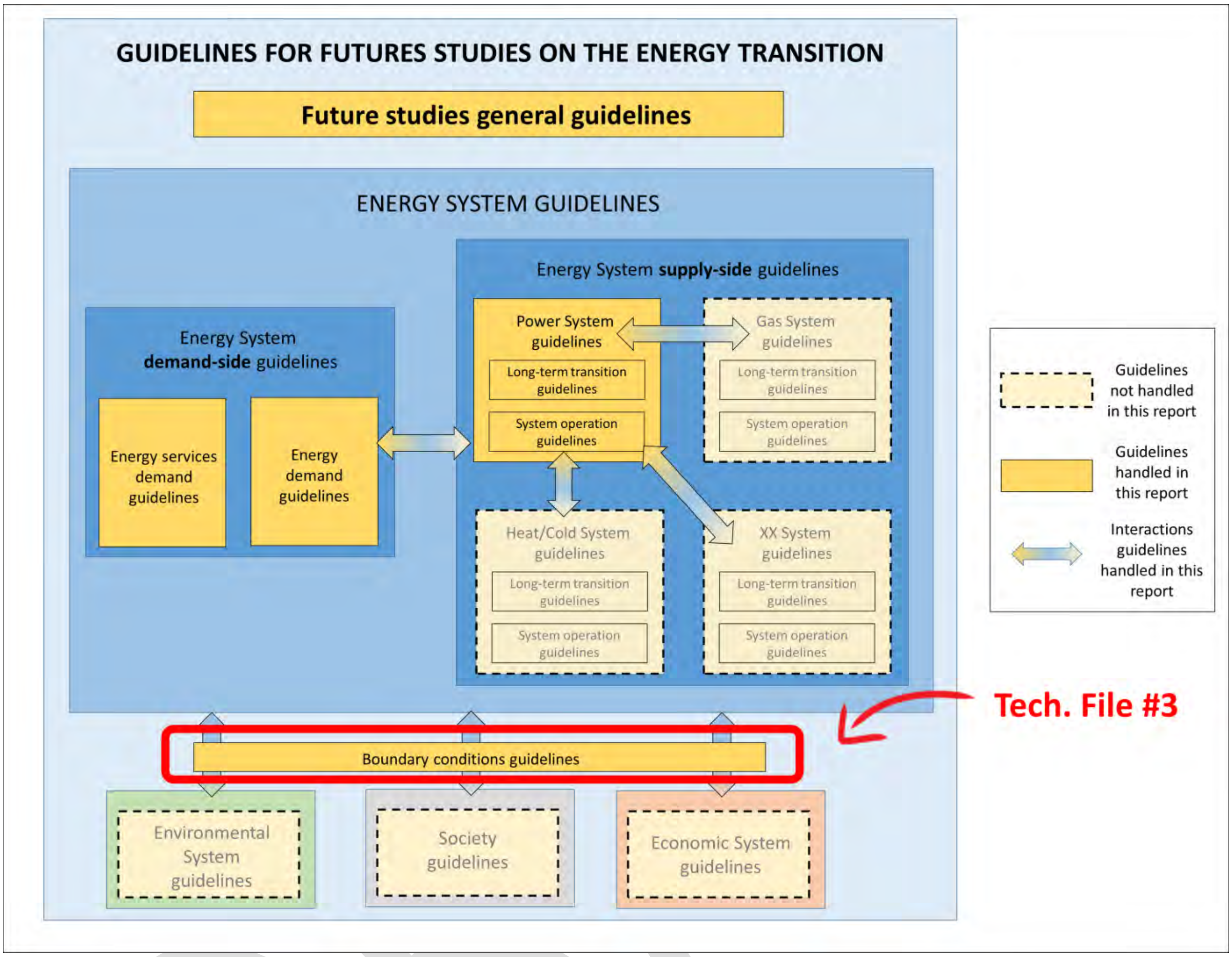
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Boundary conditions: what modeled actors cannot, or are not willing to modify

A. Boundary conditions depend on the perimeter of the considered system and on the chosen model

The notion of boundary condition is linked to what the energy system actors which are modelled cannot, or are not willing to, modify (Samadi et al., 2017). For example:

- Oil prices for Europe cannot be modified by modelled actors.
- European actors are not willing to act on demography.
- Political objectives or measures are seen as boundary conditions. Indeed, the studies within our scope are addressed to policy-makers, hence policy-makers are not included in the modelled system. Instead, their possible decisions (when considered in studies) are exogenous hypotheses which are imposed on the modelled system.

Boundary conditions are usually part of the storyline before being derived as exogenous hypotheses.

More technically, boundary conditions are the conditions which are imposed on the considered system (either the entire energy system (ES) or the power system (PS)) and which partly drive its behavior.

Of course, systems outside the perimeter and interacting with the modelled system (such as other energy sub-systems if the studied system is power system) are parts of boundary conditions.

1. The energy system can be broken down by energy carrier and by supply or demand-side

The energy system is composed of several subsystems, which can be separated by the *carrier* they produce, transport and consume (electricity, gas, hydrogen, oil, heat, etc). Each of these subsystems is composed of a *supply-side system* and a *demand-side system*. These different subsystems interact with each other, directly (supply-side interactions) or indirectly (demand-side interactions). On Figure 1, each carrier is represented with a different color and a few supply-side interactions are represented.

The supply-side system ranges from the production or import point down to the point before end-consumption of the carrier, or before transformation; it includes self-production (e.g. from roof solar panels) and storage systems (e.g. pumped hydro storage, or batteries).

The demand-side system is composed of the set of equipment, appliances or industrial processes consuming the carrier[1]. For example, washing machines, cars, trucks, industrial processes, heating systems and so on are included in the demand-side system.

[1] Physically speaking, consumption corresponds to the transformation of the energy carrier into useful energy (such as movement, light…) and heat.

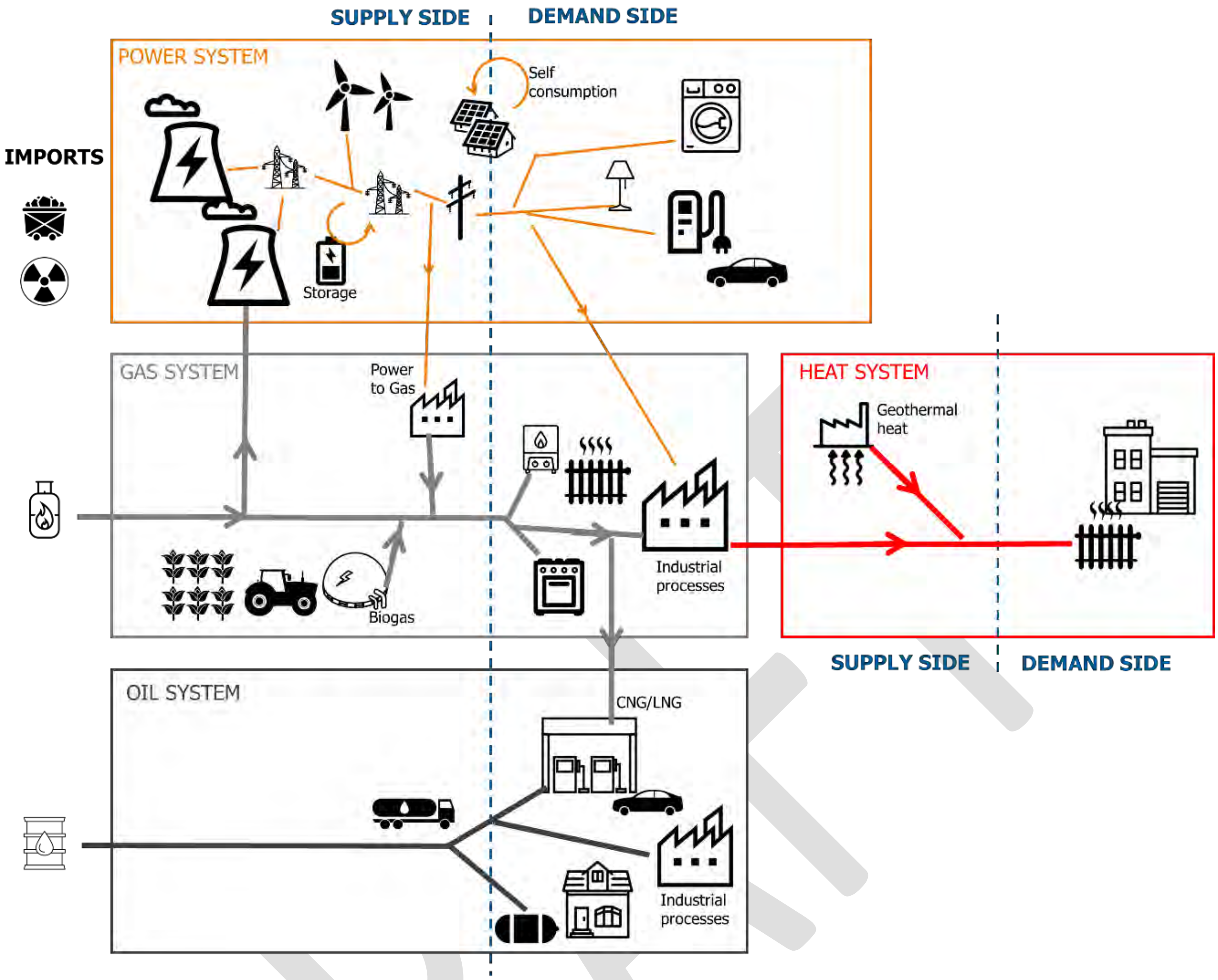

Figure 1: Simplified description of the energy system to illustrate what we call energy subsystems (the power system, the oil system and so on) and the distinction between supply-side and demand-side for each energy subsystem. Not all the energy subsystems are represented (hydrogen, coal, nuclear and so on could be represented), and no hierarchy between the subsystems is assumed here. Some interactions between the subsystems are represented, but not all of them.

2. Boundary conditions **of the studied system depend on… the studied system**

As shown in Figure 2, scenarios assume the energy system (ES) evolution is driven by several types of boundary conditions. In future studies, the most usual boundary conditions are the following:

- lifestyles and behaviors, which impact energy demand and may impact the whole energy system development through desirability issues (see desirability section);
- technologies and their evolutions impact both demand (more efficient fridges or cars…) and supply (larger wind turbines, more flexible nuclear plants, operational large-scale Carbon Capture and Storage…);
- demography impacts demand level, as well as lifestyle trends through age structure;
- macroeconomic situation, such as GDP, provides information about the overall size of the economy in which the transition happens;
- industrial offshoring pattern or, conversely, industrial activity increase impacts demand level;
- policy framework(s), through taxation and public investments, regulations, standards and social objectives may impact the whole energy system in different fashions;
- prices of imported goods and materials may impact both demand-side and supply-side systems because it impacts both demand-side and supply-sides technologies prices. Similarly, prices of imported fuels (mainly coal, gas, oil, uranium) impact both the demand-side (impacts on the prices of internal

combustion engine (ICE) car use, of gas heating…) and supply-side (especially for the PS) through variations in the prices of fuels feeding power plants;

- availability of local resources such as renewable energies impact the supply-side capability to fulfill energy demand with renewables.

When studies focus on the PS, they add direct boundary conditions to the PS: those posed by the interactions with other energy subsystems.

Such interactions can happen on the supply-side, corresponding to energy transformations from one carrier to another one. They can also happen on the demand-side, corresponding to carrier shift through technology shift when several technologies associated with different carriers compete for providing the same energy service (such as mobility, which can be performed through electricity carrier, oil carrier, gas carrier, or hydrogen carrier).

The evolution within those different energy carriers are also driven by the ES boundary conditions. Hence, in a way, ES boundary conditions affect the PS both directly (for example, lifestyles changes can directly impact the PS evolution) and indirectly (for example, very cheap gas imports may lead to increase gas use in heating at the expense of electricity).

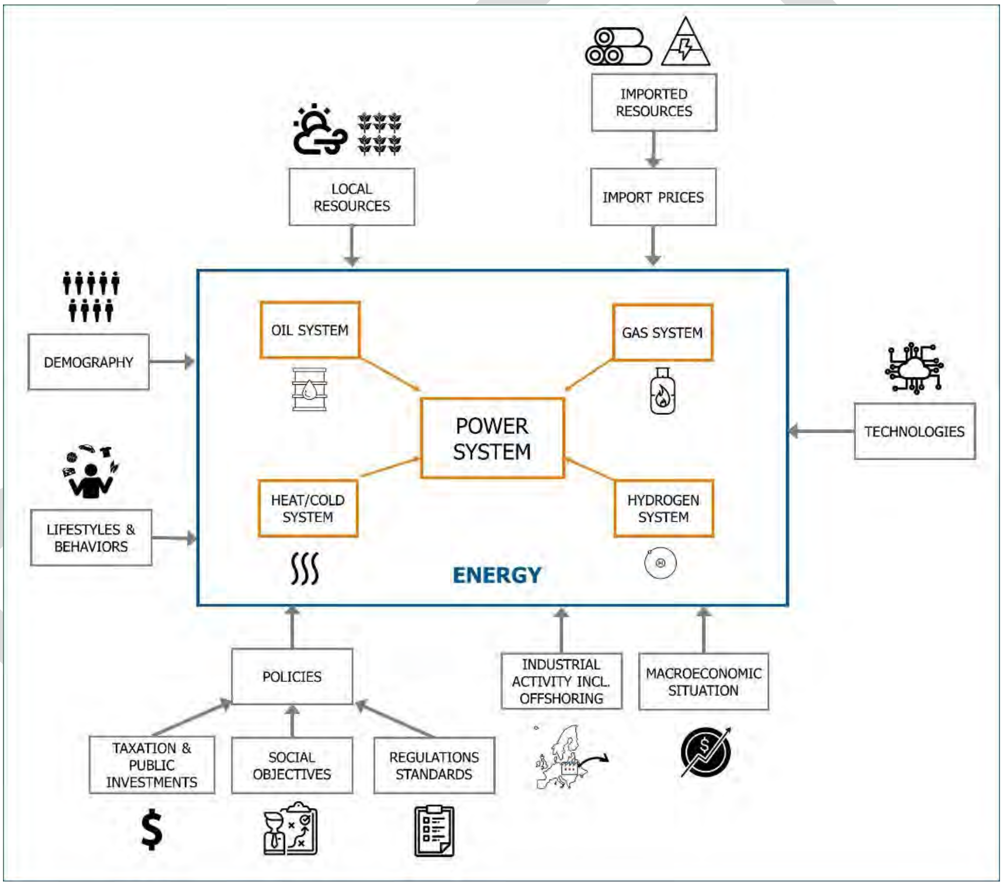

Figure 2: The usual boundary conditions for the energy system and the power system in future studies.

3. Boundary conditions are driven by the model used

As previously described, conceptually speaking boundary conditions are what simulated agents cannot, or are not willing to modify. Simulated agents are actors driving the energy mix and simulated in the model[2]. Hence the notion of boundary condition is tightly linked to that of models. Boundary conditions are translated in models into what we called "exogenous variables and parameters" (see future studies). Within a scenario, each exogenous variable and parameter is set to a given trajectory which is imposed to the simulated agents by the modeler. However, across scenarios within a future study, those variable parameters can take different trajectories so as to show the

[2] Note that even optimization models can be considered as simulating a benevolent planner which would be able to drive the energy system by its only will.

effects of setting them differently. A boundary condition is a hypothesis that the model requires in order to run properly.

As studies do not use the same models, the nature of these variables differs across studies.

Typically, benevolent planner models of the power supply-side (such as the one used by (ADEME, 2015; ADEME / Artelys, 2018; ECF, 2010; Lappeenranta University of Technology / Energy Watch Group, 2017)) require boundary conditions on the following aspects of the transition: power demand evolution (consumption due to lifestyles and behaviors, as well as consumption from industrial processes within the geographical perimeter, both depending on demographics), available technologies, evolution of their technical characteristics and prices, fuel prices, available local resources, interconnections with neighbor regions, and social objectives the benevolent planner wants to achieve (such as reducing CO_2 emissions down to a given level, or minimizing the cost of the supply-side transition).

Benevolent planner models for the whole energy system (such as (ADEME, 2012; Association négaWatt, 2014; Association négaWatt, 2017; Fraunhofer ISE, 2015)) require the same type of hypotheses but applied to the whole energy system.

Simulated agents models (such as (DGEC/CGDD/ADEME, 2015; OECD/IEA, 2017; RTE, 2017) and all studies using PRIMES model, such as (European Commission, 2011; European Commission, 2016; SFEN, 2018)) require hypotheses about the political frame and political objectives, about the available technologies, the evolution of their technical characteristics and prices, the prices of fuels, and macroeconomic situation, such as GDP evolution (which actually translates largely unspoken hypotheses about global constraints on the economic system).

Note that lifestyles and behaviors evolutions are not a boundary condition for simulated agents' models because they model them by assuming they are ultimately determined by the political frame and objectives. In other words, they have *endogenized* lifestyles and behaviors by modeling them, generally through elasticities to price (see Figure 3).

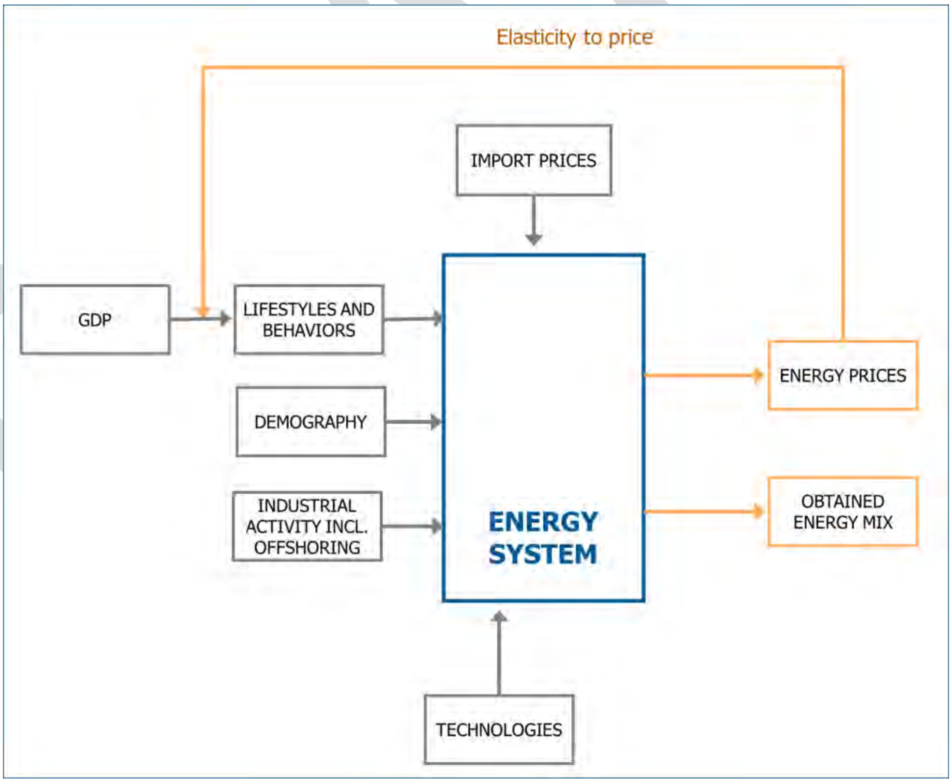

Figure 3: Illustration of the endogenization of lifestyles and behaviors.

Similarly, some models require as input the characteristics of each technology year after year whereas some others endogenize a part of the evolution by assuming a learning effect (see Figure 4). In this case, the boundary condition is one of learning effect parametrization (the technical and cost improvements with every doubling of the production, for instance).

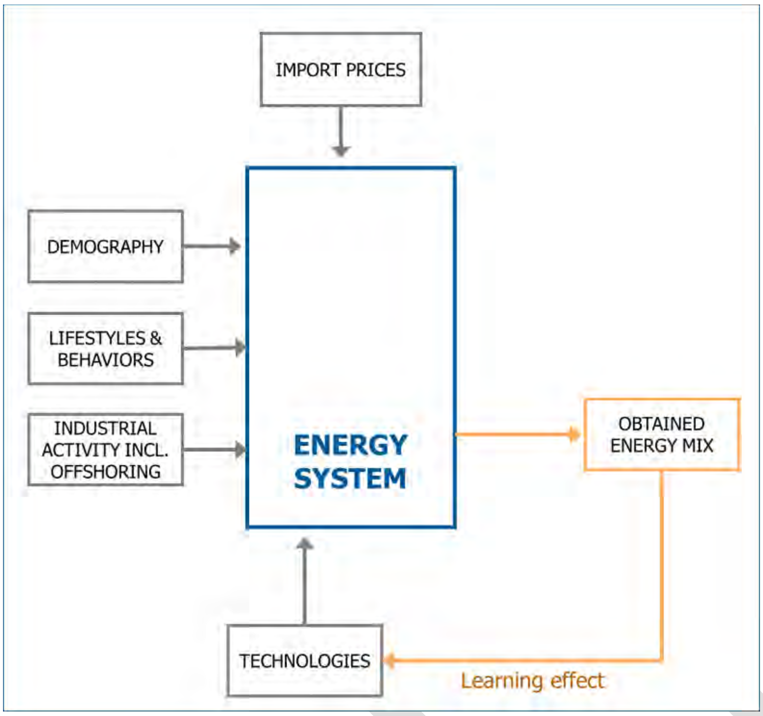

Figure 4: Illustration of the endogenization of the learning effect of technologies.

A very few models endogenized the effects of some planetary boundaries, or of the financial sector. (Bovari, Giraud, & Mc Isaac, 2018) modeled the climate change feedback on the economy through different damage functions (see Figure 5) and modeled the financial sector through a stock-flow consistent monetary macrodynamics. (Donella H. Meadows, Randers, & Meadows, 2004) modeled the feedback loops between different planetary boundaries and the economy.

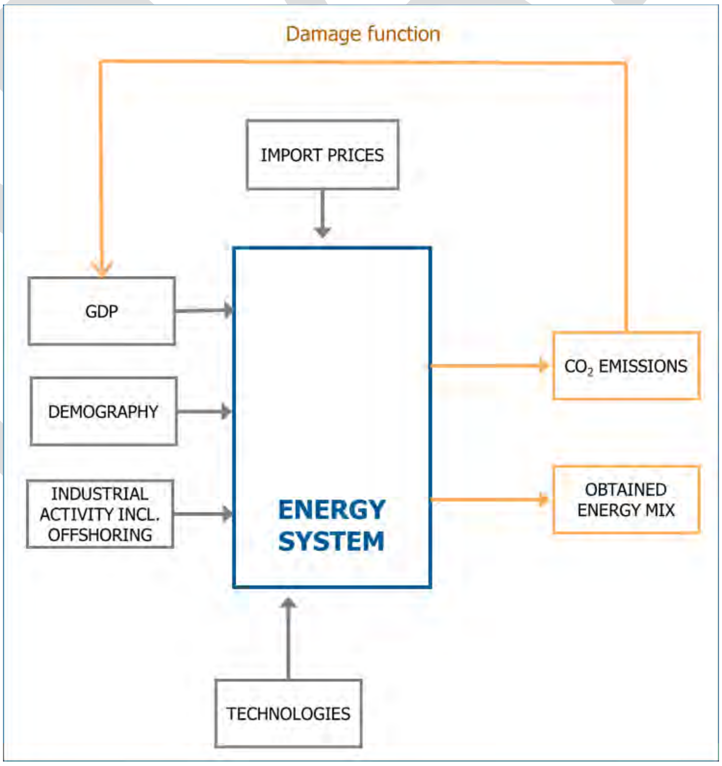

Figure 5: Illustration of the endogenization of the effect of climate change on the economy, through a damage function.

Recommendations to scenario producers

A list of the main boundary conditions fixed for the different scenarios should be provided.

B. In current scenarios, planetary physical limits are poorly, or not at all, taken into account

In current future studies, planetary boundaries[3] and non-renewable resource availability (which we call together the *physical limits*) are not taken into account through boundary conditions.

This might not be a problem for scenarios in which the proposed energy transition prevents from coming too close to these physical limits, though. Often, transformational scenarios have a social objective, or policies leading to a dramatic decrease of greenhouse gases (GHG) emissions over the scenario timeframe. Hence, in these scenarios climate change may not have significant physical impacts on the economy since mitigation effort has been great enough. (that is, the climate change boundary is not transgressed in these scenarios[4]). Presumably, in scenarios which do not transgress the climate change boundary, a GHG emissions assessment only is enough to show the absence of transgression.

This might not be a problem neither if the physical limits are endogenized in the model used by the study so that they do not have to be taken into account through boundary conditions. However, as just shown, only a very few models have this capability.

Hence, most scenarios (and even transformational scenarios):

- Do not take into account the impacts of the already triggered climate change, which may be significant and which will increase (even modestly) during the scenario timeframe. Indeed, no scenario implements a feedback loop between climate change and its impacts on the economy, demographics, or any human activity in general. This could be done through different boundary conditions, such as hypotheses on demographics (e.g. including migration waves), hypotheses on adapted consumption behaviors and supply-side adaptations with climate change (as mentioned in sections about energy consumption and transition of the power supply-side), or directly through a macroeconomic hypothesis about GDP. This is not performed yet to our knowledge.
- Do not assess the impacts on other planetary boundaries or on non-renewable resources. Indeed, in a similar fashion as for climate change, no feedback loop is implemented in current models used by future studies, and those physical limits are neither described in storylines nor integrated in boundary conditions. They could be integrated in boundary conditions through higher, and more volatile, import prices for non-renewable resource, through impacts on demographics, GDP and so on.

For scenarios which do not have the objective of reducing GHG emissions (this is typically the case for reference scenarios), physical limits may be transgressed. As no feedback loop is implemented in models, those scenarios are openly unrealistic (not to mention, extremely risky), sometimes without being clear about it.

Recommendations to scenario producers

Scenario producers should make their strategy about planetary boundaries and non-renewable resources (physical limits) explicit. They should first be explicit for each scenario if they consider those physical limits or not. If they do:

- They should detail if those limits are endogenized in the model they used and if yes how.
- If those limits are not endogenized, scenario producers should detail if they are embedded into the boundary conditions and if yes how

[3] "The boundaries define a safe operating space for humanity that should not be transgressed if we want to maintain stable conditions at the Earth System level." (The University of Cambridge Institute for Sustainability Leadership / Kering, 2017)
[4] Following the planetary boundary framework vocabulary.

- If the limits are neither endogenized nor embedded into boundary conditions, scenario producers should explain how those limits are integrated into the scenario design, or provide a narrative to substantiate the fact that they are not significantly impacting for the scenario.

If those limits are not considered, this should be clearly mentioned. A qualitative analysis should be provided to detail the potential impacts on the scenario of taking those limits into account, or to substantiate the absence of impact of taking them into account.

C. Boundary conditions for the energy system

1. Lifestyles and behaviors assumptions greatly drive energy, and power, demand

Lifestyles and behaviors (including investment behaviors in equipment) greatly drive energy demand through energy services demand (lighting, cooling, washing), demand for goods (requiring energy to produce them through industrial processes), and energy intensity (investments in more energy efficient appliances, in house insulation, or through practices changes such as telework or carpooling) (see section on lifestyles).

Lifestyles and behaviors largely depend on policies, economic conditions and available technologies, which are also part of boundary conditions.

Lifestyles in interaction with the energy system also determine energy consumption on the near-term, through daily behaviors. Hence some aspects of daily habits may have an importance on instant demand, especially for the power system as electricity cannot be stored per se (unlike gas, oil, coal or uranium) (see power system operation).

Recommendations to scenario producers

Scenarios should make explicit the behavior changes happening in their scenarios (either in the storyline or in the results) and explain them for example through the links between those changes and other boundary conditions (such as policies, economic conditions). Also see lifestyle section.

2. Assumptions about technologies play a key role in scenarios

In general, scenarios do not model the emergence of new technologies which can be used in the modeled system. Instead, scenarios include in their storylines a list of technologies which are used in the power system, and the date at which they are mature. They also sometimes describe the way technologies evolve during the scenario timeframe, especially in terms of costs reductions (technology learning rate). Very rarely do they explain why such reductions would happen. Instead, those hypotheses derive from historical projections or expert judgement.

The availability of technologies in scenarios as well as the date they become mature are key drivers of the energy system supply-side evolution. For example, the availability of a mature and efficient power-to-gas technology provides season flexibility for power systems with a large share of VRES, enabling the integration of significantly more VRES. The availability of mature and efficient CCS technologies in scenarios with strong carbon constraints dramatically changes the power supply-side mix: coal can remain a major power producer if CCS is commercially mature, but must be replaced otherwise.

Demand-side technologies (cars, lightbulbs, industrial processes…) are also assumed to improve, for example by reaching best available technologies (Association négaWatt, 2014; European Commission, 2011).

The evolutions of technology prices (demand-side equipment or supply-side technologies) are also key drivers of the energy system evolution in scenarios, especially for studies using models which determine the energy system through decisions based on prices, such as simulated agents models or benevolent planner models seeking costs minimization (see section on supply-side LTT).

The availability of some technologies can play a great role for the near-term control of the PS. This is the case for all the technologies providing anciliary services, as described in the operation section.

see section on supply for more details about technologies

> Recommendations to scenario producers
>
> Scenario reports should provide the list of technologies used in the scenario, their date of maturity, the nature and speed of their improvements (in terms of costs or technical characteristics) and provide explanations for these elements. Why do technologies improve? What cost component decreases in total cost and for what reason?

3. In scenarios, demography is an uncontrollable certainty

Demography is a key driver of ESs, as it is a key driver for demand. In future studies, demography is a boundary condition for the energy system. Indeed, in models there is no feedback from the ES to demography so demography is imposed to it. Demography is determined through the storyline, and data are usually selected from demographic projections. Scenarios do not perform any sensitivity analyses on demography, which shows this variable is considered as suffering no uncertainty.

> Recommendations to scenario producers
>
> Scenario reports should make their demographic assumptions explicit, as well as the source of data they used.
>
> For each scenario within a study, scenario producers should substantiate the fact that demography is not affected by the proposed energy transition.

4. A great diversity of policy tools affecting individual and corporate behaviors

Political framework (taxation system and regulations/ standards) affect individual behaviors as well as companies behaviors.

a. Tax system and public investments

Tax system is implemented by the State and as such it is considered as a boundary condition for the ES in scenarios. A tax system plays a role on households and companies behaviors. In order to be an efficient incentive on the long-run, a tax system must ensure stability for targeted actors.

Here are different examples of tax/subsidies having effects on the long-term evolution of the ES:

- feed-in tariffs for production ensure a stable price for several years; hence it plays a role in the long-term bankability of production plants benefiting from it, fostering the investments in these plants.
- A carbon tax with a clear, defined in advance, value provides key incentive for investors to favor the phasing-out of high carbon production and consumption and the emergence of low carbon production and consumption.
- Subsidies for building insulation for households foster the greater average energy efficiency of residential buildings.

The choices of taxation in scenarios can lead to very different pathways. For example, the specific evolution of a carbon tax determines if a scenario mainly implements gas power plants or coal power plants. As mentioned in the desirability section, taxation system may lead to, or solve, desirability issues. Scenarios often neglect this aspect.

Taxes partly drive the behaviors and choices of economic agents in scenarios because it impacts the costs and benefits associated with these behaviors and choices. Considerations on whether or not taxes should be included in total cost assessment of the transition can be found in section about economic evaluation.

Some taxes may have effects on the near-term behavior of the PS: a carbon tax leads to favor production by low carbon means, which may have impacts on the flexibility and inertia of the PS, as explained in the operation section.

Public investments are also a lever to foster the energy transition when public infrastructure need to evolve. For example, (Association négaWatt, 2014) proposes investment in public transportation; (ADEME, 2014) proposes to develop a finely meshed bike network in urban areas, which requires public investments.

b. Regulations and standards

Regulations and standards can lead to:

- Improved energy efficiency and reduced emissions of technologies on the demand-side and on the supply-side through more stringent production standards. Examples include standards on car emissions, standards on the energy efficiency of industrial processes, on coal power plants emissions or on fridges energy efficiency.
- Improved energy efficiency through regulations favoring information about it (labelling regulations for appliances and buildings).
- Energy demand reductions through regulations favoring practices and new organizations, such as car bans in city-center, new regulations on territory planning, new regulations on building insulation and heating system, etc.

Studies produced by the European Commission put into play a large set of European directives including regulations and standards (European Commission, 2011; European Commission, 2016).

c. In simulated agents scenarios, any social objective can be reached through policies (in particular, any GHG emission cap can be respected through a carbon price)

In scenarios, social objectives are boundary conditions for the ES as it is imposed by the benevolent planner (in the benevolent planner model philosophy), or policy makers (in the simulated agents model philosophy). Social objectives are very often about GHG emissions and security of electricity supply, more rarely about air pollution and access to energy. They are key drivers of the LT evolution of ES as they are considered in models as hard constraints (usually they are backcasted components, see section on future studies).

Studies using a benevolent planner philosophy perform some form of optimization or systematic method to reach an optimal point assuming these social objectives are reached (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015; Barton et al., 2018).

On the opposite, studies using a simulated agents philosophy implement policy levers such as taxes, standards, regulations etc in their transformational scenarios in order to reach these social objectives (ECF, 2010; European Commission, 2011; SFEN, 2018; IIASA, 2012). In other words, in these studies, dedicated policy levers lead to reaching the social objectives: a functional equivalence exists in those scenarios between social objectives and policy levers. More concretely, social objectives are set before the model is run, and then the policy boundary conditions are tuned in order to reach the social objectives.

The most typical example of this practice is the use of the carbon pricing policy lever to reach a GHG emission target: in many simulated agents transformational scenarios, carbon price is computed in such a way that simulated agents behave to reach the GHG reduction objective, such as in (European Commission, 2011; IIASA, 2012).However, in some studies, when the carbon price which is required to reach the GHG emissions objective is above an arbitrarily high value, the scenario is considered as "infeasible", such as in (IIASA, 2012).

(ECF, 2010) uses carbon price to define the carbon abatement measures which are implemented in the scenario: all the measures whose abatement cost is lower than 100$/t$CO_2$ are assumed to be implemented.

For their Sustainable Development Scenario, World Energy Outlooks (WEOs) define a carbon price trajectory (reaching 140$2016/t$CO_2$ by 2040 for WEO 2017 and 140$2017/t$CO_2$ for WEO 2018) to reach emissions targets (International Energy Agency, 2017; International Energy Agency, 2018; OECD/IEA, 2017; OECD/IEA, 2018).

In some scenarios using PRIMES model, assumed carbon tax or cap and trade mechanisms alone are not sufficient to reach the CO_2 emissions reduction. In those scenarios, PRIMES model computes an implicit carbon value corresponding to the achievement of the CO_2 emissions objective and make all the economic agents act as if their consumptions included this carbon value in their prices. In other words, economic agents act as if they perfectly had in mind the CO_2 emissions objectives to optimize their decisions (E3MLab, 2017).

All these mechanisms use carbon price, or carbon implicit value, to model the changes in economic behaviors so as to respect a set GHG emissions objective. As a consequence, the carbon value which is reached actually reflects the intensity of economic behavior changes. These methodologies to curve behaviors may hide desirability issues because they use a single value to depict behavior changes, which is not concrete enough about how behaviors actually change during the scenario. Desirability issues should be concretely discussed in these studies (see section on desirability).

Recommendations to scenario producers

A scenario strategy about taxation and public investment, regulations and standards, and social objectives should be defined and justified. It should include considerations on the decision to study this subject or not. This choice depends on the Planning Question and on the study overall strategy. In case the subject is studied, the different aspects of it which are considered should be reported, and their links to the study strategy should be outlined.

- Type of policy tool which is used
- Main effects of this tool

Policy tools as well as social objectives and in particular carbon value lead to economic behavior changes (either through end-consumption behaviors or through investment decisions for household; through investment decisions for industries and corporations). Scenarios should provide details about possible behavioral trend discontinuities for individuals' behaviors and explanations about why those discontinuities are accepted in the scenario (see lifestyles section).

5. Prices of imported materials and goods are not a subject for energy transition scenarios

Prices of imported materials and goods are usually not part of the boundary conditions of the ES in scenarios. However, they might have an importance for ESs requiring more physical capital to produce energy (such as ESs with high RES shares).

Depending on the behaviors of other regions of the world in their materials consumption, supply of some materials might not be able to follow demand, which would impact prices. This would lead to price variations for the technologies requiring such materials.

Hence technologies prices depend on the world context about material resources, both for demand side technologies (such as telecommunication devices, or electric vehicles) and for supply side technologies.

However, we could not find any scenario which consider such prices evolutions even though they estimate costs; they all determine prices evolutions of the technologies independently of materials, or fuel prices. Hence no inflation effect is accounted for in scenarios from rises in commodity prices (ANCRE, 2013; ECF, 2010; European Commission, 2011; European Commission, 2016; Greenpeace, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017).

The underlying assumption of making technology prices independent from import prices for goods and materials is that no significant evolution of these prices happens, in particular no shortage of materials and no geopolitical tension with exporting regions will happen during the scenario timeframe. Details on material resources criticality can be found in the dedicated analysis note.

For world scenarios, considering local prices may be interesting if disparities in world markets exist. However, the ultimate boundary condition for world scenarios is the availability of yearly flows of materials and fuels and how fluently they are distributed to balance demand (viscosity could happen with geopolitical tensions).

Recommendations for scenario producers

Scenario producers should report about whether or not the prices of the technologies involved in their scenarios are linked to material resources availability, and substantiate their choice.

In case they do, scenarios should provide elements to explain the evolution of key material resources prices in their storylines.

6. A very low diversity of assumptions about GDP evolution

For some scenarios, GDP is an essential input which determines the aggregated demand level and hence is a key driver of consumption behaviors, determining in turn both demand and supply sides of the energy system.

Scenarios use different strategies to determine their GDP evolution hypotheses: either they base them on a reference source which is judged robust enough to be accepted by the rest of the scenario community, or they use a storyline to substantiate the assumed evolution.

For example, the European Commission reference scenario (European Commission, 2016) uses a storyline explaining why GDP growth would be sustained at a 1.5% rate on the long run:

"*Over the longer term the impacts of the financial crisis are projected to fade away, structural reforms start to yield results, labour markets improve and more supportive policies and financing conditions are projected to be put in place sustaining the growth in the EU Member States.*"

This scenario is then used as a base scenario for the EUCO scenarios (E3MLab & IIASA, 2016), which are themselves a basis for scenarios of the SFEN study (SFEN, 2018). It can be deduced – even though it is not explicitly said – that GDP assumptions for all the scenarios of those studies are derived from this narrative.

Usually, these hypotheses are used to build a baseline scenario. Then a storyline or a quantitative assessment is used to justify the fact that GDP evolution is the same in the transformational scenarios as in the baseline scenario.

For example, the transformational scenarios of the European Commission' roadmap have the same GDP evolution as the Reference scenario following this line of reasoning:

"[...]*in the context of necessary reductions by developed countries as a group it is assumed that competitiveness effects throughout decarbonisation would be rather limited. Therefore, the decarbonisation scenarios are based on the same demographic and macroeconomic assumptions as the Reference scenario [...]*"

In European scenarios, or EU Member States scenarios, growth is always assumed to be greater than 1 %. For world scenarios, growth is also assumed to be positive on the long run, but with higher rates due to a larger growth in developing countries (such as in (Greenpeace, 2015; IIASA, 2012)).

Given the way GDP hypotheses are selected, or built, they are collectively very homogenous, in terms of values and trends (stable growth of roughly the same rates for all scenarios). However, growth is not as stable as demography, hence such a unity can be questioned. No scenario seriously considers the question of very low to negative GDP growth. This represents a collective blind spot for future studies, insofar that such negative trends for GDP may not be impossible.

GDP is used as a global constraint on the economic system in simulated agent models. In other words, the GDP hypothesis represents how much the economy will grow in the scenario. The GDP hypothesis ensures a consistency between consumption (in monetary value) and production (in monetary value) in the scenario, representing the global ability to produce goods and services on the geographical perimeter. Hence the GDP hypothesis translates hypotheses about:

- Geopolitics of the world, such as the relative economic power of different countries: The usual hypothesis is that of slowly changing geopolitical situations. No geopolitical crisis is assumed, which might be considered as a collective blind spot for future studies.

- Hypotheses about the financial sector and its possible crises: The usual hypothesis is that no more crisis will happen during the scenario timeframe. Theoretically, the reverse hypothesis could also be selected for some scenarios in order to think such a possibility.
- Planetary boundaries, such as the feedback effect of climate change on the economy, or the possible effects of peak oil in the scenario geographical perimeter: The usual hypothesis of a steady growth implicitly assumes that planetary boundaries are not significant determinants of the global economy during the scenario timeframe. This is largely questionable for "reference" scenarios leading to a significant climate change.

All these underlying hypotheses are largely unspoken. Detailing them leads to question the unity of GDP hypotheses across future studies.

Recommendations for scenario producers

A scenario strategy about GDP should be defined and justified. It should include considerations on the decision to study this subject or not. This choice depends on the Planning Question and on the study overall strategy. In case the subject is studied, the different aspects of it which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of GDP which may be reported about.

- Status of GDP in the scenario building: is it a driver of the whole scenario process (exogenous variable), or one of its results (endogenous variable)?
- Evolution of the GDP for each considered scenario
- Considerations on the differences (or absence of difference) between GDP evolutions across scenarios
- Positioning of the adopted hypothesis relative to other studies using a GDP hypothesis as a boundary condition: *is it a "usual" hypothesis for future studies? Does the scenario test a new style of GDP hypothesis?*
- In case GDP is exogenous:
    - o reasons why such an evolution was selected for each considered scenario
    - o narrative substantiating the described evolution: *why does GDP evolves this way? Under what drivers?*
    - o considerations on the sensitivity of results to GDP: *how would results be different if GDP stagnates, or decreases in the scenarios?*

7. A very low diversity of assumptions about imported fuel prices

For European scenarios, (imported) fuel prices are considered as boundary conditions as the EU has no impact on them. Data about their evolutions usually come from selected databases produced thanks to world commodity models (such as the World Energy Model by IEA, PROMETHEUS by E3M, DECC 2050 Calculator by the UK Department of Energy and Climate Change). In some scenarios, a storyline is provided to explain prices evolutions. In other scenarios, they are considered as uncontrollable uncertainties, subject to sensitivity analyses.

For example, (European Commission, 2011) produced its assumptions on fuel prices through a world energy model called PROMETHEUS. Two sets of fuel prices assumptions are proposed, each associated with a different storyline about world evolution. PROMETHEUS incorporates assumption about global energy demand, resources and reserves, extraction costs and bilateral trade between regions. (European Commission, 2016) provides a detailed storyline supporting its assumptions for oil, coal and gas prices evolutions, also generated by PROMETHEUS model.

Many studies use World Energy Outlook (WEO) fuel prices projections for at least one of their scenarios (DGEC/CGDD/ADEME, 2015; Greenpeace, 2015; RTE, 2017; WWF, 2011). The methodology used by IEA to come up with fuel prices is based on a storyline of the world energy demand evolution matching a storyline about world supply system and resources availability. Storylines are different for the 3 scenarios proposed in the WEO.

Those prices are key drivers of the ES as they partly determine demand structure (consumption level, demand side technology mix, final energy carrier) and the power system supply-side (through shifts within different fuels to produce power).

Those prices evolutions all share common patterns: prices are not volatile at all, and they steadily increase during the scenario timeframe (except in the WEO's Sustainable Development Scenario, in which a high worldwide carbon tax is implemented and no more subsidies to fossil fuels exist except in a few countries).This leads to two consequences: the diversity of the fuel prices trajectories across scenarios is low, and the trajectories are not representative of the volatility which has been observed in the past.

Recommendations for scenario producers

Scenario producers should make the source of their hypotheses about fuel prices explicit, and they should substantiate their trajectory choices. They should provide a quick summary of the storyline accounting for each trajectory.

8. Industrial offshoring pattern and industrial activity increase

a. Industrial trends have various important impacts on the energy transition

Industry represents a significant part of energy, and electricity demand in EU. On the long run, offshoring patterns can significantly affect the energy and electricity system. They also affect the various impacts of the energy transition:

- Employment structure is obviously impacted when an activity is offshored (a need for labor force disappears) or re-shored (new need for labor force).
- Costs of technologies used in the scenario may be impacted by offshoring/re-shoring patterns, depending on the differences in wages levels in the considered countries. For example, if an industry producing a technology is offshored in a lower wages country, then the corresponding imported technologies are less expensive than technologies which were produced on-shore. In other words, offshoring patterns can lead to changes in technology prices, e.g. through using cheaper labor in less developed countries. This applies both for demand-side and supply-side technologies. However, to our knowledge no scenario makes such explicit assumptions. The evolution of technologies costs are usually exogenous hypotheses in scenarios, based on learning rates projections or expert judgement, as explained previously.
- GHG emissions[5] associated with production processes spatially follow these processes when they are offshored: if steel production is offshored, then its GHG impacts are also offshored. This reduces the GHG emissions impact of the considered territory, but might increase or decrease the GHG impact at world scale. E.g, if the offshored activity is more carbon-efficient than when it was on-shore then the global impact is reduced (and the other way round) (Barton et al., 2018).

b. Past trends are little considered in industry activity assumptions, and no storyline is provided to account for trend discontinuities

Some scenarios explicitly talk about industry offshoring or re-shoring:

For France, (Association négaWatt, 2014) assumes that all French end-consumption is produced on the French territory, which impacts supply-side design, GHG emissions and employment (however, the employment impact assessment performed does not take into account this re-shoring pattern (Quirion, 2013)). This approach leads to a GHG impact assessment which is equivalent to a footprint approach (see section on impact assessment).

[5] Or other environmental or society impacts

(Association négaWatt, 2017) makes a different assumption: it keeps steady ratios of imports and exports over end-consumption for each type of goods/materials.

(Barton et al., 2013) reports the changes in industry activity level leading to importation levels changes. They assumes for several UK scenarios a steep decline in energy intensive industry at the expense of more imports, subsequently to energy and carbon prices increases. This effect decreases the territory GHG impact assessment but not necessarily its carbon footprint.

Many scenarios are less explicit about offshoring / reshoring patterns because their main hypothesis about demand in industry is GDP evolution. (RTE, 2017) assumes different trends in industry production, which are globally higher than current trends. (European Commission, 2011; European Commission, 2016) both assume an increase in industry activity, hence probably an industrial development in EU.

In most cases, scenarios do not provide explanations in their storylines about trend discontinuity in industrial activity. However, the industry sector is very slow to change, in terms of physical infrastructures, which are long-lived[6], but also in terms of employees' skills and training. Also, industries evolve in an economic and institutional frame. Trend discontinuity in industrial activity might not be compatible with this frame. For example, relocation patterns in France may not be consistent with free movement of goods and capital between France and less developed countries.

Recommendations to scenario producers

Scenarios should be clear about their industry relocation hypotheses. The following aspects may be considered:

- Trend discontinuity: if the industry offshoring or activity trend exhibits a sudden reversal (for example, a reindustrialization after ten years of offshoring), or trend discontinuity (e.g. offshoring patterns suddenly decrease), an explanation for this may be proposed: *does the economic and institutional frame driving industry behavior evolve in the scenario?*
- Inertia of change: *how fast does the industry sector evolve? Does this change imply sunk costs?*
- Social impacts of offshoring, especially in terms of transition desirability in the scenario geographical perimeter (also see section on desirability)
- Environmental impacts of offshoring: for example, offshoring may lead to actually greater GHG emissions if industrial processes outside the scenario geographical perimeter are more emissive. Such global impacts of offshoring or (re-shoring) should be made explicit in order to inform the consistency (or inconsistency) across future studies handling different regions. For example, if all national studies assume offshoring patterns, then they are not compatible taken together: no global impact assessment can be based on these studies.

D. Boundary conditions for the power system (PS)

In this section, we focus on the power system (PS) and detail its specific boundary conditions.

1. Interactions with other energy subsystems are mostly on the demand-side in scenarios

a. Two types of energy carrier shifts: demand-side and supply-side

The PS evolution depends on the evolutions of the other energy subsystems (supply and demand-side).

Energy needs outside the power system (space and water heating, cooling, energy for transport etc.) must be taken into account in order to include all the aspects of the problem. Similarly, the other energy carriers

[6] Industrial facilities can last 40 years (Shalizi & Lecocq, 2009).

aside from electricity should be considered, as well as the possible interconnections between networks and possible inter-conversions between energy carriers (especially storage) (Hache & Palle, 2019).

These interactions are very important in the final scale and design of the PS, especially when the main driver of the energy transition is decarbonizing, as opposed to fulfilling a steadily growing energy demand. In times of strong energy demand growth (such as the post-WWII period when power systems where developed in Europe), this growth can be easily translated into growth rates for each energy subsystem, without much considerations on the interactions between energy carriers. When the driver of the system is a cross-carrier constraint such as decarbonizing, then the interactions between carriers are key for the sizing of each subsystem.

Interactions can be separated into two types of interactions:

- Supply-side interactions between carriers: these interactions consist in adaptations of the energy system's supply-side to convert one carrier into another. Examples include Power to H2 through hydrolysis or Power-to-gas through hydrolysis and Sabatier reaction.
- Demand-side (indirect) interactions between carriers, through shifts between technologies using different carriers for fulfilling the same service. Examples include the shift from ICE cars to electric cars, or from gas heating systems to power heating systems.

These evolutions can be better understood as a carrier match between energy system supply-side and energy system demand-side. In other words, demand-side technology share, corresponding to a demand-side carrier share, must correspond to the supply-side final carrier share (see section on demand).

Recommendations to scenario producers

Scenario producers should ensure consistency during the scenario timeframe between energy supply-side and energy demand-side systems, for each energy carrier.

Utilization of Sankey diagrams, or input/output matrices can be useful.

Consistency between the sector scope of the study, the evolutions proposed in the scenario and the driving questions should be substantiated. *For example, if a scenario proposes that mobility mainly switches to gas carriers and if the aim of the study is to assess the impacts of this change, then the study's sector scope should include the gas system.*

b. Demand-side: numerous technologies to shift between energy carriers but most scenarios assume demand shifts towards electricity

Several levers act on demand level and on the demand-side energy carrier share. Section on demand describes the different levers on the energy demand-side system (demand sobriety, technical and organizational sobriety, technology share, load rate and energy efficiency).

We focus here on the demand-side interactions between the power system and other energy subsystems. This corresponds to all the demand-side technology shifts leading to a switch between electricity and another carrier.

Scenarios make similar assumptions about these shifts:

- All transformational scenarios assume technology shifts within space heating systems, toward greater electrification: For France, (Association négaWatt, 2014) assumes a shift from heating systems based on oil or electric heaters to heating systems running on wood, electric heat pumps, micro CHP gas, district heat or thermal sun. (RTE, 2017) assumes a shift from oil to heat pumps. For UK, (Barton et al., 2013) assume a massive development of heat pumps. Similarly, for EU, (European Commission, 2011) assumes a greater electrification of space heating. For water heating, it proposes shifts from gas boilers and resistance heaters to heat pump heaters or thermal sun heaters.

- Similarly, all scenarios assume technology shifts within the mobility sector (more commonly called mode shift), from ICE car to lower carbon modes (public transportation, bike…) or to hybrid car, electric car, CNG/LNG car and so on. Most often scenarios assume a shift towards electric car, but a few exceptions exist ((Association négaWatt, 2014) propose a massive shift toward CNG/LNG cars).
- Some scenarios make assumptions about technology shifts within the industry sector, usually from heat processes (for compression or heating) to electric processes (Association négaWatt, 2014; RTE, 2017).

Many shifts can be imagined. For each energy service, PRIMES model documentation provides a list of technologies and the associated vector (E3MLab, 2017).

These shifts impact the long term evolution of the power system both through different energy needs during the year and through different power load patterns (the power at peak demand, or the time and duration of peak demand may evolve). For example, the electrification of mobility may lead to significantly greater peak demand depending on the management of the charging of batteries (RTE, 2017; Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018).

Recommendations to scenario producers

Scenario producers should describe the evolution of the carrier share and total demand on the demand side, through technology uses evolutions.

This evolution should be described in terms of annual energy amount and in terms of instantaneous power demand: *does peak demand evolve?*

c. Supply side: a few tools to go from power to other energy carriers, used sparingly in scenarios due to uncertainties on their economic viability

The supply-side of each energy subsystem on a given territory is composed of the following elements:

i. extraction industry and technologies to extract primary energy from the environment (hydropower, PV, wind turbines, biomass production, fossil fuels extractive industries, uranium mining industry, geothermal power plants, geothermal heat…),
ii. transformation technologies to convert one carrier into another (thermal power plants, power to gas technologies, coal to liquid fuels technologies etc), of into several others (Combined Heat and Power plants…),
iii. imports or exports of different carriers.

Supply-side interactions are included in point (ii). For the power system they are transformations from one carrier to electricity (that is, usual power plants, which are handled in the technology section) and transformation from electricity to another carrier. The latter category includes power-to-hydrogen, and power-to-gas.

Power-to-hydrogen and power-to-gas technologies are actually applied in a sequence, with the following processes:

- Hydrolysis is performed to convert power into chemical energy stored under the hydrogen (H_2) form, through decomposing water. H_2 can be directly used by industry, or by fuel cell cars, or it can be stored and converted back into electricity via a fuel cell later (in this case H_2 is used as an electricity storage technology). Finally, it can be injected in the natural gas network (up to 30 % of the gas volume, representing 20% of the energy) and burnt with natural gas.

- Synthetic methane (CH_4) is obtained starting from H_2 and making it react with carbon atoms from carbon dioxide (CO_2) through Sabatier reaction. The obtained methane can be totally incorporated to natural gas. CO_2 can be obtained from CCS or from biogas purification.

Hydrogen plays a more or less important role in scenarios depending on time horizon, type of power mix and economic hypotheses.

Some scenarios give an extensive role to hydrogen, which totally replaces natural gas (Greenpeace, 2015). In other scenarios, hydrogen plays a power storage role (ADEME, 2015). (European Commission, 2011) uses it to feed the natural gas network and as a storage technology. Similarly, (SFEN, 2018) assumes the emergence of H2 production from hydrolysis on the long-term (from 2050 to 2070), for injection in gas network and as a storage technology.

(RTE, 2017) points out that hydrolysers are currently heavy investments so they need a steady power supply in order to be bankable.

Other technologies or techniques to convert power into other energy carriers are mentioned by (Véronique Beillan et al., 2018), under the P2X concept. P2X is the set of processes to convert power into another energy carrier which can be stored: power to heat (P2H), power to gas (P2G), power to fuel (P2F), power to product (P2P), or product to liquid (P2L).

The overarching concept of P2X is to use power opportunistically to convert it into other products which can be reinjected in the energy chain. This reinjection can be either to produce power at another time, or to use X directly as an energy carrier. P2X is a way to benefit from the interactions between energy subsystems so as to use excess power production, for example when electric VRES production is higher than electricity demand.

P2X enables energy storage over seasons or weeks, which would turn useful for power mixes with high VRES share. However, some specific storage, and network infrastructure may be required. Plus, the economic viability of such technologies is still uncertain and depends on the scenario storyline.

Recommendations to scenario producers

The technologies used to transform electricity into other carriers should be described, in terms of technical characteristics, costs etc. The expected evolutions of these technologies should be detailed as should be the reasons for these evolution.

2. Interactions with neighbor power systems

The considered PS can be connected to other PSs through interconnections. Interconnections participate in the power supply balance at any time by bringing more power (imports) or by evacuating extra power (exports). Hence hypotheses about interconnections are important to understand the balancing capacity which will be available from interconnections in scenarios (this aspect is handled in operation section).

a. Interconnections: between solidarity and sovereignty

Some scenarios consider that the PS they propose should properly operate independently of the presence of neighbor PS (Association négaWatt, 2014; Association négaWatt, 2017; ECF, 2010). As such, they propose a supply-side which is sized as if it was operating independently from neighbor PSs. They assume that the situation with no interconnection at all with neighboring regions would represent a worst case situation. In their views, actual interconnections would bring more flexibility to the system. Their methodological choice is also based on the difficulty to propose a proper storyline about the long-term evolution of neighbor PSs. In a word, the underlying assumption is that of sovereignty of the different regions to control their own PS.

Other scenarios make assumptions about how the power mix in neighboring regions evolve, including for the French case pathways which might pose greater constraints for the French PS to ensure global security of supply than if no interconnection was available (RTE, 2017). This rationale assumes solidarity with neighbor regions.

b. Simulating interconnections requires assumptions about interconnection capacities…

The scenarios simulating interconnections define hypotheses to compute the evolution of the interconnection capacities[7] and sometimes the implementation of new interconnection links. Here are the different approaches we observed among future studies to simulate the long-term evolution of power system interconnections, from the most rudimentary to the most complex.

(ADEME, 2014) directly assumes an extra power capacity always available in case of need to import, or export, power, through an aggregate capacity of interconnection.

Some scenarios use results from inter-regional studies forecasting the evolution of interconnections in the considered region. Some handle the uncertainty about interconnection evolution through sensitivity analyses. For example, (RTE, 2017)'s hypotheses are based on results of public studies about the evolution of the EU interconnections.

Some other scenarios endogenize these hypotheses by modeling interconnections as market actors deciding to invest in new interconnection capacities. These actors decide depending on the benefits they can make following their expectation for internal rate of return (E3MLab, 2017).

c. … but also about neighbor PSs' long-term evolution and near-term operation

Defining the evolution of the neighbor PSs enables to simulate the interaction behaviors between the interconnected PSs: which PS needs to import and which needs to export, and at what times? Several approaches are used by future studies to simulate them.

As mentioned, (ADEME, 2014) assumes an extra power capacity always available in case of need to import, or export, power. However, this availability is assumed rather than checked through a modeling of, or assumptions about, the long-term evolution of the neighbor PSs.

(ADEME, 2015) considers five regions interconnected with the French PS and assumes an 80% RES mixes for those interconnected regions. (ADEME / Artelys, 2019) considers the rest of the European PS as evolving as described in the Ten Year New Development Plan 2018 from ENTSO-E. In those cases, studies assume as boundary conditions the evolution of interconnected PSs.

Scenarios using PRIMES model for the European energy system make implicit assumptions about interconnected PSs in Switzerland, Norway and the Balkans, even though they are not part of the modeled energy market (E3MLab, 2017; European Commission, 2011; European Commission, 2016; SFEN, 2018). In PRIMES, from the point of view of each EU Member State, the mixes of neighboring countries are co-developed in an integrated way through market mechanisms.

(RTE, 2017; RTE, 2018) assume three different pathways for the mixes in neighboring regions, including pathways which might pose greater constraints for the French PS to ensure global security of supply. Those pathways each integrate the interconnected regions into an economic model ensuring bankability of the different power generation technologies development.

In order to check the proper infra-day (hour by hour) operation of the interconnected PSs, some scenarios use climate models of the different regions which properly represent the correlations between weather patterns across regions. For example, wind patterns, or sunlight patterns are somewhat correlated across European countries (Véronique Beillan et al., 2018). Similarly, they use demand models which also represent correlations between the different demand patterns which are due to outside temperature, weather, or time of the day (ADEME, 2015; RTE, 2017).

[7] The capacity of the interconnection represents the amount of instant power which can be transported in the interconnection line.

d. Impacts measured through interconnections

In scenarios in which the PS is interconnected with neighbor regions, electricity imports and/or exports may be significant. This raises the question of how to assess the impact of those imports and exports.

As described in the Impact Assessment section, the assessment perimeter may be the descriptive perimeter, in which case no account of imports or exports are considered in the various impact assessments. However, if the assessment perimeter is of a footprint type, then the impacts associated with imports are counted in the assessment whereas the impacts associated with exports are counted out (RTE, 2017). These impacts can be assessed on an hour by hour basis, or finer time step, in order to account for the different types of power plants operating at each time step if this has an importance for the assessment (such as the costs of production of the different plants, or their carbon emissions).

This can be done for any type of assessment (such as economic assessment, or CO_2 emissions assessment).

Recommendations for scenario producers

A scenario strategy about interconnections should be defined and justified. It should include considerations on the decision to study this subject or not. In case interconnections are studied, the different aspects which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of interconnections which may be reported about. Questions in italic are examples to illustrate the aspects which are dealt with.

- Hypothesis of sovereignty or solidarity. This hypothesis should be substantiated, especially if it requires evolutions from start year situation (e.g. currently interconnected power systems which go independant). *Is the studied PS independent of other, neighboring PSs? Is it fully connected to neighboring PSs with no means to control the interconnections?*
- Interconnected power systems and their evolutions: *which regions are interconnected? How do the neighboring PSs evolve during the scenario timeframe? Why do they evolve in such a way?*
- Interconnection lines capacity: *how does the interconnection capacity evolve during the scenario timeframe? Are new lines created?*
- Demand and supply instantaneous behavior of neighbor PSs. *Specifically, for scenarios in which neighboring regions have large shares of VRES, which method has been used to simulate the supply of these regions?*
- Impacts: the strategy to integrate impacts associated with power imports/exports in the results, for each impact which is considered in the study (e.g, GHG emissions), or a substantiation for not taking them into account) should be described.

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Author

Nicolas RAILLARD

Project Manager – + 33 (0)6 46 35 43 70 | nicolas.raillard@theshiftproject.org

Nicolas Raillard joined *The Shift Project* as a Project Engineer. A graduate from ISAE – Supaéro (France) and from the Georgia Institute of Technology (USA), he worked as a complex system strategy engineer in aerospace for 4 years. Having passed an Advanced Master in "Environment International Management" at the Mines ParisTech school (France) and Tsinghua University (China), he now applies his skills and qualifications to the low-carbon transition.

The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

Press contact : Jean-Noël Geist, Public Affairs and Communications Manager

+ 33 (0) 6 95 10 81 91 | jean-noel.geist@theshiftproject.org

Long-term evolution of energy consumption in energy transition scenarios

Technical file #4 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

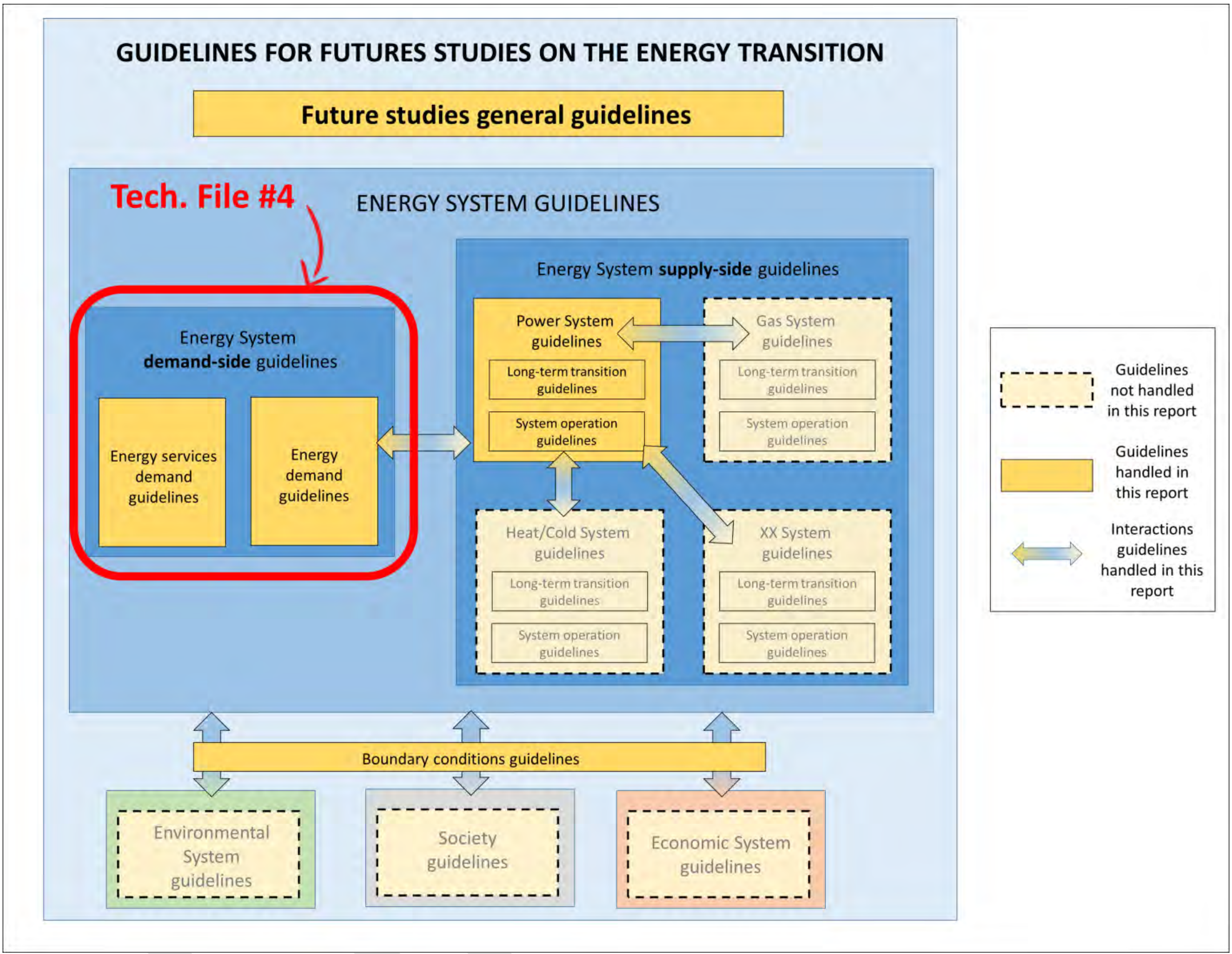
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

A. Introduction

This chapter tackles the long-term evolution of energy consumption, as opposed to hour per hour evolution. In other words, we consider here the long-term drivers of energy consumption. As a consequence, energy consumption is talked about in this section in terms of total yearly consumption rather than instant power consumption.

1. The traps of energy accounting

Energy comes in different forms, each having different uses. These forms are commonly called *energy sources* or *energy carriers*. An energy carrier is produced from an energy source (for example, electricity produced from coal combustion), and is then used for an end-use (e.g. electricity consumed in an electric engine to get mechanical energy) or is used to produce another carrier (e.g., electricity consumed to fill an electric battery as chemical energy).

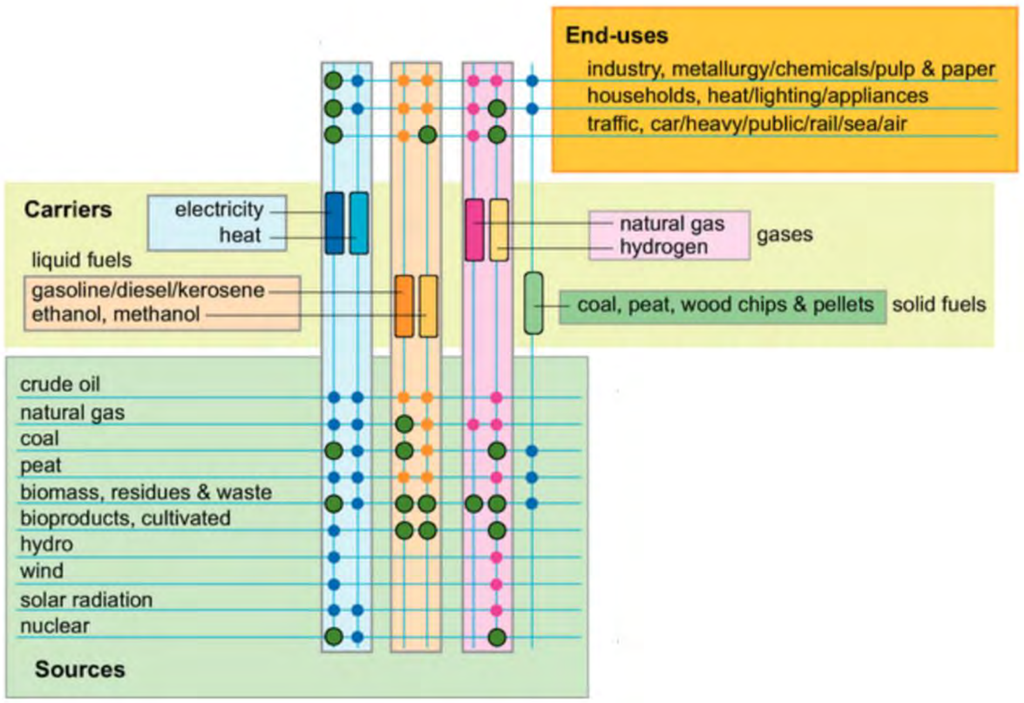

Figure 1: Dynamic interplay between energy sources, energy carriers and energy end-uses. Source: (IPCC, 2007)

These forms have different uses, hence they are not equal in practical terms. For example, petroleum is useless to power a TV set, and electricity is useless to power an internal combustion engine (ICE) car.

However, representing all the carriers on one graph can help figuring out use ratios between different carriers, for example showing the dependence level of a country to such or such carrier. This is why methods to account energy under its different forms have been developed.

Here are some methods used to account energy:

The partial substitution method:

When accounting energy under its fuels and electricity forms (for example, when accounting primary energy, including different fuels and renewables), this method converts electricity produced from renewables into the oil energy amount that would be required to produce an equivalent amount of electricity in a standard power plant (about 40% conversion efficiency). In other words, if 1 MWh of electricity is produced by a PV panel, it will be accounted as 2.5 MWh of energy[1]. Other fuels are accounted as their heat value. For example, if 2.5 MWh of oil is

[1] Indeed, 2.5 MWh of energy from oil combustion (heat) would produce 2.5*40 % = 1.0 MWh of electricity.

consumed in a car, it will be accounted as 2.5 MWh of energy. Similarly if these 2.5 MWh of oil are used to produce 1 MWh of electricity, the energy dissipated by oil will be accounted as 2.5 MWh of energy.

The physical energy content method:

This method defines a "primary" form for each form of energy, and accounts the amount of energy under this primary form. Usually, the primary energy form associated with nuclear is heat. With this method, accounting for an amount of electricity produced from nuclear reaction is equivalent to accounting the heat dissipated by the reaction in order to produce that electricity. The average energy conversion efficiency of nuclear power plants being 33 %, if 1MWh of electricity is produced from nuclear, then it will be accounted as 3 MWh of energy from nuclear[2]. For hydropower, or PV power, the associated primary energy is directly electricity; as a result, these energies are accounted as after their conversion into electricity (that is, if 1 MWh of electricity is produced from PV, it will be accounted as 1 MWh of energy).

For fuels as coal, oil, gaz and biofuels, conversion is made using the heat value as in the example of nuclear. However, different heat values obtained through combustion can be accounted: high heat value (also called gross calorific value), or low heat value (also called net calorific value). Low heat value represents the heat obtained directly through the combustion; however, exhaust gases still contain hot vapor; high heat value, in addition to the low heat value, incorporates the energy contained in the exhaust vapor compared to liquid water. In practice, the amount of energy that can be collected from combustion corresponds to the low heat value. However, the greater the amount of moisture and of hydrogen content of a fuel, the greater the difference between its low heat value and its high heat value[3] (United Nations & Statistical Division, 2018).

The physical energy content method is usually preferred, because it requires no assumption about what is the preferred energy form in a technical system. The partial substitution method assumes, among others, that electricity has a higher value for society than oil (which produces high temperature heat). But there might be societies in which electricity is plenty whereas high temperature heat is scarce, for example societies mostly running on electric renewables (hydropower, PV, wind), and in which other forms of energy would be useful (such as kerosene for airplanes). In those societies, getting oil would be more difficult and would require to convert electricity to liquid fuels. Hence the partial substitution method may need to consider that 1 MWh of oil has to be accounted as 3 MWh of electricity (as processes to convert electricity into oil generate about 2/3 of losses) (David JC MacKay, 2009).

On the contrary, the physical energy content method would not need to be altered in such cases.

A usual effect of accounting following the physical energy content method is that going to more electric renewable energies in replacement of fossil fuels or nuclear in the power mix leads to a decrease in primary energy consumption, as if the energy conversion from raw, found-in-nature energy to electricity was getting more and more efficient (for example, going from 1 MWh of electricity from coal to 1 MWh of electricity from wind is equivalent to going from 3 MWh of coal primary energy to 1 MWh of wind primary energy). Indeed, this accounting method assumes electricity can be extracted from the environment through renewables with a total efficiency (Brown et al., 2018).

Recommendations to scenario producers

Scenario producers should make their energy accounting method explicit when they compare different carriers.

They should also make explicit their choice about heat conversion values (low vs high heat value) when they use heat as an accounting reference, and substantiate their choice.

2. In most scenarios, energy demand is the main driver of energy systems

Some studies consider that energy demand is the main driver of energy systems. This is typically the case of studies exploring options about the energy supply-side system, in which demand is defined exogenously, or quasi-

[2] Indeed, 3 MWh of energy (heat) from nuclear reaction produces 3.0*33 % = 1.0 MWh of electricity
[3] For example, high heat value of charcoal (very dry and very low hydrogen content) is 0 to 4 % higher than its low heat value; high heat value of fuelwood with a 40 % moisture content is 45 % higher than its low heat value.

exogenously (e.g. directly derived from GDP) and then an energy supply-side system is defined to fulfill the demand. In this view, demand drives and sizes the overall energy system (Riahi et al., 2012). We call these studies *technical studies*.

A few scenarios (especially local scenarios) use the reverse rationale: they start from local resources to define possible supply-side systems and deduce the required evolution of demand-side and of level of demand. Their underlying assumption is that of energy independence through local (and sustainable) extraction of energy. Under those assumptions, local resources drive (local) demand.

In reality, energy demand and the energy system co-evolve, influencing each other; it cannot be said that one entirely drives the other. Some studies represent this mutual influence through market models, clearing demand and supply offers while producing a price: we call these studies *partial equilibrium studies*. Under some conditions, this is equivalent to minimizing the total cost of the complete energy system (Loulou, 2016). But even in those cases, demand is often largely driven by exogenous variables (such as GDP and population hypotheses) whereas supply-side system is essentially driven by demand.

B. Current practices for assessing energy demand evolution

1. The different approaches to assess energy demand evolution have different strengths, but all lead to inconsistencies

Two main approaches are used to assess energy and electricity demand evolutions. We call the first approach "behavior-based", the second one being called "GDP-based". These approaches are described in the following subsections:

a. The behavior-based approach usefully informs the transition debate on some of its sociological aspects but requires in turn a good knowledge of the considered population habits

The behavior-based approach starts from the behaviors of economic agents in terms of energy services. This approach is used in (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015). In this approach the storyline is about lifestyles, evolutions of energy services technologies and uses:

- hypotheses about how households will consume (sobriety, new uses or different uses, carrier shifts), and how energy services equipment (such as cars, fridges, or TV sets) will evolve in terms of energy efficiency, are derived from the storyline.
- For commercial and tertiary activities, hypotheses are made on the overall demand evolution for trade and services in the first place, and then on the evolution of energy services equipment in these sectors (such as heating systems, cooling devices for food storage, etc).
- For the industry sector, the global (domestic and foreign) demand for various commodities, industrial offshoring and inshoring behaviors and energy efficiency of production processes are the subjects on which the main hypotheses are made. During this step, some scenarios ensure a consistency between households' equipment consumption and industry production level, by posing hypotheses about place of goods production.

These hypotheses can be more or less aggregated along two dimensions:

- They can be much disaggregated at the energy service technology level. In other words, for a given service, a variety of technologies with different technical characteristics are described, such as different types of fridges characterized by their energy efficiency. Such disaggregation is often called "*technology-rich*."
- They can also be much disaggregated at the behavior level. In other words, a variety of different behaviors depending on social factors are included in the discussion, such as place of living, social category, family structure and so on. A rich set of different subpopulations is defined depending on their lifestyles. Such a disaggregation is called here "*lifestyle-rich.*"

Having defined those hypotheses, energy consumption is computed per carrier.

This approach is by nature much more lifestyle-rich than the GDP-based approach. Hence the scenarios can describe in a precise way how lifestyles evolve (for example (ADEME, 2014) describes the lifestyles associated with the Visions scenario (ADEME, 2012)). This transparency about lifestyles opens useful discussions with behavior scientists (such as sociologists, psychologists, historians…) and the greater public about the hypotheses, ensuring a greater consistency between the scenarios and behavior sciences results.

In this approach, the consistency is not ensured between industry production and the transition of the energy supply-side (such as building new power plants, a new grid architecture, etc., which may be capitalistic). Indeed, once industry demand is determined (along with other sectors' demands), a supply-side system is proposed to fulfill the resulting demand, but no feedback loop is implemented to take into account the fact the supply-side transition requires energy in industrial processes. This may be problematic for world scenarios, inasmuch their transition requires more capital, because in those cases a substantial amount of energy is dedicated to performing the transition (as opposed to running the usual economy), as shown by (Bouneau, 2018). For regional scenarios, this approach may hide significant impacts on trade balance for transformational scenarios (as high capital transition may require lots of imports).

In this approach, a macroeconomic view can be brought afterwards through models soft-linking[4]: for example, ADEME used the ThreeMe model to deduce GDP evolution and jobs evolutions from consumption hypotheses taken from their Vision scenarios (ADEME, 2012; ADEME, 2013) (see employment section).

b. The GDP-based approach is not rich enough to inform the sociological debate but can be applied on perimeters with a low knowledge of population's habits

The GDP-based approach starts from macroeconomic assumptions, such as assumptions on demographic trends and GDP trends. The storyline is about those indicators and why these assumptions have been selected (substantiation is often reduced to providing the source of data, which is considered as a reference, or to a short storyline – see section on boundary conditions). Scenarios built with PRIMES model, such as scenarios from the European Commission or from Société Française pour l'Energie Nucléaire (SFEN) (E3MLab & IIASA, 2016; European Commission, 2011; European Commission, 2016; SFEN, 2018), as well as scenarios built from POLES model (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017) (scenario used for the French Stratégie Nationale Bas Carbone (DGEC/CGDD/ADEME, 2015; Ministère de l'écologie, du développement durable et de l'énergie, 2015)) follow this approach. The Global Energy Assessment (GEA) pathways (IIASA, 2012) also follow this approach to determine demand which is used as an input to MESSAGE model.

Some studies use this approach in a very simplified way, posing GDP assumptions and global energy efficiency assumptions to deduce the overall energy consumption level by 2050 (ECF, 2010). This is implicitly the approach used by (IIASA, 2012). The energy demand in Energy [R]evolution scenarios is based on dedicated studies (Graus & Kermeli, 2012; Greenpeace, 2012; Greenpeace, 2015), which use GDP evolution per country to frame their demand projections. In the three cases, the demand for a reference scenario is defined mostly from GDP projections, and then energy efficiency measures are imagined to deduce a low demand scenario.

This approach can be endogenized in models. In this case, GDP growth is used as an input to determine the evolution of global demand per sector, using assumptions on the structure of the economy. This structure can evolve based on different policy assumption.

Some models, such as POLES, use reduced forms equations (with demand elasticities as main parameters) directly linking GDP variation to energy demand variation for each sector (E3MLab, 2017).

Other models, as a first step, link "explanatory" variables such as GDP, to "activity" indicators such as vehicle-miles travelled. In a second step, they model consumption behaviors matching this activity, which determines energy consumption. This is the strategy adopted by PRIMES, which models consumption behaviors based on different available energy services technologies (such as cars, fridges, industrial processes…) and on optimal market choice

[4] Soft-linking refers to a modeling technique to couple two different, complementary models. The technique is to run each model iteratively, each one providing inputs to the other one, until convergence is reached for the different variables, which means a consistency point has been reached between both models (Krook-Riekkola, Berg, Ahlgren, & Söderholm, 2017).

simulations. In this case, GDP represents an overall consumption "envelope" which has to be consumed, but it does not directly determine how energy is consumed and under what carrier. This approach is technology-rich as it represents the different energy services technologies.

In both cases, energy demand per carrier is eventually determined.

A few physical inconsistencies can appear with such an approach based on monetary flows for energy commodities:

- consistency between industry production (as could be measured in tons of produced materials) and goods consumption by end-users (number of built objects, such as the number of cars required to ensure mobility in the scenario, and non-energy infrastructure, such as roads) is not ensured. As a result, the energy consumed by industrial processes may be inconsistent with the projected demand in goods in the scenario. This inconsistency comes from the very determination of energy demand in all the sectors from a common GDP hypothesis, as opposed to determining industry demand from end-consumer demand first (see Figure 2 and Figure 3). Goods' markets modelling could be a way to ensure this consistency, but they are not modelled in partial equilibrium models. Another way to see that no consistency is ensured is that modelled industrial processes have no consideration on material flows. Hence no consistency is ensured between, e.g., car production and the number of cars produced.

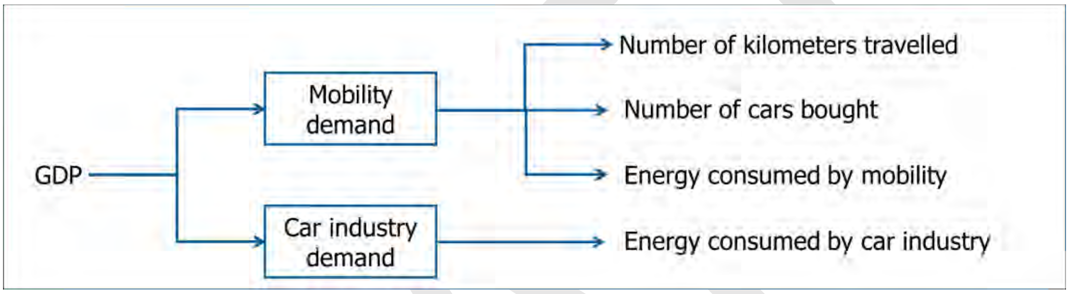

Figure 2: In the GDP-based approach, energy consumption is derived from GDP assumptions for each sector, including industrial sector. This approach ensures an economic consistency between the projected activity level of each sector and the global GDP. However, taking the example of car industry, consistency is not ensured between the number of cars bought, which have to be produced by car industry, and car industry demand.

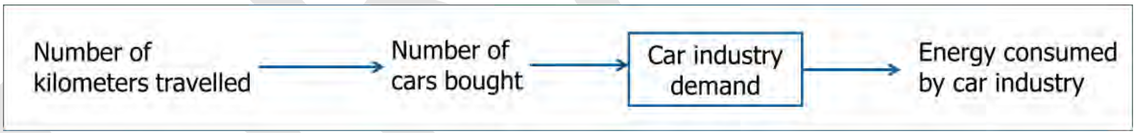

Figure 3: In the behavior-based approach, behaviors of end-consumers determine consumption of goods (cars), which in turn determine demands for industries (such as how many cars have to be produced by car industry). Demand for industry then determines energy consumption by industries.

- As for the behavior-based approach, consistency is not ensured neither between industry production and the transition of the energy supply-side (which, as already mentioned, may be capitalistic), for the same fundamental reasons: energy-infrastructure industry activity is determined by the GDP hypothesis as opposed to being determined by the sizing of the energy supply-side (that is, how many power plants or how many kilometers of high voltage lines to build). This may be problematic for world scenarios, inasmuch their transition requires more capital, because in those cases a substantial amount of energy is dedicated to performing the transition (as opposed to running the usual economy), as shown by (Bouneau, 2018). For regional scenarios, this approach may hide significant impacts on trade balance for transformational scenarios (as high capital transition may require lots of imports).

This approach is largely based, and calibrated, on observations of past economies, which can lead to inconsistencies for transformational scenarios. For example, consumers' preferences evolutions, or evolution of price-demand elasticities (representing relative choices evolution due to relative prices evolution) cannot be modelled, even for a transformational scenario. Hence some aspects of lifestyles evolution cannot be modelled (see section on lifestyles).

Furthermore, in this view, lifestyles (including employment structure) evolve totally fluently through market forces (which are themselves framed by policies). This may pose desirability issues for transformational scenarios (see section on desirability).

As a general rule, scenarios covering a large territory (such as world regions, or the world) use the GDP-based approach. Indeed, behavior-based approaches require a fine knowledge of population habits and of the heterogeneity of consumption behaviors depending on the subpopulations. Such data is more difficult to collect, and handle, for large territories modeling.

c. Hybrid approaches

Hybrid methods for power systems scenarios are sometimes used (ENTSOG/ENTSO-E, 2018; RTE, 2017), they define storylines about behaviors, technologies, vector shifts etc., but ensure their inner consistency through GDP hypotheses: e.g., the Bilan Prévisionnel from RTE (RTE, 2017) assumes that the energy efficiency is stronger in scenarios in which demand is greater because both are linked to a greater GDP.

d. Supply-side only approaches are used to inform about the possible evolutions of the power systems supply-side with an exogenously fixed demand

Finally, some future studies do not compute demand levels but reuse demand trajectories from other studies. For example, two studies from ADEME (ADEME, 2015; ADEME / Artelys, 2018) directly use power demand trajectories from other studies, as boundary conditions.

Usually, studies focusing on the supply-side of the energy system, or the power system, use the latter approach. In these studies, a supply-side system is modelled, demand being fixed beforehand. Hence no trade-off (would it be based on an economic criterion or any other criterion) can be performed between actions on the supply-side and actions on the demand-side (such as introducing energy efficient consumption devices, or shifting between technologies providing the same energy service)[5].

Recommendations to scenario producers

The scenario strategy about energy demand determination should be defined and justified.

Hereunder are aspects of energy demand determination which should be reported about.

- Approach which is adopted to determine energy demand level: GDP-based, behavior-based, hybrid, or direct demand reuse from another study. The reason why such an approach has been adopted.
- If the behavior-based, or hybrid approach has been adopted
  - Level of disaggregation of the end-use technologies may be described
  - Level of disaggregation of the subpopulation types should be described, e.g. per type of energy service use
  - Limitations induced by the approach, such as possible inconsistencies between supply-side evolution and energy demand due to the absence of feedback loop between them, should be described. Substantiation about the possible effects of these limitations on results should be provided.
- If the GDP-based approach has been adopted
  - The links between GDP and final energy demand should be made explicit and a qualitative substantiation should be provided for these links. *For example, how is activity level determined from the overall GDP? How does this link evolve through scenario timeframe, and why? Is the structure of the GDP share per sector assumed to evolve during the scenario timeframe?*

[5] For example, (ADEME / Artelys, 2018) compares the costs of a supply-side system designed to fulfill a low demand trajectory to the cost of a supply-side system designed to fulfill a high demand trajectory, without including in the cost assessment the costs related to the demand modifications between both trajectories. As a result, the cost comparison does not really hold any decision value towards a lower demand or a higher demand option.

How have demand price elasticities been calibrated, how and why do they evolve through the scenario?

- Limitations induced by the approach should be described, such as
  - possible inconsistencies between industry goods production and energy demand from industry along the scenario, or between supply-side evolution and energy demand, e.g. due to the absence of feedback loop between those aspects, should be described. Substantiation about the possible effects of these limitations on results should be provided.
  - Lifestyle evolution considerations, such as stiffness of consumers' preferences in a fast-, largely-evolving incentive context, or the fluency of job structure evolution. Substantiation about the possible effects of these limitations on results should be provided.

2. Two types of levers to reduce energy demand: energy efficiency and sobriety

"Sobriety consists in refraining from consuming energy by for instance staying home during the weekend instead of taking the car or by lowering the heating temperature in the house" (Reynès, Yeddir-Tamsamani, & Callonnec, 2011).

In a more consensual way, sobriety is sometimes referred as sufficiency.

"Sufficiency [...] addresses the "level" of output (or consumption) per se – and not in relation to the inputs (as technical efficiency does). It asks whether an activity needs to be performed at all (excess meat consumption, multiple car ownership, or extraordinarily high mobility service demand) and not whether it is performed "efficiently."" (Roy et al., 2012)

Some others talk about reducing the level of energy services demand by restructuring those energy services (such as substituting "physical" mobility by "digital" mobility through communication devices) or by organizing differently the context in which they take place (such as living closer to ones workplace to reduce mobility needs, or insulating one's house to reduce heating needs) (Riahi et al., 2012).

"Avoid, Shift, Improve" rationale is also useful to characterize energy demand transition. This an end-user rationale (The Shift Project, 2017). *Avoid* is close to sobriety (consume less of a service), or organizational efficiency (live closer to work to reduce travel, insulate house, substitute physical mobility with virtual mobility…); *shift* corresponds to carrier shift to provide the same energy service (e.g., shifting from a gas boiler to an electric boiler, from an oil ICE car to an electric car, or shifting from an oil ICE car to a muscle powered bike); *improve* is technological improvement within one carrier for the same service. *Improve* can gather two types of improvement: either using differently the same technology to get a better energy efficiency per unit of service (such as higher occupancy rate for cars, or smoother driving), or using a more efficient technology (such as a car consuming less energy in average).

C. A common frame to collectively think energy consumption and its evolutions through a behavior-based approach

In this section, we propose a simple and consistent frame and the associated terminology to help discussing about energy consumption evolution under a behavior-based approach. This frame is largely inspired by the various studies using this approach, such as (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015).

The behavior-based approach is developed as it better informs the debate about demand evolution by providing details about what concretely changes in the behaviors and lifestyles. On the contrary, the GDP-based approach is of little use to collectively think and discuss behaviors generating energy consumption because it is not concrete enough on these aspects. Behaviors are a blind spot of the GDP-based approach.

1. Overview of the proposed behavior-based frame

Energy demand can be determined through a behavior-based approach starting from *human demand*. Human demand, as defined here, emerges from human needs like eating, being at a comfortable temperature, feeling clean, having clean laundry, having access to leisure and entertainment, to medication, etc, and its fulfillment involves energy consumption.

We call *energy-service system* the macro, aggregated system fulfilling a given type of human demand. Energy-service systems are produced to fulfill human demand by consuming different forms of energy. For example, the mobility system fulfills demand for people accessing activities; the laundry washing system fulfills demand for people having clean laundry, and so on. The definitions of such macro systems is subject to debate about their usefulness in each study's context: for instance it may be more relevant to distinguish, and define, a long-distance mobility system and a short-distance mobility system rather than an aggregate mobility system, depending on the needed resolution on mobility description.

The following diagram describes the chain going from human demand to energy consumption, for several energy-service systems. It is not a dynamic description of the transition but rather a picture of the demand-side of the energy system at a given time. However, in green (top line) are represented the levers triggering evolutions of this picture.

For the sake of illustration, the following energy-service systems have been described in the diagram:

- The (passenger) mobility system fulfills the needs of people to access a variety of activities, goods and services (Briand, Lefevre, & Cayla, 2017).
- The laundry washing system fulfills the needs of people to wear clean garments
- The space heating system fulfills the needs of people to feel warm
- The material goods production system participates in fulfilling the needs of people to have access to material goods

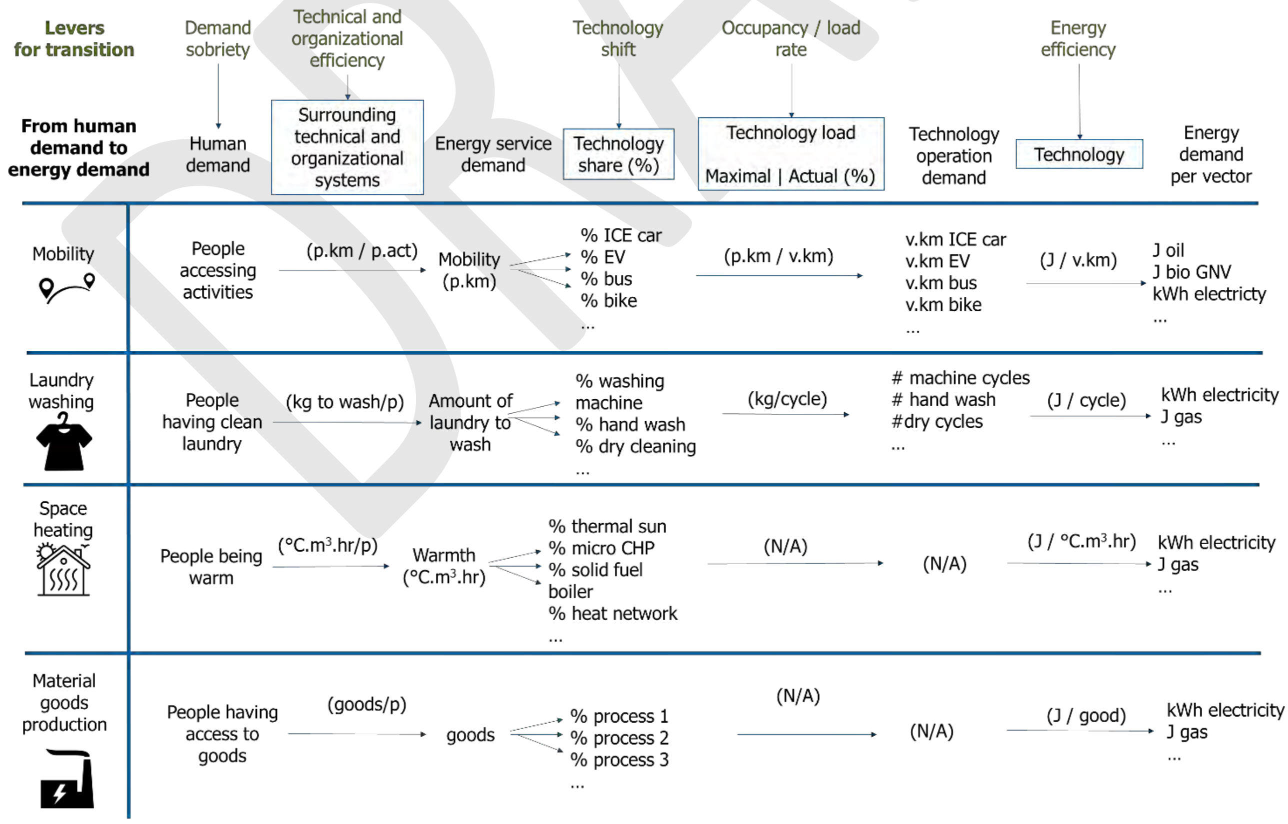

Figure 4: The energy consumption frame for a common behavior-based approach

There is not necessarily a bijection between a human need and a specific energy-service system fulfilling it. For example, the steel production system is linked to several human needs (all the applications of steel). The other way round, eating needs are associated with several energy-service systems (farming system, agricultural system, food transformation industry, freight…); "having access to goods" needs are also associated with several energy-service systems, such as the material goods production system, the freight system, and the (passenger) mobility system.

2. Central concepts of the framework: a chain from human demand to energy consumption per carrier

This diagram provides a useful frame to think energy demand and all the levers which can be activated to act on energy demand. By no means does it represent the causal chain of how energy consumption is determined in reality. Rather, it helps taking into account all the influencing factors of energy consumption. Here are the main concepts of the framework:

a. Human demand

There is certainly no proper way of measuring human demand, but it is conceptually a growing function of population: the more people, the more "people feeling clean" need, hence the more demand for people feeling clean. This concept is very close to what economists call "utility", or welfare. Utility is maximized for a person when the greatest possible share of its human demands are fulfilled (for a given income, for example).

Communication campaigns (advertisement) promoting consumption which does not exist yet (such as new entertainment devices, or, in past times, the invention and mass production of cars, or of phones), or the mere observation of others using new technologies, lead to create new, or increase, human demand.

b. Energy service demand

This term is coined by (Le Gallic, Assoumou, & Maïzi, 2017). It represents how much the energy service system must operate to fulfill human demand. In essence, an energy-service system transforms its environment; this transformation is what is called here the *energy service*. For example, the mobility system moves people from places to places. The laundry washing system makes dirty laundry clean. An entertainment system (for example composed of TV sets and computers) modifies the visual and sound environment of people for entertainment purpose. The space heating system makes ambient air warmer. And so on.

In Figure 4, examples are provided with specific units for energy service demand, such as p.km for mobility, or kg of laundry to wash. These units can be discussed to better represent the energy service. For example, laundry washing could also be measured as a volume, in m^3 of laundry to wash instead of a weight.

c. Technology operation demand

It represents how much the considered technology has to operate given how loaded it is. For example, how many kilometers must be run by ICE cars each year, or how many wash cycles must be performed by washing machines each year.

d. Energy demand per vector

Finally, energy demand represents the amount of energy which is required for each specific technology to operate under the previously described conditions. This amount is associated to specific energy vectors.

3. Levers triggering evolutions of the energy demand

In Figure 4, arrows do not represent a transition through time from the left to the right but rather "influence" links between different concepts within a static image of the energy demand-side, for different energy services. Here are some reading keys illustrating those influence links:

- The activation of the *demand sobriety* lever can be read as: *less* human demand is fulfilled. For example, people accessing less activities, people having less clean laundry, and so on.
- The activation of the *Technical and organizational efficiency* (TOE) can be read as: *same* human demand is fulfilled, *with a lower amount of* energy service demand. For example, people accessing the same activities with a lower amount of passengers.km; people keeping the same laundry cleanliness with a lower amount of laundry to wash; people filling as warm with a lower amount of heat transmitted to the air in living places, people having access to the same goods with less goods, and so on.
- The activation of the *technology shift* lever can be read as: energy-service demand is fulfilled *by a different* technology share.
- The activation of the *load rate* increase can be read as: For a given technology, the same energy service demand is fulfilled, with less technology operation demand. For example, the same amount of passengers.km by ICE car can be performed with less cars.km; the same amount of laundry can be cleaned by washing machines with less machine cycles, and so on.
- The activation of the *energy efficiency* lever can be read as: *the same amount of* technology operation demand can be performed *with less* energy demand. For example, the same amount of cars.km by ICE car can be performed with less oil; the same amount of washing machine cycles can be performed with less electricity; the same amount of heat transmitted to room air can be reached by thermal sun panel with less sun light; the same amount of goods produced by "process 1" can be performed with less energy; and so on.

The following sections describes the levers.

a. Human demand might be reduced through demand sobriety

The lever decreasing human demand (for a given population) is usually called sobriety. It is also sometimes referred as sufficiency (Roy et al., 2012; Samadi et al., 2017). We call it *demand sobriety* in order to differentiate it from technical and organizational efficiency, which is sometimes also referred as sobriety. It is the direct reduction in the human demand per capita ("utility" decrease), leading to energy consumption reduction all else being equal. For example, buying 1 TV set every 2 years instead of 1 per year for a household would be demand sobriety for TV set production. Using one's personal computer 3 hours/day instead of 4 hrs/day would be demand sobriety for access to entertainment.

Some authors argue that sobriety is not necessarily associated with unhappiness, even though it corresponds to a decrease in utility (less can still be enough (Samadi et al., 2017)). Notions of luxury and basic needs are relevant to think about demand sobriety: it may be considered as easy to reduce luxurious demand but unacceptable to reduce demand for basic needs (Demski, Thomas, Becker, Evensen, & Pidgeon, 2019; Roy et al., 2012). What "luxury" or "basic need" mean depends on each culture, economic context and era.

People may be willing to reduce their human demand for example under the influence of communication campaigns or education (Roy et al., 2012), on the long-term environmental or ethical impacts of their behaviors. It can also be activated through pull (reinforcement, carrot) or push (coercion, stick) measures (van Sluisveld, Martínez, Daioglou, & van Vuuren, 2016).

b. Surrounding technical and organizational systems (STOS) are a source of efficiency and of interactions within the energy service basket of consumers

The surrounding technical and organizational systems (STOS) are the set of systems surrounding the considered energy service system and having an influence on how much the energy service system needs to operate to fulfill the human demand.

For example, for the mobility system, people can have access to work through telework, which reduces the amount of trips people have to perform while fulfilling demand for accessing work; similarly, groceries can be delivered at home, etc. Also, city planning plays a role in the distances to travel to access activities through city density and functional diversity. The telework system, grocery delivery system, and city organization, are such surrounding systems.

For the laundry washing system, maybe clothes which need less washing can be produced, or cities can be less polluted, so that the same number of people feel they have clean laundry while washing less laundry. These would also be examples of surrounding technical and organizational systems.

For the space heating system, thermal insulation of buildings, design and orientation of the buildings, vegetation shading the building, city planning (taking into consideration dominant winds, vegetation effects, local climate…) etc are such surrounding systems. Design plays a role in heat naturally received from the environment (windows, shape etc) but also a role in how many inhabitants live in the same volume of building (Ko, 2013; Rickwood, Glazebrook, & Searle, 2008). Thermostat control through time enables to fulfill the same amount of thermal comfort while requiring less heat. Available warm and comfortable garments have the same role, and as such they are also part of the surrounding systems.

All these systems represent a source of efficiency levers (*technical and organizational efficiency, TOE*) enabling to fulfill the same human demand with a lower energy service demand, maybe at the expense of increasing the demand for another energy-based system; for example, telework system may require additional ICT equipment, additional buildings etc.

Energy services should be seen as a consumption basket (Roy et al., 2012) whose share evolves if TOE lever is activated, such as moving around less but using more ICT equipment.

These levers to modify the surrounding technical and organizational system are activated by the productive sector through technical innovation and new practices and/or by the public sector through investments in infrastructures or tax system evolutions (such as for city planning).

These systems are often long-lived and can lead to lock-in effects, such as energy inefficient houses' designs or energy inefficient urban forms (Roy et al., 2012).

Compared to the sobriety lever, TOE lever uses an artefact, or new way of organization, to reduce consumption while fulfilling the same human demand.

c. Technology share evolves through technology shifts

Technology share represents how much of the energy service (or transformation need) is performed by each different technology present in the system. It is based on a list of available technologies fulfilling the considered need in the scenario. A percentage of the total need can be allocated to each technology. Usually technologies use one energy vector, but some technologies might use several (e.g. hybrid rechargeable cars use electricity and oil).

For example, in the mobility system, different technologies of cars (fuel cell, Internal Combustion Engine (ICE), compressed gas…), buses, bikes (e-bikes, or traditional…) can be used to fulfill the mobility need. In the space heating system, different heating systems and types of buildings (especially categorized by thermal energy performance) fulfill the warmth need.

Levers modifying the technology share are provided by the productive sector through new technologies which may become part of the share (such as new personal mobility devices), new services and infrastructures around the existing technologies (such as charging stations for EVs, or bicycle repair shops for bikes); and accompanied by the public sector through investments in infrastructures (such as bicycles lanes) and through incitation (for example, subsidies for buying EVs). Communication campaigns by the private sector for one type of technology (advertisement campaign) or by the public sector can also modify the technology share.

In the mobility system, infrastructures lead to physically favor specific technologies. As they are long-lived, they can lead to lock-in effects (such as a road system designed for car use).

d. Technology load may be increased to make a given technology more energy efficient

Some technologies might be used differently so as to perform the same service while being used less (or more service while being used by the same amount). This is described by the occupancy, or load rate. This rates describes how loaded the technology is when it operates. The more loaded (up to the maximal efficiency load), the more efficient the technology when it operates. For example, washing machines, dishwashers, clothes dryers, vehicles, can be more or less loaded. In a similar fashion, lighting can be turned off when nobody is in the room, which enable to perform the same service by using the bulb less. This use characteristic does not apply for technologies which can only be used in one fashion (such as hair dryers, irons…) though. Modifying load rate requires modification of consumer's behaviors or of industry behavior (e.g in the freight sector), possibly through public incitation or communication campaigns.

In this framework, concerning heating system, heating more people with the same use of heating technology because more people live in the same place represents technical organizational efficiency.

e. Energy efficiency may be improved by technology improvement or by technology use optimization

Each technology used has a specific energy efficiency[6]. Energy efficiency is the lever associated with the technology. Energy efficiency can be associated to the design of the technology, or to the way it is used. Some technologies have energy optimal operating points and use cases. For example, ICE cars have an energy optimal speed, and an energy optimal way to be driven. For many technologies though, operation is automatically energy optimized.

Energy efficiency improvements from design evolution are uncertain. They are often explained in scenarios through global mechanisms such as the learning effect, with no concrete explanation for each technology of why the improvements should go on in the future on the same trend as before (see boundary conditions section).

Some technologies might be associated to several energy vectors, which may require to define several energy efficiencies.

f. Disagregation levels to get deeper in behaviors details

This framework provides questions to detect levers to reduce energy consumption; it also provides a way to think about the key explanatory factors of energy consumption from lifestyles, technical and organizational environment (infrastructures, available technologies…).

However, it handles only the average situation, which might not be sufficient for a detailed sociological account of how the demand evolves. To overcome this limitation, the framework can further be broken down into energy service sub-systems when it is deemed relevant with regard to different practices among sub-populations. For example, the mobility system can be broken down into three sub-systems depicting significantly different mobility practices: "Mobility in urban areas" / "Mobility in rural areas" / "Mobility in intermediate density areas".

A more sociologically detailed representation is proposed in (Le Gallic et al., 2017): they model the population and lifestyle system. Hypotheses can then be taken for specific groups of people which are homogenous in terms of energy service demand. For example, short distance mobility evolution can be proposed for households aged between 30 and 35 with 2 children living in rural areas for their daily commute trips. The model then computes the associated new energy service demand (in this example, the total number of travelled kilometers for passengers for short distance mobility).

The proposed model encourages scenario producers to be consistent between the new transversal lifestyles they imagine, their diffusion in the population, the demographic structure of the population, and the level of service demand.

For example, it may be difficult to imagine the overall, average effect of implementing a bike system in a country. Systematically imagining what different groups of individuals would do with such a system enables to make the sociological storyline much more precise and to provide an substantiated hypothesis for travelled kilometers for different modes with a bike system (The Shift Project, 2017).

g. Sobriety of efficiency? Often a subjective matter

Often, levers excluding demand sobriety are collectively called "efficiency measures", except for some TOE measures. Indeed, as TOE measures modify the energy services basket, some might consider that the overall

[6] Efficiency of an aggregate of technologies may be defined as the energy efficiency averaged over the whole set of the considered technology and the many ways they can be used). For example, small ICE car consumption may be averaged over the type of roads and driver profiles.

comfort of life is reduced. For example, it may be considered that wearing a sweater to reduce thermostat set point is an overall loss of comfort/utility. Similarly, it may be considered that reducing floor space par inhabitant by sharing more space represents an overall loss of comfort, and hence it would be called sobriety (such as in (Association négaWatt, 2014)). In other words, the use of the terms "sobriety" and "efficiency" in literature are often linked to a (necessarily subjective) judgement of loss of comfort. Sobriety is associated with an overall loss of comfort whereas efficiency is associated with no loss of comfort (Brown et al., 2018).

h. Different actors can trigger different levers

As illustrated in the examples hereabove, it is not only individuals who have to be targeted for energy consumption policies. Lifestyles with certain levels of comfort and high energy services demand have not necessarily evolved from individual choices. For example, industrial offer for cars scarcely provide small and low power vehicles. Infrastructure design might make low-energy mobility modes dangerous, etc (Roy et al., 2012). Hence the different levers affecting energy demand involve political, cultural, physical environment and individual aspects. Such levers rise important questions about loss-of-comfort sharing among society (see desirability section).

Recommendations for scenario producers

For scenarios determining demand evolution through a behavior-based approach, the described framework should be used for adopting a common language about demand evolution. A list of the different energy service systems may be provided; e.g. long-distance mobility (system), space heating (system), and so on. For each of them, a list of the different sociological aspects which are taken into account may be provided; e.g. fabric of living place: urban or rural; level of revenue; type of building, and so on.

For each energy service system, the types of levers which are activated may be described. If levers other than energy efficiency are activated, substantiation might be provided about the desirability of the lever. In order to do so, the possible losses of comfort should be qualitatively assessed for each lever, as well as its possible side-benefits. Considerations on time horizon may be included in this assessment. For example, carpooling may generate a loss of comfort on the short-run for schedule reorganization, but generate social link on the medium-term.

D. Rebound effect: a complex economic effect heterogeneously integrated in future studies

Now that the proposed frame to think energy demand has been described, we use it to discuss rebound effect and how it is integrated in the computation of energy demand in different future studies.

1. Rebound effect on energy demand is a complex economic effect corresponding to a greater energy demand than what would have been expected after some energy saving actions

Rebound effect is the reduction in expected gains from a policy, market and/or technology interventions aimed at environmental efficiency improvements, because of behavioral or other systemic responses.

Typical examples of rebound effect are an increase in car use when fuel efficiency is increased, or the purchase of a journey by plane thanks to money from energy savings at home.

It is generally expressed as a ratio:

$$RE = \frac{Expected\ savings - Actual\ savings}{Expected\ savings}$$

For instance, if a 5% improvement in vehicle fuel efficiency results in only a 2% drop in fuel use, there is a 60% rebound effect. Rebound effect can be higher than 100%. This is called 'backfire'.

Rebound effect theory can apply to the use of energy consumption but also on any natural resource or other input, such as labor. It usually happens after a change in costs, but can more generally be related to other types of changes like time savings, change in weight, available space, etc. Despite these are interesting elements to keep in mind, we focus here on rebound effect on energy consumption happening through change in costs.

It is a key phenomenon with broad spectrum and significant impact: it should be addressed for every measure related to energy efficiency (thermal building renovation, vehicle fuel efficiency, etc.) or additional purchasing power (through additional growth, energy prices reduction, sobriety, etc.). However it is also challenging to quantify.

As explained in note about Rebound effect, three types of rebounds regarding energy services are usually depicted in the literature:

- Direct rebound is an increase in demand for the now cheaper energy services. For example a reduction in heating costs after energy efficiency measures is followed by an increase in chosen household temperature.
- Indirect rebound is an increase in demand for other energy services after the initial cost reduction in some goods or services. For example the same reduction in heating costs after energy efficiency measures can also be followed by the purchase of a bigger and more polluting car thanks to money savings. Indirect rebound tends to be less studied than direct rebound effect but should not be neglected. In some cases it has a bigger impact than direct effect.
  Both direct and indirect rebounds are demand-side behavioral responses, and thus microeconomic effects. They are also both composed of a substitution and an income effect.
- Economy-wide rebound is an increase in energy use after an energy efficiency improvement through market adjustments and innovation channels. It is thus a macroeconomic effect. For example the reductions in energy and carbon intensities lead to a reduction in producer's costs and, therefore, prices and consequently more output and exports (Barker, Dagoumas, & Rubin, 2009). It is far less understood than microeconomic rebounds. Economy-wide effect is composed of macroeconomic price and growth effects.
  Evaluating economy-wide rebounds brings the same challenges as in most macroeconomics research: global economy is a single, interconnected, complex dynamic system, making definitive arguments about cause and effect probably impossible.

These rebounds in consumption can be described as emerging from different mechanisms:

- Income mechanism[7] is related to extra-money. By making energy services cheaper, energy efficiency improvements increase the real income of households. The question here is: "If a consumer is given an extra euro, how is it going to be used?" The consumer can thereby increase consumption of the improved service (direct rebound) or spend it on another good or service (indirect rebound). This is determined by consumption structure (ADEME, 2016).
- Substitution mechanism is related to a change in relative prices. After an energy efficiency measure, the improved service is now cheaper than before. Therefore, with the same real income, households may shift their consumption patterns according to the new relative prices between goods and services. This mechanism can both lead to an increase and decrease in energy consumption and/or GHG emissions depending on the substitution choices that are being made.
- Macroeconomic price mechanism applies through the equilibrium price of energy: after an energy efficiency improvement the energy demand is reduced. This drives down the price, which encourages a re-increase of demand.
- Macroeconomic growth mechanisms arise from innovation and reduction in energy costs for producers (particularly for energy-intensive industries), especially through three main channel:
  - Deployment of inframarginal resources, which is money in the economy that would previously have been spent on energy. It can be seen as a supply-side analogy to the income effect.

[7] The different mechanisms are usually called "effects" in the literature. However the word effect is usually used to describe an impact *on* something, whereas we want to describe here a process *by which* rebound effects appear, hence the use of the word "mechanism".

- o Sectoral reallocation. It can be seen as a supply-side analogy to the substitution effect and is most commonly discussed: if an industry acquires a more energy efficient process, it then spends more in using this extra process.
- o Induced innovation in one sector that may spill over to others. For example, the development of lighter, stronger materials for fuel-efficient cars might lead to better airplanes, boosting energy use in the aviation sector (Gillingham, Kotchen, Rapson, & Wagner, 2013).

Note that those rebounds and mechanisms may be described under different terms in the literature, or may contain slightly different meanings. These descriptions always relate to the economic theoretical frame which is used. As explained in the note about rebound effects, measurements of the different rebounds in developed countries economies lead to a low estimate of 20 % for the aggregate rebound effect after energy efficiency measures.

Rebound effects are complex effects involving the whole economy. In the meantime, they are known to happen in specific cases which extensively happen in future studies' scenarios such as energy efficiency improvements. Sobriety measures may be considered to trigger the same kind of effects as energy efficiency measures (e.g., income mechanism and macroeconomic price mechanism would happen under such measures).

2. Rebound effect is heterogeneously integrated in different studies

a. Technical studies do not implement any economic feedback between the energy system and energy service demand whereas this feedback is the essence of rebound effects

Future studies using the behavior-based approach to simulate energy demand implicitly cover the rebound effect by entirely defining the energy consumption behaviors of individuals and companies. The studies we reviewed in this category do not explicitly consider rebound effect: lifestyles and behaviors are described as if rebound effects were already accounted for but no narrative is provided to explain how this happens.

Conceptually, this aspect could be handled in two ways for behavior-based approaches:

- either rebound effects are prevented by some political measures in scenarios. The goal of these political measures would be to contain, or reduce rebound effects. For example, measures diverting purchasing power to lower energy consumption activities, or to lower CO_2 emissions activities. Note that to be efficient these measures must take into account macroeconomic effects. For example, taxation on energy for all economic actors could be an efficient way to divert consumption from high energy activities, but the fact that taxation income for the State will be redistributed in some way should be taken into account.

- or they are already included in the described behaviors. The second way would consist in providing rebound effect simulation results, or a narrative, to justify the fact that consumption behaviors could be re-organized in the proposed way without requiring any policy to contain rebound effects.

In a very similar fashion, some studies using GDP-based approach for demand define demand in their transformational scenarios by applying some energy efficiency measures to their reference scenario (such as in (ECF, 2010; Greenpeace, 2015)). However, the results of these energy efficiency measures do not consider any rebound effect. The measures are just applied, and the resulting demand becomes an input to determine the supply-side of the energy system.

Similarly, studies using the supply-side only approaches merely assume an energy demand level with no regard to rebound effects.

Finally, the German study (Fraunhofer ISE, 2015) cost-optimizes the energy system supply-side along some parts of the demand-side. Technology operation demand is a boundary condition for this study (whereas in the supply-side only approaches energy demand is the boundary condition). The optimization algorithm then selects the specific demand-side technologies fulfilling this demand, considering their costs and the energy savings they enable. No direct rebound effect is considered in the hypotheses of these energy savings.

All these studies have a common point: their demand levels are economically independent from the energy system evolution. In other word, there is no economic feedback loop between energy demand and energy system evolution.

Hence by nature those studies cannot model any form of macroeconomic rebound effect. We call those studies the *technical studies* (as opposed to the *partial equilibrium studies* in which the demand is influenced by the energy system evolution with feedback loops).

b. Partial equilibrium studies implement this feedback to some extent; however this does not necessarily imply they model rebound effects

Partial equilibrium studies use models implementing a feedback loop between the energy system evolution and the demand evolution. As a consequence, they have the potential to simulate some forms of macroeconomic rebound effects.

We found two main types of models in this category. PRIMES represents the first type and POLES and the WEM represent the second type.

PRIMES computes energy demand through representative consumers (a consumer for households and a consumer for industries); each representative consumer is actually a distribution of consumption behaviors (for example, modeling different mobility behaviors, distributed over different modes). The representative consumers have a global budget to spend, directly determined by the exogenous GDP hypothesis. They allocate this budget on different activities, some of them triggering an energy service demand (driving one's car, turning on the oven, producing goods (for industries)...), the others not (for example, buying a table, food or an oven) (see Figure 5). Hence if the budget increases, or if energy efficiency increases, or if energy price decreases, the representative consumer spends its extra purchasing power in extra consumption.

For example, if representative consumers acquire energy efficient appliances (for example, a more energy efficient car), then their energy consumption decreases, and their extra purchasing power is reinjected in other consumptions, as defined by the utility function (that is, the modelled preferences of the consumers). Note that if the extra purchasing power is reinjected in more of the same energy service consumption (more driving), it is called direct rebound effect. If it is reinjected in other energy services (such as heating more their house), it is called indirect rebound effect.

If the extra purchasing power comes from an energy price decrease (e.g. because the supply-side system becomes less expensive), then the simulated rebound effects are macroeconomic price effects.

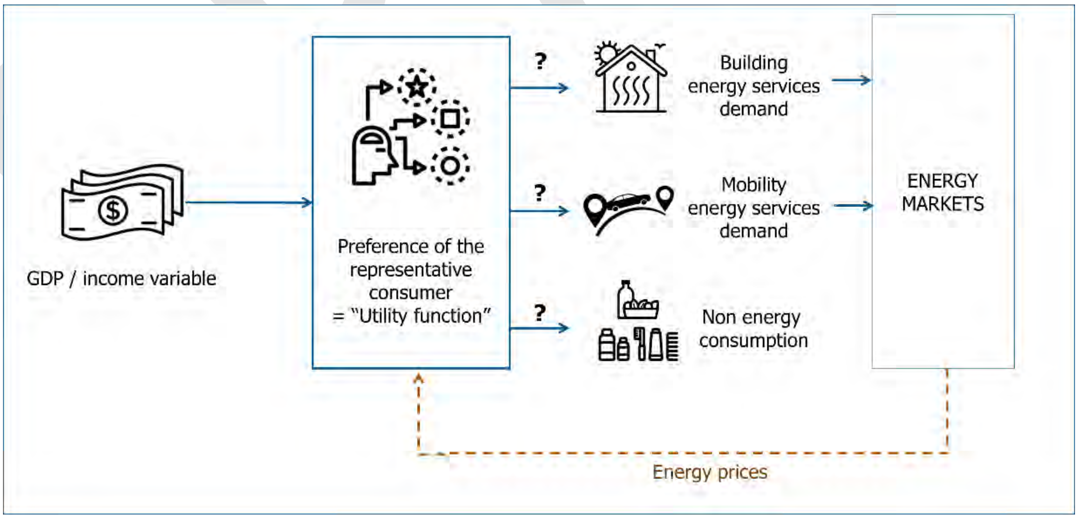

Figure 5: PRIMES model simulates representative consumers which allocate an exogenously fixed income to different consumption activities. Hence if the budget increases, or if energy efficiency increases, or if energy price decreases, the representative consumer spends its extra purchasing power in extra consumption. This models direct, indirect and macroeconomic price rebound effects, as long as some growth rebound effects.

Hence PRIMES models several types of rebound effects (direct rebounds, some indirect rebounds and price rebounds). However, PRIMES cannot model all the rebound effects because it only models the energy sector. Hence, for example, extra purchasing power leading to buying more goods does not loop back to the goods production sector.

POLES and the WEM operate in a different way to determine energy demand evolution. They first compute the energy service demand from GDP and other macroeconomic variables of the different regions they model. From the energy service demand, they define which technologies will fulfill the demand based on different exogenous variables as well as on endogenously computed energy prices. These technologies then lead to energy carrier supply-side evolutions, and to new energy prices.

The nature of the feedback loop from the energy system to the energy demand is one of demand elasticity to price for technology choices. This way to operate only partially models rebound effects. No purchasing power is modelled hence energy efficiency directly leads to a lower energy consumption without direct or indirect rebound effect.

However, for some consumption sectors, extra feedback loops are implemented directly towards the energy service demand: energy service demand depends on energy prices. This enables to take into account macroeconomic price rebound effects (at least partially).

The most advanced account of rebound effect in these models is the transport sector of the WEM: a specific elasticity coefficient for overall transport demand is included based on the unitary consumption of vehicles. This feedback loop is specifically dedicated to modelling the direct rebound effect in this sector.

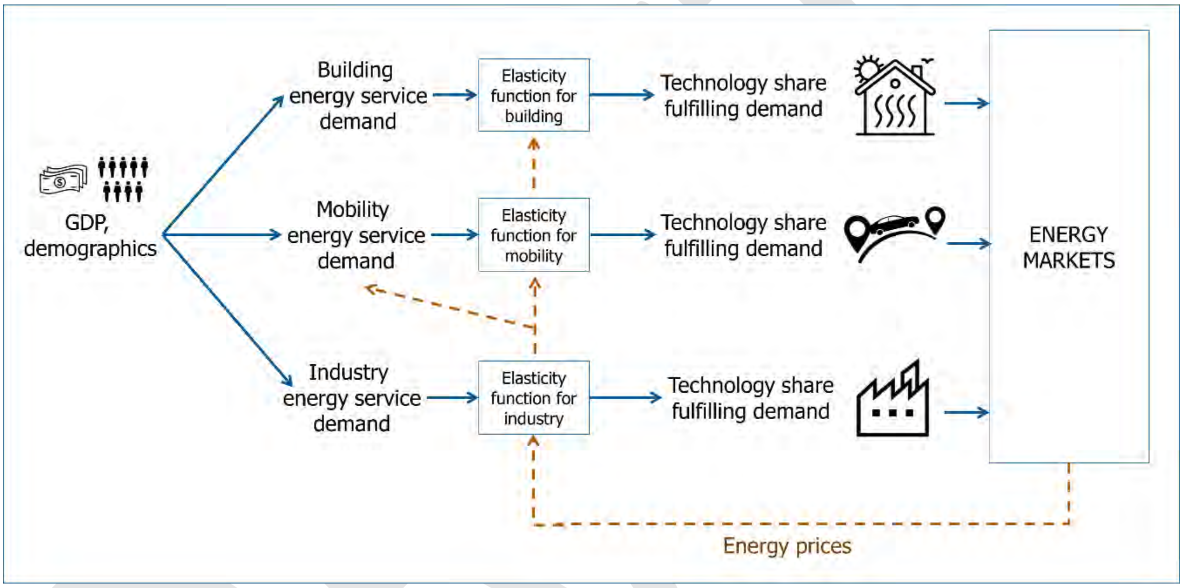

Figure 6: POLES model does not implement specific mechanisms to model rebound effects. However, its structure enables a partial account of price rebound effects, especially in the mobility sector through an elasticity feedback loop between energy price and mobility service demand.

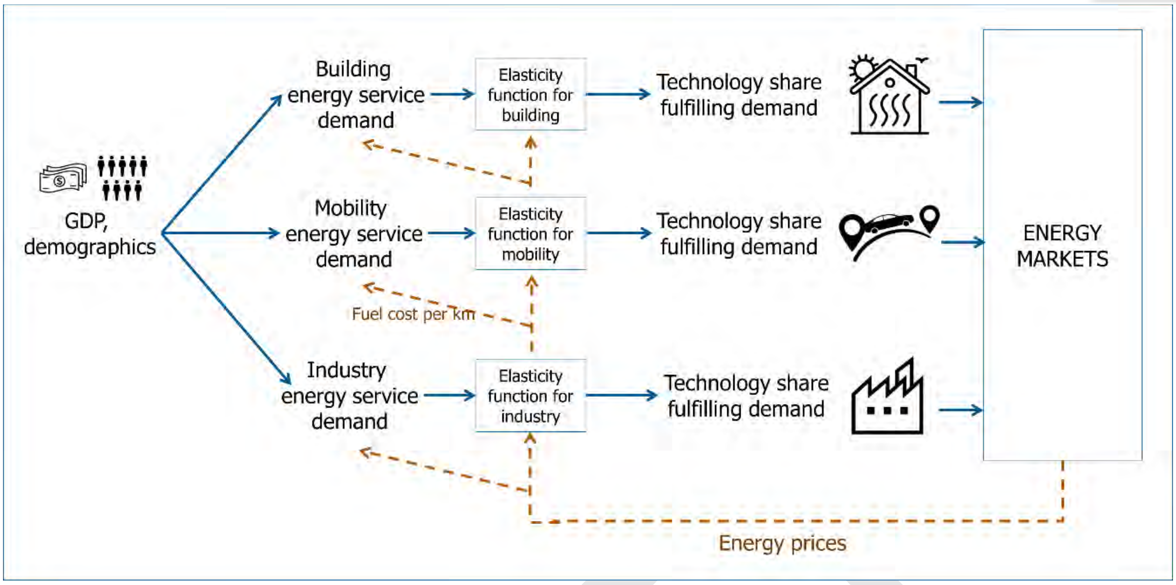

Figure 7: The WEM implements a specific mechanism to model a direct rebound effect in the mobility sector. In other sectors, no specific mechanisms are implemented but price rebound effects may be partially simulated through elasticities between energy prices and energy services demand.

Hence these models implement some form of price rebound effects, and partially some direct rebound effects.

Note that the simulations of some rebounds in PRIMES, the WEM or POLES depend on the specific parameters defining their magnitudes (such as the utility function in PRIMES, and the different elasticity functions in POLES and the WEM). These parameters are tuned based on measurements of the real world, hence they depend on the economic frame and economic policies that have been implemented in the real world so far. These values might not adequately model what would happen under policies different in nature or in magnitude than what happened in the past. In other words, this tuning may not be adapted to simulate transformational scenarios[8].

Recommendations for scenario producers

Scenario producers should be explicit about the interaction between energy service demand evolution and the energy system evolution in their study: *is the study a technical one or a partial equilibrium one?*

Scenario producers designing *technical studies* should consider and report the following aspects of rebound effect:

- behavior and technology evolutions, or economic evolutions prone to generate rebound effects such as behavior changes driven by sobriety, or more energy efficient technologies, or large investments in the transition industry
- policies required to obtain the described overall behaviors, such as policies limiting the rebound effects. By doing so, macroeconomic considerations may be required.
- other reasons to justify the fact that the described overall behaviors would not be prone to rebound effects (such as already manually integrated rebound rate).

Scenario producers designing *partial equilibrium studies* should consider and report the following aspects of rebound effect:

- transition actions which are prone to generate rebound effects, such as energy efficiency measures or large investments in the transition industry
- the different types of rebound effects which are modelled

[8] In PRIMES, preferences of the representative consumer seem to be fixed for the whole scenario timeframe, as suggested in (European Commission, 2011).

- the parameters at the origin of the modelled rebounds (elasticities, utility function…), and if they are static along the scenario timeframe. If they are dynamic, considerations on their determinants may be provided.

In case some rebound effects are not modelled, a narrative substantiating the fact that the absence of modelling does not impair the scenario internal consistency (policies dedicated to avoid these rebound effects, demonstration that these effects have negligible impacts…) should be performed.

Some more details on typical values for rebound effects can be found in fiche rebound effect.

E. Energy efficiency is the king of levers in the scenario community, leading to an overall focus on technologies

1. Levers other than pure energy efficiency modifies the comfort of use

Energy efficiency is generally seen as the best and top priority lever. Indeed, it enables to reduce energy consumption without changing habits at all.

Demand sobriety requires significant behavioral changes (also see section on lifestyles); all other levers do not reduce human demand, in theory. In practice, losses of comfort or side benefits may appear:

- TOE enables to fulfill human demand with a lower energy service demand; however, it might come with an overall reduction in comfort, or utility, depending on the cases. For example, putting two sweaters on may feel less comfortable than having a T-shirt (T-O sobriety for heating system). Teleworking comes with side effects (for example, not seeing team members so often) which may be felt as uncomfortable, or may not be accepted by companies (loss in productivity). Flat sharing enables to lower heating space service demand, but may be seen as uncomfortable.
- Technology shift towards lower consumption technologies may also be associated with some sort of incomfort. For example, switching from ICE car to electric car is associated with a shorter range, and longer charging times, which may be felt as less flexible and practical. Switching to bike for shorter trips may be associated with lower comfort especially during rainy, or hot weather; it is however associated with health positive effects. Switching from gas house heating system to a heat pump may be associated to a lower comfort during very cold period (heat pump less efficient).
- Load rate increase to decrease energy consumption may also be associated to a lower level of comfort. For example, long-distance carpooling is an uncomfortable practice for some, and it may be inconvenient to adapt schedules for short distance trips; for others, carpooling may be a source of positive social link.

As a consequence, all the levers but energy efficiency may lead to acceptance issues, as they can impact lifestyles. On the contrary, energy efficiency measures are not associated with any inconvenience. Hence it represents a central lever for policy to target (Riahi et al., 2012).

It comes as natural that most scenarios gives energy efficiency measures the greatest role in energy consumption reduction. On the contrary, few scenarios see demand sobriety, T/O sobriety, technology shift or load rate increase as levers.

2. The scenario community mostly focuses on technological improvement through energy efficiency, risking to neglect the insights from social sciences

In virtually all scenarios, energy efficiency through technological improvement is the preferred way of action because it is easily translated into market-based levers (which easily fit market-based models) or into technology-levers (which easily fit optimization models), and because it apparently goes towards all sustainability goals with putting all the transition effort on corporations, asked to propose more energy efficient designs at lower costs, and ideally lower social and environmental negative impacts; in turn, no change at all in lifestyles or in society organization are required, which avoids to rise more difficult questions such as geopolitical, political, institutional and cultural questions (also see lifestyles). In other words, energy efficiency provides a substantial comfort for scenario producers: even their transformational scenarios remain in a roughly *business-as-usual* world, except for the availability of technologies part. This considerably limits the amount of extra-hypotheses necessary to describe the world and also limits the possibilities of critiques from stakeholders, as a low number of transformations is proposed. In turn, questions and critiques naturally focus on the technological feasibility of such improvements (in terms of dynamics with regards to the transition deadlines) as well as on their various impacts on environment, society and economy.

Through this massive use of energy efficiency in scenarios, the debate on energy transition naturally focuses on technologies, their costs and impacts instead of keeping a global outlook including a larger amount of insight from social sciences (psychology, sociology, political sciences…). Technological improvement, in those scenarios, is actually a necessary condition for not adapting behaviors and institutions. Hence technological improvement is a key parameter of those scenarios and as such should be thoroughly substantiated.

Only local/national scenarios which are resources-driven propose other ways of action. Indeed, they adapt behaviors and practices to local resources, as mentioned in the introduction.

3. In scenarios, energy efficiency evolution is determined through a technology-rich approach or directly assumed

As previously explained, scenarios using a GDP-approach to determine demand start from GDP and then determine demand per sector in line with the GDP evolutions.

Most of them assume global energy intensity of the GDP evolutions per sector in an aggregated way. Hence they make no study about individual technologies and instead make macro assumptions about technology improvements (DGEC/CGDD/ADEME, 2015; ECF, 2010; Riahi et al., 2012). The assumed energy intensity trends are usually in discontinuity from historical trends, as illustrated for the developing countries' trend in (Riahi et al., 2012), going from -1.0% per annum in the past to a sustained -3.1% per annum until 2050 in the Efficiency pathway.

Even though PRIMES has a GDP-based approach, it is also *demand-side technology-rich*. In other words, it defines precisely different technologies in a disaggregated way, and the evolution of the stock of these technologies through models of the stock and the associated flows (technology being bought and being discarded).

Hence studies using PRIMES model define several vintages ("base", "improved", "advanced" and "best technology") for demand side technologies. These vintages have increasing capital costs and efficiency (the more advanced technologies are more expensive but more energy efficient). PRIMES assumes a trend to buy best technologies as market barriers are removed and as carbon price increases. Hence a link is created between energy efficiency policies and technologies demand and production. In other words, technologies share evolves through market-based mechanisms (European Commission, 2016). Energy efficiency improvement emerge from the best technologies being integrated to the technology mix through market mechanisms.

Studies using the behavior-based approach to determine demand, define a storyline for the evolution of demand including evolution of technologies and their uses. They are also demand-side technology-rich, but the use of the technologies is largely driven by energy consumption behaviors and by the benevolent planner defining the technology share. In those scenarios, the technology choices of the benevolent planner are substantiated through a storyline (ADEME, 2012; Association négaWatt, 2014; RTE, 2017; SLC, 2017; Barton et al., 2013).

4. Providing a *concretely* substantiated storyline for energy efficiency improvements is key

Technology-rich scenarios can easily provide a storyline about how and why technologies evolve as they do, unlike technology-poor scenarios (those assuming a global energy efficiency evolution). However, as a key hypothesis, energy efficiency improvement should be concretely substantiated (see Future studies).

(Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012) suggests several ways to foster energy efficiency: increase energy price, measure energy consumption at household level to provide an incentive to reduce consumption through a proper price signal, provide more information about appliance energy consumption at selling point, raise awareness among industry professionals about energy consumption of the appliances they produce.

On the one hand, mitigation scenarios assume a large leap between the currently observed energy efficiency gains and the ones happening all along their timeframe, asking the question of the feasibility of such a sustained leap (Samadi et al., 2017). On the other hand, it may be argued that no strong effort has been made in that direction because incentive is for most products to reduce production costs (mostly accounted by work force) as opposed to reduce energy consumption[9].

Recommendations for scenario producers

Scenario producers using the GDP-based approach should provide an assessment of the technological demand-side effort which is performed in their scenarios in terms of energy efficiency, via the evolution with time of the relative decrease in GDP energy intensity compared to previous year.

All scenario producers should provide a storyline to thoroughly substantiate how this energy efficiency effort will be sustained in their scenarios, especially for scenarios putting emphasis on energy efficiency, along the following aspects:

- Sustained technological improvement: under what incentive will companies decrease energy consumption of their products? Where is the room for technological improvement as seen from today, for each technology (including business-to-business (B2B) technologies)?
- Sustained incentive to buy energy efficient technologies: under what incentives will consumers (individuals, companies, and states) buy energy efficient products? In particular, in which domain(s) and under what incentives will companies switch to energy efficient processes?

F. Zoom on the practices for determining demand evolution in different consumption sectors

The proposed framework can be used to summarize the future studies practices when it comes to determine demand evolution under a behavior-based approach. We propose such a benchmark of observed practices for the usual different consumption sectors: building, passenger mobility, freight and industry/agriculture.

1. Building sector

Building demand is usually composed of space heating, water heating, and electric appliances. Demand for space heating has a large inertia since it is linked to building envelope. Other aspects of building demand (water heating, cooking, electric appliances) have a lower inertia (Association négaWatt, 2014).

Demand in the building sector can be segregated by the functions of buildings: housings or commercial, tertiary or industry buildings and by the types of buildings: individual house or shared buildings.

a. Space and water heating and cooling

Space heating/cooling directly depends on level of temperature demand (human demand), building surface and building thermal performance (technical and organizational system). Hence for space and water heating/cooling, building stock can be usefully separated into existing buildings and new buildings.

Existing buildings are those existing at start year of the scenario. Their number decreases with time, with the demolition rate. They can be retrofitted for thermal insulation. Scenarios usually specify the type of retrofit which is performed (what parts of the envelope are insulated, double glazing, etc) (Barton et al., 2013). Within the existing buildings, further distinction can be usefully made per thermal insulation performance and per type of space

[9] Only for a few products/services does energy consumption represent a significant cost. For example, commercial aviation sector has a strong incentive to reduce kerosene consumption because kerosene represents the greatest part of the price for final consumer.

heating/cooling system. Thermal insulation performance can be evaluated through the age of the building (Association négaWatt, 2014). Similarly, water tanks for hot water can be insulated.

For new buildings, growth has to be estimated: population growth as well as hypotheses about surfaces per inhabitant. These buildings are generally not retrofitted as they are built with insulation standards and heating systems standards. This is why they can be separated from existing buildings. The energy efficiency standards for new buildings may evolve during the scenario timeframe.

Dwelling size significantly depends on the type of dwelling: individual houses or shared buildings.

For tertiary and commerce buildings, the volume of buildings can be associated with demographics, amount of service per inhabitant, and surface per unit of service. Services address different audiences. Hence the level of each particular service can be indexed on the evolution of its target population. For example, education targets people under 25 and as such demand for education can be projected using demographic assumptions for this share of population (Association négaWatt, 2014).

Determining air cooling consumption is more difficult for temperate countries because population is not yet equipped in cooling systems and the emerging need from climate change is difficult to assess (Association négaWatt, 2014). (Schweizer & Morgan, 2016) perform an assessment for the US based on a regression of equipment rate versus ambient temperature for different States.

Energy demand from space heating then has to be translated into vector demand, through the *technology share*. District heating, community scale biogas CHP, fuel cell micro CHP, stirling engine micro CHP, solid fuel boiler, oil fired boiler, resistive heating, ground-source heat pump, gas boiler… (Barton et al., 2013)

Each technology is associated with a vector and an energy efficiency. Hypotheses on energy efficiency evolution can be made for each technology.

The same has to be made for water heating. Technology choice can be made depending on the type of building: individual house or shared building (Association négaWatt, 2014).

b. Domestic appliances

Domestic appliances cover equipment for lighting, cooking (cooking robots), cooling (fridge-freezers, refrigerator and freezers), wet appliances (washing machines, dryers and dishwashers), and brown appliances (TV, video/ DVD players, set top boxes, ICT, telephone chargers, etc), as well as fans, pumps for ambiance conditioning, vacuum cleaner, iron, hygiene appliances (hair dryer, hair), DIY appliances, elevators…

These appliances are very generally thought of as fueled by power, as opposed to other energy vectors. Hence demand analysis is a bit simpler than for other types of demands: all the technologies are associated with electricity. However, still several technologies with different energy efficiencies and costs can be modelled, and the evolution of the appliance mix can be modelled.

Demand from electric appliances can be estimated based on a highly disaggregated method, by analyzing each use: within what context the appliance is used, how these uses can evolve, what the efficiency of the used equipment is. Hence several types of human demand are defined, such as laundry washing, laundry drying, ironing, dish washing, cooling food, freezing food, lighting, TV entertainment, sound entertainment, communication, air circulation, elevators and so on (Association négaWatt, 2014). Also, for conservative rationale, new, unknown uses can be added (Association négaWatt, 2014).

The primary driver which is used in scenarios to determine demand is households' number growth, based on demographics hypotheses.

Then some scenarios implement demand sobriety: reduced demand for TV entertainment, stabilization of the size of TV sets, enabling a stabilization of their consumption (Association négaWatt, 2014).

Scenarios propose the following TOE levers:

- evolution of the number of appliances per household (greater household density favors communalization of equipment use such as lighting, fridges, cooking, fans) (Association négaWatt, 2014; Barton et al., 2013).
- Evolution of electronics so that appliance sleep mode consumes less power.

They propose load rates evolutions for washing machines and dryers as well as for fridges and freezers, based on an analysis of current practices. These evolutions are slow because they happen through an adaptation of the appliance size to household demand (Association négaWatt, 2014).

Finally, some hypotheses about energy efficiency of appliances are made.

The same kind of method can be applied for tertiary specific electricy uses. These can be gathered into the following categories: lighting, informatics, tertiary processes (medical imagery), building management (elevators…). It also includes such services as public light, telecommunication operation, food storage, water management. Finally, some research facilities, as well as the military sector could also be considered for demand analysis.

2. Mobility sector

a. Different types of mobility demands

Mobility system is a complex system, aggregating several different natures of human demands. Hence in the behavior-based approach, mobility demand is divided in several categories in order to estimate its evolution in a realistic way.

Human demand can be categorized along the following dimensions (Association négaWatt, 2014).

- Type of trip (based on its distance, frequency and motive)
- Urban density of the trip
- Distance of the trip

Other categorizations have been proposed (The Shift Project, 2018):

- Urban density of the trip
- Distance of the trip
- Popularity of the trip (possibility to communalize the trip with other people)
- Specific need to transport a load or person

These categories are important because they are drivers of TOE, occupancy rates and technology share[10]. For example, the urban density of the trip determines which mode can be used and hence influences the technology share. (Le Gallic et al., 2017) determine those important categories by decision tree analyses based on large mobility surveys.

b. The levers to curve energy demand in mobility

A few scenarios implement sobriety through a reduction in long-distance trip average distance, long distance trips being considered in this case as a luxury which can be partly questioned.

Usual TOE levers are telework, grocery delivery and city planning, each enabling to reduce the average distance of trips for different motives while still providing access to the motive.

These levers are triggered by energy prices increase, flight taxes, regulations on access to city center by car, investments in infrastructure and so on.

Within passenger mobility, technology shift is usually from ICE cars to electric cars, and/or from privately owned car use to other means (public transportation, bike, shared small vehicles). The shift may be triggered by space densification hence shorter distances to travel; public transportation development for urban areas and specialized taxis for rural areas; car sharing systems; bike system development; or natural cultural trends from the youth.

[10] Usually called modal share for mobility

Load rate (usually called occupancy rate for mobility sector) may be increased for car use through carpooling policies (infrastructure implementation, infrastructure allocation).

Scenarios also assume energy efficiency improvements for the different types of vehicles.

Energy efficiency, as measured in consumed energy per km travelled, depends on the use of the vehicle, such as heating and cooling of the vehicle, the way to drive (especially speed and acceleration patterns), the quality of the road and outside temperature for ICE vehicles (colder weather means a lower engine efficiency).

For ICE cars, heating the car requires no extra consumption because heating comes from the heat losses from fuel combustion. However, cooling the car leads to extra consumption, between 3 and 20 % (« Heating and Car Mileage », 2009).

For EVs, engine operation and efficiency does not depend on temperature. However, car heating (and cooling) comes from extra power consumption, which represents a 10 to 20% extra consumption compared to no car heating or cooling (« Heating and air conditioning in cars », 2019). Hence climate and weather dependence is greater with EVs than with ICE vehicles.

3. Freight sector

Freight system induces an energy demand. Freight could be seen as the system enabling the connection between end-consumers and products. As such, last mile delivery could be included in freight system even if it is performed by the end consumer herself, which is the view we adopt here.

For freight demand, no scenario invokes demand sobriety (which would be equivalent to deciding not to transport some goods which have been produced).

However scenarios put into play TO sobriety through changes in the supply chain structure, supply chain philosophy (just on time), routing optimization, changes in urban forms, implementation of last-mile delivery systems, or eco-design of products to reduce packaging size (ADEME, 2014; Association négaWatt, 2014; The Shift Project, 2017; J. Allen & M. Browne, 2010).

The usually considered technologies for modal share are train, road transport (light duty, heavy duty, very heavy duty), or inland navigation. International shipping by boat or plane are usually not considered. Several types of fuels can be imagined for road transport, other than diesel: electrical for light duty or for e-highways trucks (via electric road systems) (European Climate Foundation, 2018); natural gas, hydrogen.

Load rate evolves through more backhauling[11] (ADEME, 2014; J. Allen & M. Browne, 2010).

Finally, energy efficiency hypotheses are taken. These hypotheses can be based on precise expectations on energy efficiency technologies deployment rates (European Climate Foundation, 2018).

4. Industry/agriculture sectors

c. Top-down approach

Energy demand from industrial processes (including energy processes within agriculture) can be assessed through PIB evolution and energy use per unit of economic output (energy intensity).

Economic output depends on offshoring and inshoring (in case the assessment perimeter is geographical) or on imports and exports (if the assessment perimeter is associated with end consumers).

Electricity demand can then be deduced from energy demand evolution by making assumptions on the technology share (new processes using electricity appearing, or processes switching from heat vector to electricity vector). Energy efficiency evolution is exogenously assumed for each industrial processes.

[11] a truck which backhauls transports goods on its way back to its usual loading point / warehouse

d. Bottom-up approach

Another method to assess industrial energy demand is to compute the necessary production of goods and materials in the scenario, based on the hypotheses in the end-consumption sectors (mobility, housing).

Also the part of the goods demand which is produced in the studied territory must be assumed, for example through hypotheses of offshoring or inshoring behaviors of industries.

Then hypotheses on demand sobriety and the STOS are taken: demand sobriety for goods which are deemed useless, stabilization of the sizes of some equipment (size of TV sets), evolution of entertainment appliances (TV sets, boxes, etc.) providing each a greater number of services so less equipment is produced, eco-design (reduction in size and weight of cars…); longer life durations from more maintenance and design standards; reuse of packaging (bottles).

Then specific energy efficiency measures are assumed for each type of process.

G. Climate change impacts long-term energy consumption

The effects of climate change on consumption apply on the total amount of energy consumed per year as well as on the instant power to produce. Peak load may evolve both in terms of magnitude and in terms of periods during the year (see section on power system operation). For example, peak load might increase in hot countries due to increased use of air conditioning, but it might decrease in colder countries due to decreased use of heating.

The most obvious changes on demand are those on weather sensitive demand, such as demand for space heating and cooling. But other changes can be expected, mostly changes related to the adaptation to the impacts of climate change.

Climate change may increase summertime temperatures, in turn increasing demand for air conditioning for buildings. Estimating this increase requires to estimate the temperature increase for different areas and for different periods so as to assess the increase in air conditioning use (more air conditioning devices, which are turned on more often, and use more power because outside air is warmer) (Schweizer & Morgan, 2016). On the other hand, wintertime temperatures may also increase, reducing the need for building heating.

Similarly, the use of air cooling and heating for cars and trucks will be affected by climate change. Also, internal combustion engine economy depends on air temperature: the colder the outside air, the more fuel must be injected into the cylinder at each cycle to provide the same amount of mechanical energy to the wheels (« Heating and Car Mileage », 2009). Hence average consumption of cars and trucks might evolve with climate change.

However, these effects depend on the engine technology which is used: internal combustion engines do not consume more fuel for air heating, as the heat is directly extracted from heat losses in the combustion engine and injected in the passenger compartment. However, they consume more fuel when air cooling is on[12]. On the opposite, electrical cars produce nearly no engine heat loss, hence they consume 10 to 20 % more power for heating or cooling (« Heating and air conditioning in cars », 2019).

Industrial processes also require heating and cooling. Industrial heating and cooling are often neglected in studies about climate change impacts, presumably because the associated temperatures are far from ambient temperatures for many industrial processes. But cold temperatures are actually not so far from ambient temperatures, especially in the food industry (food processing, storage and transportation), hence the associated energy consumption could be considered as dependent on climate change (Hekkenberg, Moll, & Uiterkamp, 2009).

Finally, the efficiency of air conditioners and heaters may depend on the outside air temperature, leading to some nonlinear effects. For example, air conditioners lose efficiency when outside air is too hot and heat pumps lose efficiency when outside air is too cold (Vidalenc, 2018).

[12] From 0.2L to 1L per 100 km (« Heating and air conditioning in cars », 2019)

Fresh water availability might decrease in some regions of Europe due to climate change. Depending on the scenarios, desalination plants might have to be built and to be operated, which requires energy (Schweizer & Morgan, 2016). Fresh water is required for domestic use, for irrigation, for industrial use including power plants cooling, and for leisure activities.

Climate change will affect the frequency and intensity of extreme weather events. Either energy systems[13] are preventively adapted to resist to this novelty or they undergo damages more frequently. In the first case, energy demand increases to build the infrastructure and produce the technologies required for adaptation. For example, energy may be required to build dykes in order to prevent flooding from sea water rise and storms, or to adapt buildings and infrastructure to extreme storms and hurricanes. In the second case, energy demand increases to repair the damages of extreme events, for instance to rebuild dwellings and plants after hurricanes or violent storms, including hail storms, or to pump water after floods.

Even more generally, climate change may also affect human health and the overall biosphere, possibly leading to consume more energy to protect and restore them.

No study to our knowledge integrates in its scenarios the future effects of climate change on demand (nor on production).

(RTE, 2017) integrates in the projections the already observed climate deviation from pre-industrial climate, but does not integrate future deviations. (ADEME, 2015; ADEME / Artelys, 2018) have a similar approach, the climate model being calibrated on 7 observed climate years at the beginning of the 2010's.

As just explained, climate change can have various impacts on demand, depending on the level of climate change, the geographical location of the scenario, and the adaptation measures which are implemented in the scenario. Hence assessing this effect first requires to determine these storyline and perimeter elements.

Recommendations to scenario producers

Scenario producers should make their strategy about climate change consideration on energy demand explicit for all their scenarios.

Specifically, a warning should be introduced for scenarios inducing a significant climate change (as is often the case for business-as-usual scenarios) and which do not assess the effects of this climate change.

If scenario producers decide to consider the effects of climate change on energy demand, they may address the following aspects:

- Climate change and adaptation storylines.
- Effects of the projected climate change on the geographical location of the study, taking into account the adaptation storyline.
- Induced effects on demand for space heating and cooling, in dwellings, tertiary buildings, transport, and industries

Induced effects on demand for other adaptation measures such as desalination or reaction to extreme events

[13] including demand-side, that is, houses, cars, industries and so on

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Authors

Nicolas RAILLARD

Project Manager – + 33 (0)6 46 35 43 70 | nicolas.raillard@theshiftproject.org

Nicolas Raillard joined *The Shift Project* as a Project Engineer. A graduate from ISAE – Supaéro (France) and from the Georgia Institute of Technology (USA), he worked as a complex system strategy engineer in aerospace for 4 years. Having passed an Advanced Master in "Environment International Management" at the Mines ParisTech school (France) and Tsinghua University (China), he now applies his skills and qualifications to the low-carbon transition.

Valentin LABRE

Assistant Project Manager – valentin.labre@theshiftproject.org

Valentin Labre joined the *Shift* to work alongside Nicolas Raillard on the "Power Systems 2050" project. Its goal is to develop a methodological guideline on the scenarization of electric power systems. Valentin obtained an engineer's degree from the Ecole centrale d'électronique de Paris (ECE) and later achieved a postgraduate degree in "Energy, Finance and Carbon" from Paris Dauphine University. Before joining the Shift, Valentin had various experiences working in the energy field for companies such as Enedis (Public energy distribution) and GreenYellow (Decentralized energy solutions).

The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

Press contact : Jean-Noël Geist, Public Affairs and Communications Manager

+ 33 (0) 6 95 10 81 91 | jean-noel.geist@theshiftproject.org

Lifestyles and consumption behaviors in energy transition scenarios

Technical file #5 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

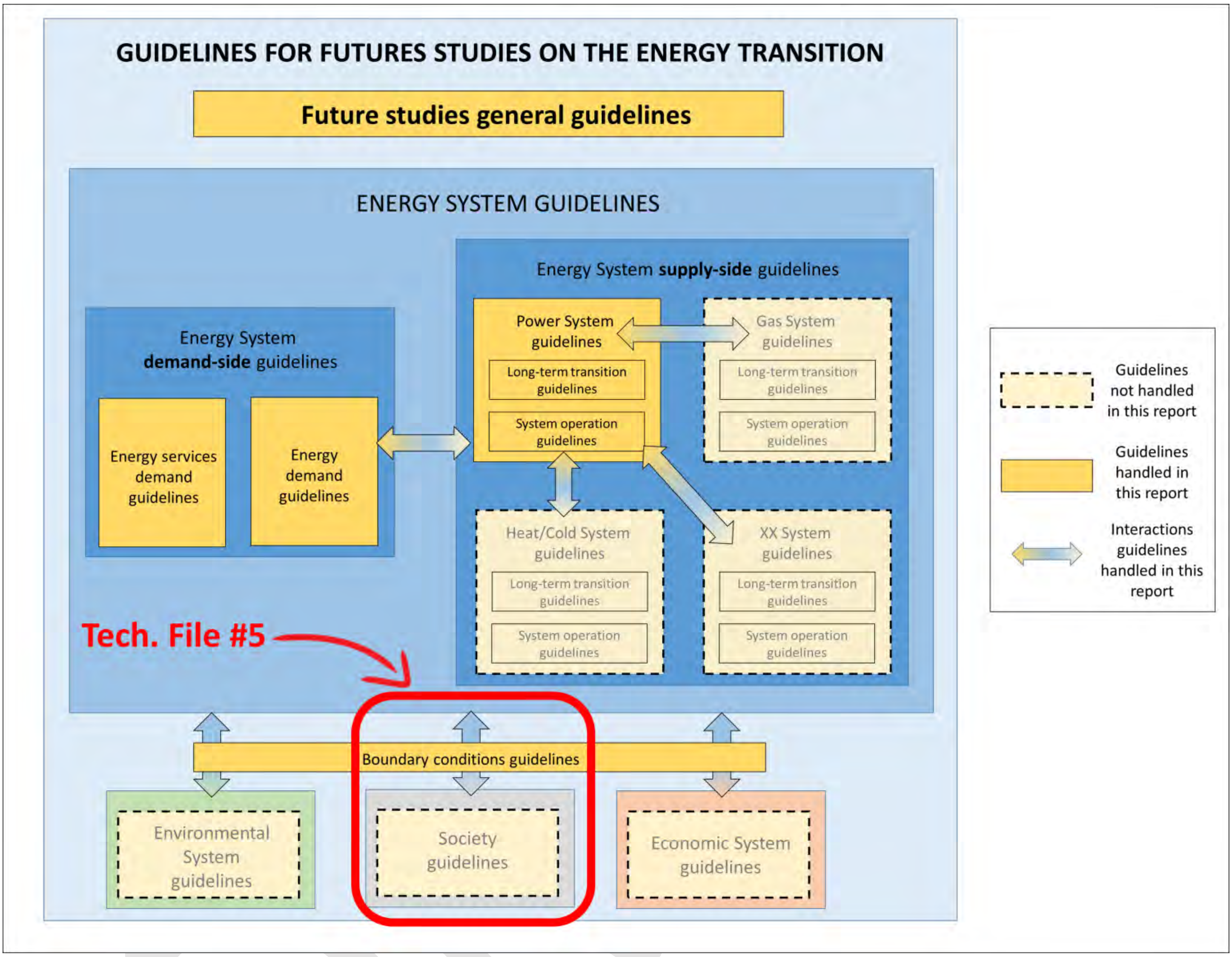
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

There is a strong link between energy system evolution and society evolution.

The first, clear interaction between both systems appears when people negatively reacts when an energy related infrastructure (a new power plant, a new high-voltage line…) is being installed. These reactions have pushed research to study the public acceptance phenomenon: why do people desire, accept, or reject, a project? Too often, scenarios assume that if a technology is cost beneficial it will be readily adopted (Stern, 2017). Section about desirability handles this question.

But further than this aspect, energy is at the core of our lifestyles, having a strong influence on public health, economic inequality, employment, and even social stability and international relations (Stern, 2017). Energy is embedded in our socio-cultural systems, as one may realize when she thinks about the changes brought about by the electrification of our lifestyles (Ruotsalainen, Karjalainen, Child, & Heinonen, 2017), or by the uptake of oil mass production (Auzanneau, 2018).

Some scenarios recognize the importance of the psychological, sociological and cultural determinants of demand (IIASA, 2012), which complements the usual technical and economical approaches. Integrating lifestyle and behavior considerations in energy transition scenarios makes them more robust to social reality, and provides useful tools for decision makers to understand the social risks associated with a scenario.

A. Main aspects of consumption behaviors: lifestyles and inertia

1. Lifestyles and consumption behaviors are deeply interwined

The notion of lifestyle is ill-defined but relates to "our ways of "doing", "having", "using" and "displaying", our behavior and all of the related products, objects and infrastructures. They are marked by our relationships to time, to space, to others, and to ourselves" (Le Gallic, Assoumou, & Maïzi, 2017).

Lifestyle is often evoked as linked to, or as a determinant of, consumption behaviors. Lifestyles "contain a set of key determinants of mobility, housing, spatial planning or the organization terms of the productive sectors (industry, agriculture, services). They thus constitute a fundamental component of direct and indirect energy consumption" (Le Gallic et al., 2017).

"Energy services demand is determined by needs and preferences for multiple services, which in turn depend on, in addition to income level and prices, home country characteristics, dwelling area and type, job and leisure activities, diet preferences, cultural context, religion, etc. A certain lifestyle is characterized by a bundle of these determinants combined with a more or less explicitly framed worldview, a set of values and convictions, preferences, and behaviors. (IIASA, 2012)"

Concretely, the concept of lifestyle is used through typologies. Most proposed typologies are developed along two broad types of dimensions: the first type gathers the aspects pertaining to the environment in which the individual lives, such as her physical environment (dwelling area and type, home country geographical and climate characteristics…) and social environment (people the individual gets along with for example colleagues, friends, family members) and economic resources (income level and prices, savings). The second type gathers the aspects pertaining to more subjective, less concrete, concepts such as values, cultural capital, or life objectives (Tabbone, 2017).

Pragmatically, we consider here that the first dimension (social, physical, economic contexts) represents the different aspects of the present context whereas the second dimension (values, cultural capital…) represents an internalization of the past environment of the individual, that is, a more or less conscious memorization of past experiences which still influence current practices, intertwined with an expression of her inner tastes (Baum, 2016a, 2016c).

In that sense, lifestyles can be said to determine consumption behaviors: the present context (physical, social, economic, institutional…) influences consumption for example through prices, advertisement, imitation of significant others, marketing, physical accessibility[1] and so on; past experiences with consumption also influence present consumption, through learning how fulfilling a product, or a service is on the short and long run, through past

[1] Some products or services may be more accessible in urban areas than in rural ones, in summer than in winter, and so on.

reactions of significant others to one's consumption and so on (these learning effect are sometimes called "brand attachment" when their outcome is positive for the product, or service).

The other way round, "material goods are important to us, not just for their functional uses, but because they play vital symbolic roles in our lives. This symbolic role of consumer goods facilitates a range of complex, deeply engrained 'social conversations' about status, identity, social cohesion, group norms and the pursuit of personal and cultural meaning. In the words of Mary Douglas (1976) 'An individual's main objective in consumption is to help create the social world and to find a credible place in it'" (Jackson, 2005). Hence lifestyles can be said to be influenced by the results of these consumption behaviors. For example, the use of an acquired good can trigger positive reactions from a group of people the individual wants to, or already, belong to, acting as a positive mirror and reinforcing the type of consumption and lifestyle shared within this group of people.

In a word, lifestyles and consumption behaviors co-evolve.

2. Some behaviors require more time to evolve than others: behavioral inertia is a key determinant of transition desirability

Two aspects of this co-evolution are key for our understanding of energy services demand: diversity of lifestyles among a population, and inertia.

Diversity of lifestyles is inherent to the concept of lifestyle, which is mostly applied at the individual level (Tabbone, 2017).

The inertia of the co-evolving couple "lifestyle and consumption behaviors" is often talked about in terms of "identity", "values", "convictions", "social norms", such as in (Bögel & Upham, 2018; Martin & Gaspard, 2016; Roy et al., 2012). These factors of inertia are said to be "internalized". They are deeply rooted in individuals as they emerge and build up from an early age, through social interactions with significant others, local community and society as a whole, including parenting and education. They are also generally shared, and maintained, by a large number of individuals through social norms and cultural traits. Hence they represent high inertia aspects of individuals' behaviors and thoughts.

Some behaviors driven by inertia are sometimes described as "habits, routines and automaticity" by cognitive psychology (Jackson, 2005), in the sense they have been acquired within a context which might have changed since then, but they are not questioned yet. Habits and routines can be said to be partly driven by deeper values, convictions and so on, and partly by more short-term considerations (fashion, prices…). In that sense, some habits and routines present a lower inertia than values, convictions or social norms.

Behavior inertia also occurs through the architecture of incentive structures, including institutional barriers, inequalities in access and restricted choice for consumption behaviors (Jackson, 2005). The physical environment (homes, urban planning, artefacts such as tools and technologies…) is also a source of inertia, shaping and maintaining lifestyles (Martin & Gaspard, 2016).

Changes in lifestyles thus require a sustained change in the environment of individuals, whether it be their physical, social or economic environments. On the medium term, such changes eventually get internalized and build up into new shared values.

High inertia behaviors are those behaviors which are very slow to change. They correspond to more rooted behaviors, such as behaviors linked to convictions, values, identity. If such behaviors are required to change in a fast way, this may lead to desirability issues. This situation much resembles that of stranded assets: because the transition is too fast, some assets become useless and their value is lost. Some values and convictions, in a fast transition, may become useless or go against what would be required to do by the transition. This produces psychological pain, frustrations, and may lead to aggressive behaviors.

3. Different roles in the same individual embed different inertias

Individuals play roles other than their consumer's roles. Each role embeds a certain amount of behavioral inertia. For example, professional skills are a major source of inertia for employees because acquiring new skills (that is, new behaviors and ways of thinking in the professional setting) takes time, all the more in economies based on labor division into highly specialized jobs (requiring up to several years of training) (Bögel & Upham, 2018) (also see Jobs section). Similarly, "society decision-makers" have a certain amount of inertia in the ways they make-up their decisions, would it be citizens as voters or as elected representatives or participants in social organizations. Note that the inertia of the latter role (society decision-maker) does not interest future studies, as they aim at influencing this role rather than modelling it. "Business decision-makers" (board of directors and business executives) have a certain amount of inertia, which is partly modelled in simulated agents studies. For example, PRIMES model, or the model used by RTE model investment decisions based on assumptions on technology maturity and associated risks (E3Modelling, 2018; RTE, 2017).

B. Collectively speaking, scenarios little address the question of behavior change

1. Most scenarios do not consider behavior change during transitions

Often, scenarios just assume lifestyles changes without explaining how they happen. Behavior change is not seen as a lever nor as a constraint. It is simply ignored. Assumedly, if technique and economic viability is ensured, then people will accept to change their behaviors and accept the installation of new infrastructures.

Future studies can be separated into two broad groups regarding lifestyles:

- The *lifestyle-mute studies*, in which no concrete information is provided about lifestyle evolutions. In those studies (such as (ADEME / Artelys, 2018; CGDD, 2016; RTE, 2017; Barton et al., 2013)), it is difficult for the reader to imagine what the lifestyles would look like. This does not come as an issue for scenarios in which lifestyles little evolve, but may trigger desirability questions for scenarios in which lifestyles significantly evolve. By being largely mute about lifestyles, these studies do not address the key issue of desirability.
- The *lifestyle-as-usual studies*, which assume no lifestyles changes happen but those induced by market mechanisms. Those changes always happen under "easy" situations, such as a GDP steadily increasing over the scenario timeframe, energy service technologies continuously improving and a better information being provided about the products (De Vita et al., 2016; E3MLab & IIASA, 2016; ECF, 2010; European Commission, 2011; Fraunhofer ISE, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017). Note that these studies are also largely mute about lifestyles, because they implicitly consider the few behavior changes they describe are largely desirable. In those cases, individuals are assumed to get equipped with more energy-efficient technologies through effortless consumption behaviors, such as investing in house insulation, or getting a more fuel-efficient car. In other words, no consumption behavior change is assumed as individuals keep thinking in an economically "rational" way and keep the same preferences during the whole scenario timeframe: only the release of more efficient technologies, and the changes in relative prices, trigger changes in bought products towards the most rational choice. Individuals are either modeled as consumers[2] through the "*rational choice model* which assumes they make decisions by calculating the individual costs and benefits of the different courses of action and choosing the option that maximizes their expected net benefits" (Jackson, 2005); or they are not modeled at all and a storyline about energy efficiency of energy service equipment is provided. In both cases, individuals are not described as engaging in more energy-sufficient behaviors. In those studies, (nearly) perfect markets are the main drivers of the transition, with the help of engineering improvements towards more efficient technologies. These markets have nonetheless to be equipped with a way to internalize the externalities which are deemed unacceptable, as private decisions do not always take account of social costs. This is why those scenarios implement a carbon price, which does curb consumption behaviors towards low-carbon technologies along the scenario timeframe. However, those behaviors changes are not concretely described and their desirability is not discussed. The second and last lever which is used in those scenarios to change behaviors is a better information about products, such as their efficiency, their carbon content and so on (Jackson, 2005).

[2] Generally, one representative macro consumer, with different techniques to simulate a distribution of different behaviors around the behavior of the macro consumer. The macro consumer has predetermined and stable preferences, which are assumed not the be determined by the social or institutional contexts (Jackson, 2005).

- A few studies go further than imagining no changes in lifestyles by detecting emerging behavioral trends and assuming they keep going, such as Vision 2030 by ADEME which assumes the continuation of shared mobility trends and more health-oriented food habits (ADEME, 2012).
- The *lifestyle-transformational studies*, which assume significant changes in lifestyles happen towards energy-sufficiency in addition to changes in energy efficiency of energy service equipment such as Vision 2050 by ADEME or négaWatt scenario (ADEME, 2012; Association négaWatt, 2014). In those studies, the desirability of behavior changes are sometimes substantiated through a technical storyline, and sometimes not substantiated. Behavior changes are sometimes merely assumed, and sometimes they are linked to the implementation of policies. In (The Shift Project, Kahraman, Guérin, & Jancovici, 2017), which is also lifestyle-transformational, the possible impacts in terms of desirability of the proposed transition are described for different actors (households, corporates).

As just shown, apart from lifestyle-transformational scenarios, studies and scenarios assume no lifestyle changes, or they explain the few behavior changes through unconstrained and natural changes in the average personal preferences. In the latter case, policy makers are assumed to react to the new, emerging social norms (such as a "heightened environmental consciousness"), as opposed to triggering and fostering them (Samadi et al., 2017). Most often, values and other inertial behavior components are implicitly considered as part of the most unalterable elements of the described world[3] (Bögel & Upham, 2018) and as such are assumed to remain in line with current lifestyles. This may lead scenario readers, including decision makers, to believe that no measures can be taken to promote energy consumption decrease, or that such measures are not needed (Samadi et al., 2017).

2. In reality, behaviors can and do change

However, behavior science has extensively shown that behaviors do change during one's lifetime and has explained the reasons for the changes in large parts (see box below). Theoretically, two broad types of political levers account for significant behavior changes (Samadi et al., 2017):

- Modification of relative prices, comfort, or any other preference criteria between several activities through policy levers. For example, reducing car speed modifies the relative speed between car and public transportation, fostering a modal shift from car to other modes. (possible feeling of coercion)
- Politically imposed bans or limits (possible feeling of coercion)

In addition, other causes than political levers may lead to behavior changes and modifications of preferences. From a political point of view, it can be said to happen through politically unguided culture evolution. We call this type of behavior change the *"no lever" behavior change*. Such cultural tendencies, mostly expressed within the social environment, influence the effectiveness of political levers because changing habits is much easier in a supportive, social environment (Jackson, 2005).

3. The type of models used by lifestyle-as-usual future studies explains why they consider behavior change so little

The rational choice model assumes consumption behaviors follow optimization rules which do not evolve through time (as consumer preferences do not evolve). Hence behaviors evolutions cannot be studied, or projected with such a model. There exists other types of behavior models, which account for the fact that "human behaviors are not purely rational and self-interested". For example, these models take into account the following:

- Habits, routines and automaticity in our behaviors. These patterns illustrate what the rational choice model would consider as "suboptimal" behavioral inertia and that it would avoid through "better information." Indeed many frequent, routine behaviors do not call for a deliberation anymore after they have been tested out several times and their consequences are known by the individual, even though they might not be optimal anymore because conditions changed. They are nonetheless very useful rules of thumb for not spending energy into endless deliberation before each behavior.
- "Our preferences are largely dependent on social and interpersonal factors" (Jackson, 2005). This implies that these preferences can change not only within individuals during one's lifetime but also within a

[3] These inertial elements are called "landscape level" in the Multi-level perspective of transition.

whole culture[4]. Preferences apply largely on non-commensurable commodities (that is, commodities which cannot be measured under the same unit because they are different in essence, such as health, safety, comfort, speed and so on), making the evolution of their relative weights in a "utility function" difficult to understand in terms of cultural changes and as a consequence difficult to tune.

These alternative behavior models are not used by scenario producers, even though they could provide more diversity across studies in hypotheses about lifestyles.

4. A collective lack: scenario production should fully integrate social sciences instead of being mostly driven by engineers and economists

Part of the issue comes from the fact that evolutions of lifestyles are mostly studied by social sciences but results from this field are rarely included in future studies (Hache & Palle, 2018). Future studies are largely led by economists teams, which more readily use the rational choice model or by engineers teams which consider the technical aspect of the transition; sociologists, or behavior scientists are poorly, inadequately (e.g. too late in the scenario production process), or not at all included in the future studies teams.

The exclusion of behavior scientists from scenario production lead to two main risks for the scenario community as a whole:

- Ignoring interesting political and economic levers (such as public investment in infrastructures, bans, imposed standards and so on), by focusing only on market-based levers. This is one collective shortcoming for studies using the rational choice model. As a result of this collective ignorance by future studies, scenario readers, including decision makers, may conclude that measures promoting non-market levers (such as energy-sufficient lifestyles) are not efficient, not available or even detrimental for society (Samadi et al., 2017).
- On the opposite, underestimating behavioral inertia and hence overestimating behavioral changes' speed. This bias is equivalent to neglecting some non-desirability issues induced by the speed of change. Such a bias may appear in lifestyle-transformational scenarios when strong assumptions on behavior changes are made. E.g., some scenarios assume mass building insulation without dealing with the subject of desirability of the investment decision and of the works.
  Surprisingly, this bias can also appear in lifestyle-as-usual scenarios when they implement a strong carbon price: in this case consumption behaviors change unrealistically fluently under the effect of the carbon price (implicitly assuming this effect, called "disutility,"[5] is deemed desirable by citizens) (E3MLab, 2017). However, in lifestyle-as-usual scenarios, individuals are usually supposed to live in wealthy situations (GDP is assumed to grow) and they can easily afford more expensive, more efficient, and lower carbon technologies so that the induced disutility might be argued to be acceptable.

As a conclusion, when a collective look is taken at published future studies, either behavior changes are not considered at all (true for most scenarios using the rational choice model), or they are assumed to change fluently and naturally. When behavior change occurs in scenarios, no account is provided for the expected changes and no political lever is proposed except for a few exceptions ((Association négaWatt, 2014; The Shift Project et al., 2017) and some aspects of Vision 2050 (ADEME, 2012)). As a result, costs associated to behavior changes are not taken into account (sometimes referred as transition costs).

[4] Equivalently, the "distribution of preferences" might significantly evolve within a population.
[5] Disutility is an assessment of the utility loss compared to a situation in which the constraint does not exist. It is concretely composed of buying more expensive technologies, paying for more expensive energy, and consuming less in some sectors due to this buying more expensive goods and services, all those effects being in comparison to a situation without (carbon) constraint.

Recommendations to scenario producers

Scenario producers should make their strategy about behavior change explicit. In case they chose not to address this question, they should substantiate the fact that this choice does not hide desirability issues.

If behaviors change in a scenario, the reasons for the changes should be made explicit. The following reasons may be considered: no-lever change, or political levers activations.

Scenario producers should report the way they consulted social sciences in the course of the study: who they got in touch with, or what social sciences sources they resorted to, in what ways, and at what points in time during the study.

Good practices include:

the study of lifestyles should be an integrated part of the process of scenario production. Social scientists, such as sociologists or psychologists should be involved at the very beginning of the process and remain part of the team during the whole process. Their role is to inform scenario producers

- about the implications of their hypotheses during the storyline definition
- about the implications of their results during the interpretation of results

C. Curving cultural trend is difficult in reality: transformational scenarios should address desirability issues

1. Changing behaviors may require time and lead to desirability issues

Understanding cultural trends (new, emerging ones as well as solidly rooted ones) and their translation into consumption behaviors is key for producing behavior-transformational scenarios.

The more social norms are shared and associated with a strong social punishment in case of deviation from them, the more difficult to change they are. Body hygiene, eating and drinking habits or dwelling habits are examples of behaviors whose trends are difficult to change. For example, constraining dwelling surface per inhabitant may be a real challenge. They are anthropologic realities which evolve little and slowly (Martin & Gaspard, 2016). Hence cultural trends are socially shared behavior patterns which have a certain inertia.

If such trends are to be changed through judiciary norms, the costs to enforce the new trends through coercion means can be extremely significant. They can include mass monitoring of individuals' behaviors and means to punish deviations from the new trend as systematically as possible. In case coercion power is limited, new judiciary norms must be first accepted within large parts of the population (Martin & Gaspard, 2016). By and large, this fact legitimates the idea that proposed transitions should be desirable. This concept is developed in the desirability section. In other words, the social body should not be considered as an adjustment variable, as it is not necessarily more flexible than the built environment.

2. Detecting cultural trends is complex but improves storyline design by rooting it in the current culture

Understanding and monitoring cultural trends is complex and requires a certain amount of data. Indeed, different groups of people can exhibit different cultural trends, as a function of their characteristics, such as: their revenue level, their age, their gender, the type of urban tissue they live in, their working status (unemployment, retirement, etc.), their rural or urban lifestyle, their household structure (number of children, are the parents together, how many persons of the same family are living in the house, etc.), information about their housing context (owner or tenant status, house or apartment, suburb or city-center, metropole or village, etc.), their attitude towards environment. These are factors which can highlight some cultural trends in some domains. For example, younger generations in developed countries are less attracted to owning, or using a car than older generations.

Some "no-lever" cultural changes can be noticed in developed countries such as France. Here are examples of some of them, applying to small, but growing, portions of the population:

- Regional, or local governance is preferred. The emergence of this preference is accompanied by a loss of trust in national governance.
- Preference towards more energy autonomy/autarchy
- New collaborative and local investment practices (local crowdfundings) (Hache & Palle, 2018)
- Small project size in electricity supply (OECD/IEA, 2017)
- Buying bigger and more powerful cars (Sport Utility Vehicles, SUV) for buyers of new cars in France (Chassignet, 2019).
- Meat consumption reduction in younger generations (ADEME/CREDOC/RDC Environment, 2015)
- Attachment to material goods and strength of habits for people above 40 year-old (ADEME/CREDOC/RDC Environment, 2015)

Recommendations for scenario producers

Scenarios should make their strategy about cultural trends consideration explicit.

If they are considered, a description of the observed and expected trends should be provided for the studied geographical perimeter.

If observed cultural trends are curved in a scenario, discussion about the inertia of those trends as well as the levers which are used to curve them should be provided. Inertia should be assessed with regards to how shared the trends are and how associated to a social punishment in case of deviation from them they are. In case of high inertia, considerations on desirability of these changes should be made (see desirability section).

For example, if the scenario assumes the trend towards new energy production and consumption structures (local production, short supply chains, etc) reverses back to a centralizing trend, this reversal should be explained in a narrative.

For example, in France, the trend is currently that people have greater and greater living area. Hence scenarios assuming a reduction, or stabilization of the living area per inhabitant should warn about this trend discontinuity.

The evolutions of lifestyle during the timeframe of a scenario should be described.

Lifestyle evolutions should be qualitatively described for a few highly contrasted household categories.

D. Detailed considerations on policy levers and their effects on behavior changes during transitions

We now develop some ideas about the different levers on behaviors, such as the different useful levels at which they can be thought out, the main different types of levers available to policy-makers, and some considerations on the way they should be activated for more efficiency and desirability.

Levers to change behaviors have been extensively studied by behavior analysis

The science called behavior analysis have extensively studied the determinants of behavioral changes. Along the view of behaviorism, the philosophy associated with behavior analysis, changing behaviors is equivalent to changing the determinants of behaviors.

Here are the main findings of this science on behaviors (summarized from (Baum, 2016b)):

Human behaviors are determined by what has been called 3-terms contingencies, and which corresponds to *incentive feedback loops* (increasing the occurrence of behaviors under the incentive) and *constraint feedback loops* (decreasing the occurrence of behaviors under the constraint). Incentive feedback loops provide rewards when the behavior considered as appropriate happens. Short-term rewards include smiles, nice words, or money and in the long-term diplomas, a rewarding job, good health, rewarding relationships, and more globally a rewarding environment. Constraint feedback loops produce punishment when the behavior considered as inappropriate happens. Punishment include in the short-term cold or angry reactions by others or fines, and in the longer-term, lawsuits, imprisonment, a lack of, or negative relationships, bad health and more globally a difficult to live environment.

The better these feedback loops are known (through communication campaign, through imitation of others knowing these feedback loops, through mouth-to-hear tips, advice…), the more easily individuals can engage in preferred, more rewarding feedback loops.

These feedback loops, to have a lasting effect on behaviors, must themselves remain stable.

The more probable and systematic the consequences of these feedback loops are, the more efficient they are to change behavior and maintain novel behavior.

The faster the consequence of the feedback loop after the occurrence of the behavior, the more efficient the feedback loop.

1. Behaviors are under the influence of several *influence levels*: close relationships, society and the physical environment

Behaviors evolve, and are maintained, by incentives and constraints applying to them. Several levels of incentives and constraints apply on individuals. Here are the three influence levels usefully framing discussions about levers on behaviors:

- People closely related to the individual (such as family members, friends, colleagues, neighbors…) produce incentives and constraints through their interactions with the individual. They influence one's behaviors through advice, tips, education (for children within the family), exemplification followed through imitation…
- society as a whole (including institutions, economic rules and economic structure, justice, social norms…). Economic structure directly influences our behaviors through the services it proposes, as well as indirectly via our physical environment, through the goods it produces. It also influences our behaviors through advertisement ("information campaigns") (IIASA, 2012). Business practices can also influence the behaviors of their employees. Institutions influence our behaviors through the taxes, subsidies, bans and so on they implement and enforce through administration, police, justice etc.
- the physical environment (such as infrastructures, technologies and tools). It most directly influences our behaviors and also constitutes an element of inertia (see future studies).

To be as efficient as possible, measures towards behavior changes should implement incentives and constraints on all those aspects. However, policies are best applicable on society as a whole (laws, bans, taxes and subsidies…) and on the physical environment, directly through design and building of public spaces, and indirectly through production standards for the technologies and tools individuals use. As was explained above, levers on society as a whole can be implemented only if they are deemed acceptable, that is, only if they are largely accepted at the small group level.

2. Policy makers have access to four *policy levers* to change behaviors

These different levels can be derived into four different policy levers to change behaviors (Martin & Gaspard, 2016).

- Communication and information tools, including individual counselling or group support. They aim at informing about the existence of alternative behaviors or about the pros and cons of each alternative. They can also aim at altering the perceptions on these pros and cons. Examples include consumption labelling for appliances or cars or communication campaigns about car accidents for speed limits enforcement. Exemplifying the desired changes within State's own policies and practices also belongs to communication tools (Jackson, 2005).
- Infrastructure tools, aiming at providing new possibilities for alternative behaviors, by providing new goods or services, or at making more difficult former behaviors. Examples include new cycling or pedestrian infrastructure or city planning to reduce trip distances or car use. Infrastructure and public space design can have an influence on behaviors with so-called "nudges". However, this technique has a more anecdotal

and less sustainable effect since they seek to modify behaviors without individual knowledge building: with this technique individuals change their behaviors sometimes without knowing why they should do so.

- Economic tools (taxes and subsidies). They aim at modifying the relative weights of pros and cons between alternative behaviors. Examples include purchase taxes depending on the fuel consumption of cars, or subsidies to reduce public transportation price. Subsidies towards specific fields of research, such as specific technologies or tools, can also lead on the medium-term to changes in the physical environment, which is in part composed of the technologies and tools we use.
- Legal tools (obligation or ban, standards). They also aim at modifying the relative weights of pros and cons between alternative behaviors, through coercion. Examples include car bans in some parts of cities, speed limits for vehicles, or emission standards for cars. It also includes standards for companies leading to producing products with novel characteristics, which in turn end up in individuals' physical environment as new available technologies and tools. It also includes laws to promote novel behaviors among employees, such as changing commuting trips.

3. The ways policy packages are framed is key for efficiency and desirability: the *lever activation modes*

For more efficiency of the levers, the following aspects are key (Bögel & Upham, 2018). We call them the four *lever activation modes*.

- Ability to adopt: As previously mentioned, behavior changes happen much more easily when they are deemed acceptable, that is, when they are already shared and largely encouraged within portions of the population. In other words, some form of knowledge and emerging cultural norms should be present to enable behavior change. Many scenarios evoke an environmental consciousness to explain the adoption of novel, eco-friendly behaviors in a "no-lever" way.
- Tailored approach: several levers should be activated together and in a consistent way, that is, they should clearly all direct towards a limited set of behaviors, as opposed to directing towards novel behaviors and former behaviors at the same time. Generally speaking, goods and services providers invest large amounts of money in marketing and advertisement, contributing to shape shared cultural norms directing behaviors towards consuming those goods and services (Martin & Gaspard, 2016), which may go against measures implemented in transformational scenarios. This illustrates how incentives and constraints in place can be contradictory and lead to desirability issues.
  Ideally, levers should be activated along all the mentioned levels (small groups of close relationships, society and the physical environment).
  Different types of levers should be activated together for each targeted behavior:
  - push measures (that is, incentive feedback loops promoting the novel behavior)
  - pull measures (that is, constraint feedback loops constraining the former behavior)
  - information campaign *if needed to inform about the presence of the new feedback loops*. Note that the information campaign informs about the novel situation (shaped by the new pull and push measures) in which behaviors take place. On the contrary, leading an information campaign about the existing situation without any new push or pull measure have little chance to be efficient if its goal is to signal the presence of opportunities that people assumedly (in a collective way) have not understood or seen the presence of opportunities around them. "Information campaigns have been widely used for achieving public interest goals. But they are known to be less effective than other forms of learning. Research suggests that learning by trial and error, observing how others behave and modelling our behavior on what we see around us provide more effective and more promising avenues for changing behaviors than information and awareness campaigns" (Jackson, 2005).
- Continuous priming: Behavior changes cannot be maintained by sole information, even continuous information. Context has to evolve and be sustained in its novel state to maintain new behaviors. This applies to all the mentioned levers (infrastructure, economic incentives and so on).
- Extent: Information and context changes lead to behavior changes more readily if they target behaviors with direct consequences on the individual than if behavior consequences are further away in space, time, and probability. For example, parking ban in some places is more efficient if it systematically and quickly enforced. Energy use is more easily reduced if it is directly monitored and displayed to the consumer. On the contrary, far ahead consequences of climate change have less effects on behaviors. Communication campaigns may be useful to act on the extent aspect of levers, by presenting the long-term consequences of a behavior in order to make them more concrete so that individuals better take them into account. For example, communication campaigns could highlight the links between some behaviors and climate impacts.

Introducing and sustaining lifestyle change is thus not as straightforward as a (prescriptive) modeling approach may suggest. The design of a successful policy strategy requires knowledge of all these factors that determine and sustain changes in specific behaviors.

4. Different behavior changes require different levers

a. The specific case of investment decisions

Social sciences for energy has mostly studied changes in daily behaviors as opposed to household decisions to invest in insulation, or other investment decisions, even though such decisions can be more powerful at changing energy consumption (Stern, 2017).

Indeed, it has been noticed that behaviors characterized as *investment* behaviors are much closer to those assumed in the rational choice model. For example, energy is most commonly framed as a basic need by individuals, except when they consider investment decisions in energy savings: in this situation, they frame energy as a commodity, with considerations on return on investment and cost reductions (Demski, Thomas, Becker, Evensen, & Pidgeon, 2019). For this category of behaviors, economic incentives are key, as well as knowledge about the investment opportunity and its consequences (in terms of savings, comfort and so on). Hence favorable enough[6] economic incentives and a communication campaign about them is likely to be efficient to direct household's investment.

Other levers may be more adapted in the case of daily consumption behaviors, which are most often habitual (Bögel & Upham, 2018). "A vital ingredient for changing habits is to 'unfreeze' existing behavior - to raise the behaviour from the level of practical to discursive consciousness." And as for any other behavior change, "this process is known to be more effective in a supportive, social environment" (action at the small group level) (Jackson, 2005).

Hence the targeted influencing levels, the selected policy levers, and the lever activation modes will certainly be different for these two types of behaviors.

b. Practical case: changing "car buying" behaviors

As an example, we consider here the case of car buying. Let us consider the different levels of incentives which apply to individuals when they buy a car, and enumerate the different incentive feedback loops probably applying:

- The physical environment: public spaces are greatly designed for car use, through a very dense and well maintain road network, with a high speed road network. City planning and activity location often requires the use of a car to have access to basic services and resources as well as to activities required to live a decent life and to stand one's role for society (access to work, to schools for children, to healthcare…). Also influencing the physical environment, standards and bans from the State affect the type and characteristics of cars which are accessible to buying.
- Society as a whole:
    - Economic system: several services are proposed everywhere on the territory for car owners, such as garages and insurances. The economic system also largely implements communication campaigns (advertisement) associating car ownership to long-term rewards, such as high social positions, positive relationships (love relationships, friendship, family…), and socially highly-valued activities (traveling, taking care of one's family…).
    - Institutions, through taxes and subsidies, as well as costs induced by car ownership (insurance, maintenance…) impact car buying.
- Small groups of close relationships: the type of car that close relationships own and the way they use it, as well as what they say about it also have an influence on car buying.

If car buying behaviors are to be changed (for example, towards less powerful cars, or towards low-carbon cars, or even towards buying less cars), then incentives and constraints around car buying must be altered in the desired way. However, they must be so in a sustained way (stability of a novel built environment and city planning, stability of price incentives…) to change behaviors and maintain novel behaviors. Plus, the overall set of incentives and constraints must be readable and consistent. For example, modifying taxes and subsidies (e.g. taxes for owning a powerful car and subsidies for replacing one's car by bikes…), or the built environment (less space for car flows

[6] Considering the specific economic situation of the different households

and for parking) without modifying advertisement for powerful cars decreases the probability to change behaviors compared to a no advertisement situation. Furthermore, such discrepancies can lead to discontent (see desirability section).

Recommendations to scenario producers

Behavior changes should be explained. For each behavior change, a narrative about the following aspects should be developed:

- The policy levers which are activated:
    - communication and information tools. For example: *What kind of communication campaign? Is exemplification used? What changes in labelling practices?*
    - infrastructure tools. For example: what changes in urban planning? What new transport infrastructure?
    - economic tools (taxes and subsidies). For example: *what activities are more taxed/ more subsidized? For what actors? Are CO2 emissions taxed, and with which tool? For who? Are some research fields subsidized?*
    - legal tools (obligation or ban, standards). For example: *what activities are banned? Is driving in city centers banned? Are there car production standards imposed?*
- The lever activation modes which are used:
    - ability to adopt: *why would actors accept the proposed levers?*
    - tailored approach. For each behavior change, push measures, pull measures and in some cases, information campaigns, should be considered. Internal consistency of the whole policy package, as well as consistency with the other incentives and constraints in place, should be considered, for the different actors and with regards to the different targeted behaviors within the scenario. *For example: is advertisement based on the price indicator still allowed when new labelling seek to promote other indicators such as energy consumption and CO2 emissions?*
    - continuous priming. *How are the proposed measures sustained during a long-enough time?*
    - extent. Do the proposed measures implement incentive / constraint feedback loops which directly act on the targeted behaviors? If not, considerations on the efficiency of the lever should be provided.

For all the impact assessments which are performed in the study, the impacts of the levers which are activated should be taken into account within the considered impact inventory.

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Author

Nicolas RAILLARD

Project Manager – + 33 (0)6 46 35 43 70 | nicolas.raillard@theshiftproject.org

Nicolas Raillard joined *The Shift Project* as a Project Engineer. A graduate from ISAE – Supaéro (France) and from the Georgia Institute of Technology (USA), he worked as a complex system strategy engineer in aerospace for 4 years. Having passed an Advanced Master in "Environment International Management" at the Mines ParisTech school (France) and Tsinghua University (China), he now applies his skills and qualifications to the low-carbon transition.

The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

Press contact : Jean-Noël Geist, Public Affairs and Communications Manager

+ 33 (0) 6 95 10 81 91 | jean-noel.geist@theshiftproject.org