Long-term evolution of energy consumption in energy transition scenarios

Technical file #4

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 nearly 2 years of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

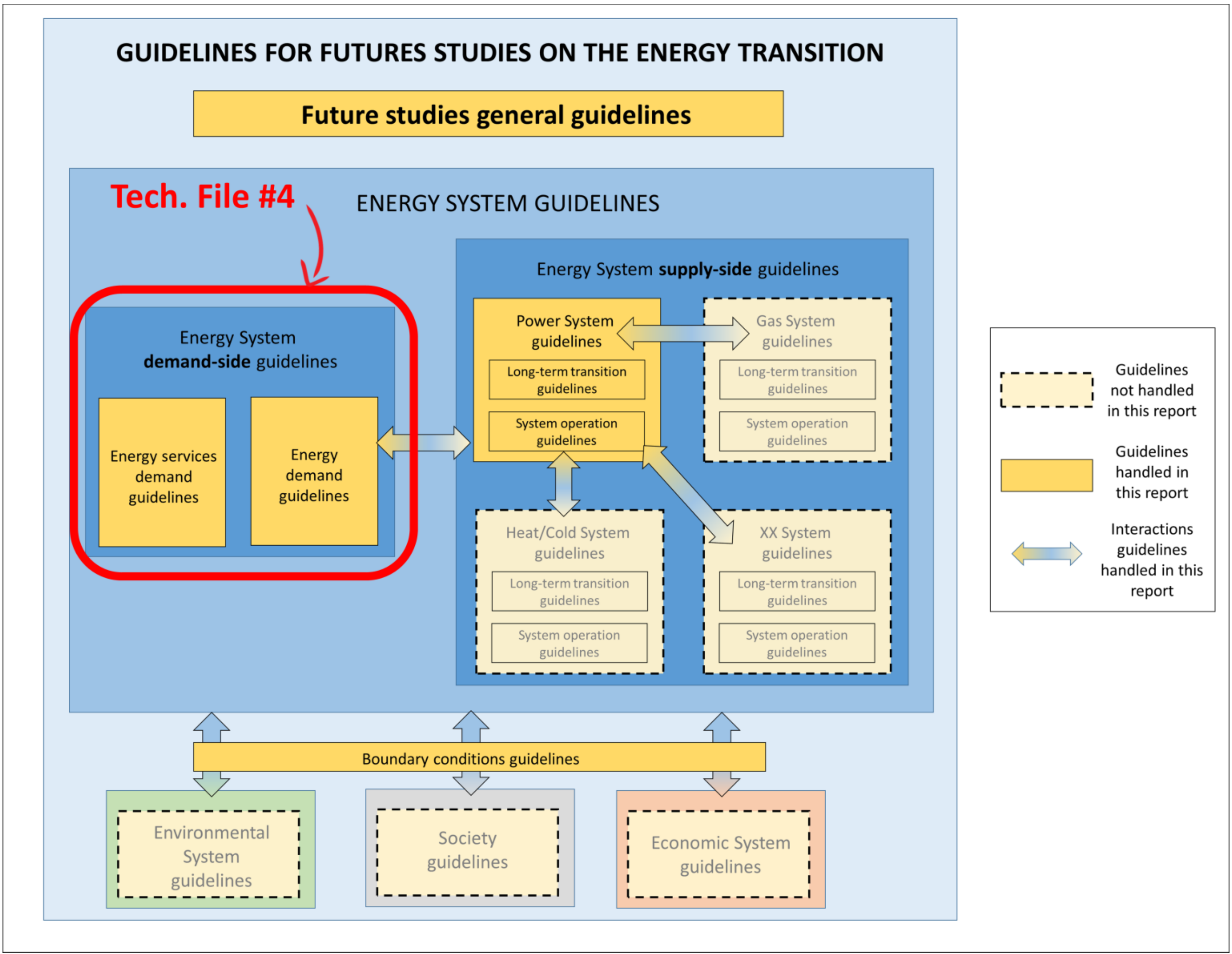
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project are discussed in the executive summary of the framework.

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 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.



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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. Consistently describing energy consumption in future studies

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).

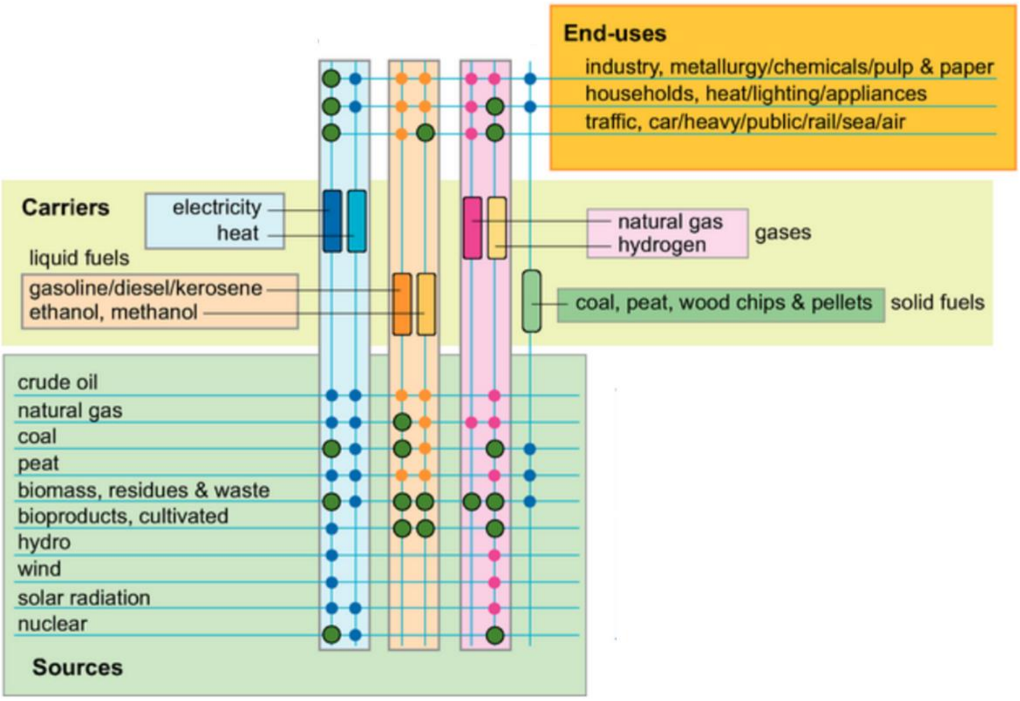

Figure 1: Dynamic interplay between energy sources, energy carriers and energy end-uses. Source: (IPCC, 2007)

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 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.

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

[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.

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-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.

Actually, the energy system exists in our daily lives through very material elements such as sockets, service-stations, and so on; on the long-run, their mere presence highly influences our consumption behaviors and lifestyles. As our consumption behaviors are typically considered as emerging out of thin air, and not as a result of our interactions with a technical system surrounding us (and many other drivers as explained in section about consumption behaviors), the only task for the energy system is to follow demand as opposed to influence it.

B. The different approaches to assess energy demand evolution have different strengths, but all lead to physical 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:

1. 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[4]. This approach is used in (ADEME, 2012; Association négaWatt, 2014). In this approach the storyline is about lifestyles, evolutions of energy services technologies[5] and uses:

- hypotheses about how households will consume (energy sufficiency / 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

[4] Energy services directly fulfil needs for changes in one's environment (such as moving objects or oneself, heating food, water, air or other materials, making clothes clean, modifying one's visual and sound environment for entertainment and so on). Fulfilling these needs requires energy consumption.

[5] These technologies consume energy to operate. They can be owned by households, such as different appliances or cars or by corporations to produce goods, such as different processes to transform materials.

the main hypotheses are made. During this step, some studies ensure a consistency between households' equipment purchase 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 (see below). Hence the scenarios can describe in a precise way how lifestyles evolve (for example (ADEME, 2014) describes the lifestyles associated with the Visions scenario developed in (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).

With the behavior-based approach, a macroeconomic view can be brought afterwards through models soft-linking[6]: 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).

2. 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

[6] 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).

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 or the World Energy Model (International Energy Agency, 2018), use reduced forms equations (with demand elasticities as main parameters) directly linking the variations of GDP, population and a few socioeconomic indicators to energy demand variation for each sector, through econometrically calibrated laws (E3MLab, 2017; International Energy Agency, 2018).

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 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.

These models assume a representative consumer for each considered sector of consumption (mobility, space heating…) and sub-sector. This consumer follows the average consumption behaviors observed in the considered region. PRIMES goes further by modeling the representative consumer as a distribution of consumption behaviors: several different behaviors are possible with different probabilities. The average behavior of this consumer is the "optimal" behavior in terms of utility[7].

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 (which cover energy markets only). 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. In other words, no physical consistency is ensured between industrial production and the transition of the demand-side of the energy system. This may be a critical limitation for scenarios in which large changes happen on the demand-side (e.g., massive shift to more energy efficient equipment).

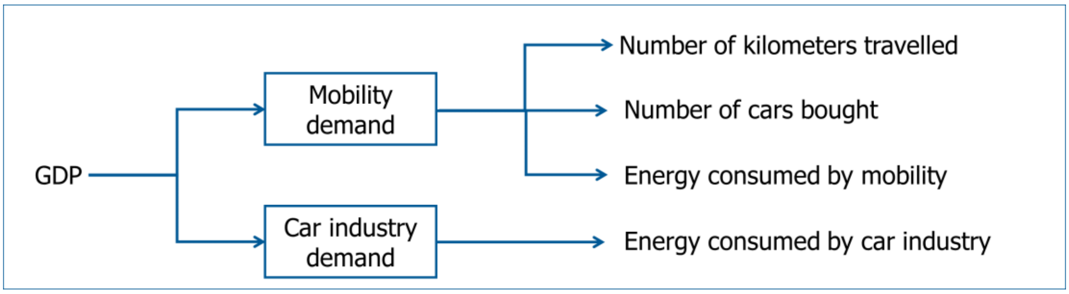

Figure 2: In the GDP-based approach, energy consumption is derived from GDP assumptions for each sector, including industrial sector. This approach ensures an economic consistency between the projected activity level of each sector and the global GDP. However, taking the example of car industry, consistency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

[7] Utility defines the preferences of consumers for a given budget, through a "utility function." To our knowledge, models using a utility function are neither transparent about the function itself nor about the way it has be defined and calibrated.

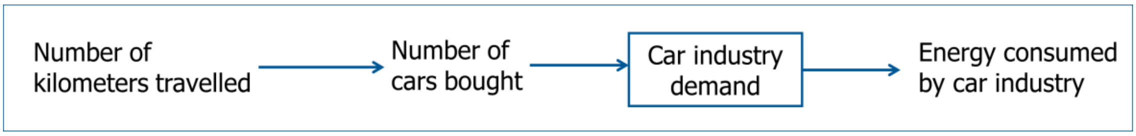

Figure 3: In the behavior-based approach, behaviors of end-consumers determine consumption of goods (cars), which in turn determine demands for industries (such as how many cars have to be produced by car industry). Demand for industry then determines energy consumption by industries.

- As for the behavior-based approach, consistency is not ensured neither between industrial 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).

GDP-based approach is largely based, and calibrated, on observations of past economies (Laurent, Cattier, Osso, & Pourouchottamin, 2011), 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; in other words, even for a transformational scenario consumers preferences and consumption decision-making are assumed not to evolve. Hence some aspects of lifestyles evolution are not be modelled, and cannot be described (see section on lifestyles).

Furthermore, in this view, lifestyles (including employment structure) evolve totally fluently[8] through market forces (which are themselves framed by policies). Hence desirability issues on consumption behaviors or work structure cannot be detected and described, which may be a serious limitation for transformational scenarios (see section on desirability).

As a general rule, studies covering a large territory (such as world regions, or the world), or studies which do not have access to precise data about consumption behavioral determinants use the GDP-based approach (Laurent et al., 2011). 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.

3. Hybrid approaches

Hybrid methods for power systems scenarios are sometimes used (ENTSOG/ENTSO-E, 2018; RTE, 2017), they define storylines about behaviors, technologies, carrier 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.

4. 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

[8] Still following the preset preferences and decision-making processes of consumers

and actions on the demand-side (such as introducing energy efficient consumption devices, or shifting between technologies providing the same energy service) (also see section on impact assessment).

Recommendations to scenario producers

The scenario strategy about energy demand determination should be defined and justified with regards to the driving questions.

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

- Degree of influence of the energy system on demand: *is demand totally independent from the energy system? Does it depend on it through price mechanisms (markets, elasticities…)? Through other mechanisms?*
- Approach which is adopted to determine energy demand level: GDP-based, behavior-based, hybrid, or direct demand reuse from another study. The choice of approach should be justified.
- 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? 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.
- If the supply-side only is studied with a fixed demand
    - Consistency between the chosen demand sources and the study strategy should be substantiated.

C. Consistently describing energy consumption through physical flows within the economy

We have seen future studies do not properly represent energy flows powering the demand-side. We explore here the possible implications of this limitation.

The energy system taken as a whole (supply-side as well as demand-side, as described in the section about boundary conditions) provides energy services, which can be measured in terms of useful energy (e.g. kinetic energy of a car, radiance energy of a light bulb, heat in an industrial oven and so on). This useful energy is available for us to sustain our ways of lives.

However, the energy system itself consumes energy to properly operate and produce useful energy.

As described in a literature review by (Court, 2016) about Energy Return On Invested (EROI)[9] and the methods to compute it, different energy inputs can be counted as "self-consumption" of the energy system:

- Internal energy consumption (such as energy for the coal mining processes, for the freight, for the energy refining and transformation processes and so on)
- Embedded energy in material consumption (such as the energy that was required to produce coal mining tools, and more generally all the energy to produce all the energy consuming appliances, devices, tools, which provide energy services, the energy to produce the infrastructures required for those devices to operate, such as roads, power grids and so on)
- Labor (from humans and animals) consumption can be added but is negligible with regards to other sources of energy.

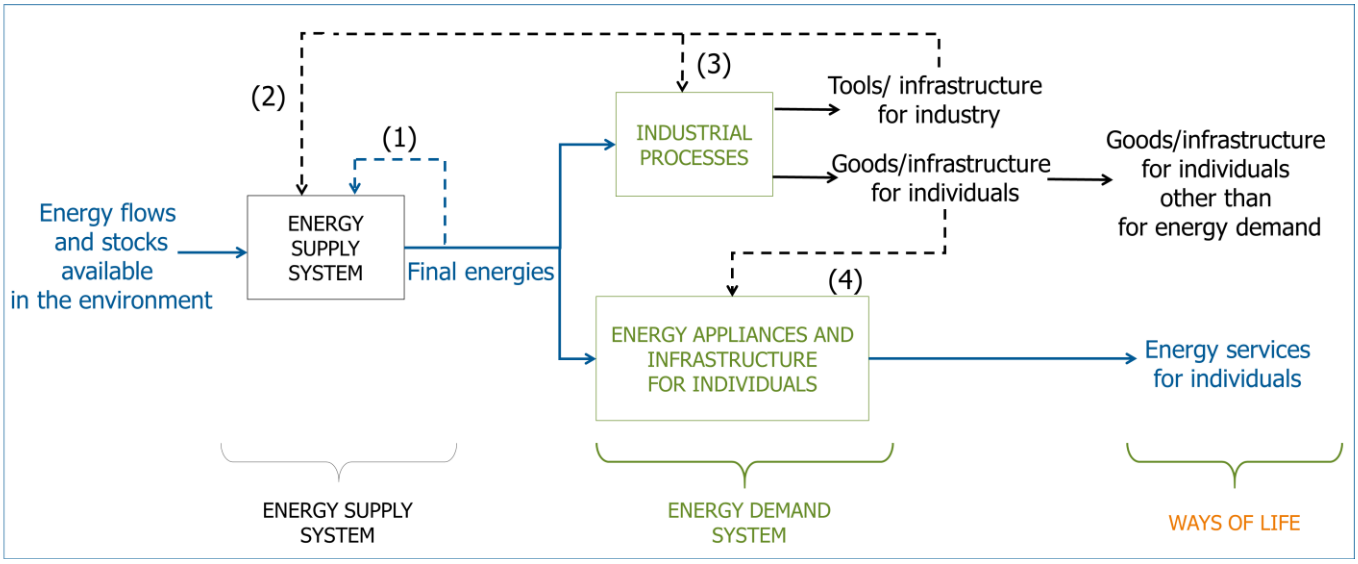

Figure 4: Energy and material flows within societies, from energy flows and stocks available in the environment to technical systems directly interacting with our ways of life.

Considering Figure 4, the energy system is composed of:

- the energy supply system, composed of several subsystems as previously described in the section about boundary conditions
- the energy demand system, in turn composed of:
  - technologies ensuring industrial processes (such as industrial ovens, robots, tool machines, computers, trucks and so on), and energy consuming equipment for corporations (such as corporate cars, appliances in the tertiary sector and so on).
  - appliances and energy consuming equipment for individuals (such as individual cars, TV sets, mobile phones, individual air conditioning systems and so on)
  - infrastructure enabling these processes to properly operate (such as road networks, information and telecommunication networks, industrial plants, office buildings and so on)

The EROI of the energy system is computed taking into account the energy services for individuals (which is the service provided by the energy system) and compare them to the self-consumptions of the energy system. There are several items of self-consumption which can be counted:

[9] EROI informs about the energy surplus an energy production process generates. By definition, the surplus, if any, can be used for other processes.

- final energy self-consumption of the energy supply system (1)
- embedded energy of the tools and infrastructure required for the industry to properly operate (2 and 3)
- embedded energy of the appliances and infrastructure required for providing the energy services for individuals (4)

All the other flows of energy are directly dedicated to the energy services for individuals or to the production of goods for individuals other than energy services appliances (such as tables, pencils, mugs, doors, houses and so on). Hence they are not part of the self-consumption of the energy system.

The greater the amount of energy services and energy embedded in goods for individuals other than energy services appliances (this is the amount of energy directly dedicated to our ways of life), compared to energy system self-consumption, the larger the EROI.

During an energy transition, the energy supply and demand systems must be modified, which requires more self-consumption of the energy system (as it needs to evolve). Hence, unless more input energy flows and stocks are extracted from the environment, less energy dedicated to our ways of life will be left. If the energy transition leads to a steady energy system for which energy extraction and transformation requires relatively more energy (through embedded energy in capital required to extract and transform it, or through energy self-consumption), then less energy can be dedicated to our ways of life, which concretely means that the average purchasing power is decreased. This is why EROI is considered as an extremely important parameter of energy transitions.

No future study to our knowledge provides estimates for the EROI of the energy system of its scenarios. Computing the EROI requires a detailed and precise mapping of physical flows (material and energy) within the considered system, which is not yet properly established in future studies, as just seen.

Computing the EROI of significant energy subsystems may be useful to inform parts of the debate if the study does not cover the whole energy system. For example, (Capellán-Pérez, de Castro, & Miguel González, 2019) computed the EROI of a global transition to renewable energies of the power system supply-side.

The EROI value along a scenario is not a concrete indicator. Hence providing it is not very informative. However, the ability to provide a consistently built EROI value demonstrates a robust modeling of physical flows. In turn, this robust mapping should enable the scenario producer to tell a consistent story about the amount of energy left for energy services and goods useful for our ways of life. **Linking the ways of life within a scenario to the physical flows supporting them is much more useful than providing an EROI value**.

In a word, the EROI concept is most useful to understand how ways of life are intimately supported by physical flows.

Recommendations to scenario producers

Scenario producers should make their strategy about physical flows consistency within their scenarios explicit. Consideration about whether or not their consistency is ensured, and where the inconsistencies lie, should be provided.

Special care should be taken about representing the following flows in their scenarios consistently with the rest of the described economy:

- Consumption of final energy by the energy supply-side system itself
- Consumption of material goods, tools and infrastructure in the industry (all sectors, including energy supply sector), and final energy consumption associated to their life cycle
- Consumption of material goods, appliances and infrastructure for providing energy services to individuals, and final energy consumption associated to their life cycle

If some of these flows are not represented, or if no consistency is ensured between them and the rest of the economy, substantiation should be provided that the narrative elements of the described scenarios, and conclusions of the study, would not be significantly modified by consistently representing them.

D. Taking into account rebound effects

Having explored how future studies compute demand, we now wonder if they take into account so-called rebound effects in their demands. We first define rebound effect, and then explore how it is considered by 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% (which is called 'backfire').

Rebound effect theory can apply to the use of energy consumption but also on any material 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. We focus here on rebound effect on energy consumption happening through changes in costs to illustrate its main aspects.

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, energy sufficiency/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 (they add up with each other):

- **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 mechanism (see below).
- **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**[10] 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 mechanism.
    - Sectoral reallocation. It can be seen as a supply-side analogy to the substitution mechanism and is most commonly discussed: if an industry acquires a more energy efficient process, it then spends more in using this extra process.
    - 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. Energy sufficiency/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 from energy system evolutions to 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, such as measures diverting purchasing power to activities consuming less energy, or to activities emitting less CO_2. 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.

[10] 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".

- 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 a GDP-based approach for demand define demand in their transformational scenarios by applying 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 with 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 those studies (technical studies) do not model any form of macroeconomic rebound effect and do not cover the subject so far. On the contrary, the partial equilibrium studies implement feedback loops between the energy system evolution and energy demand.

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). 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.

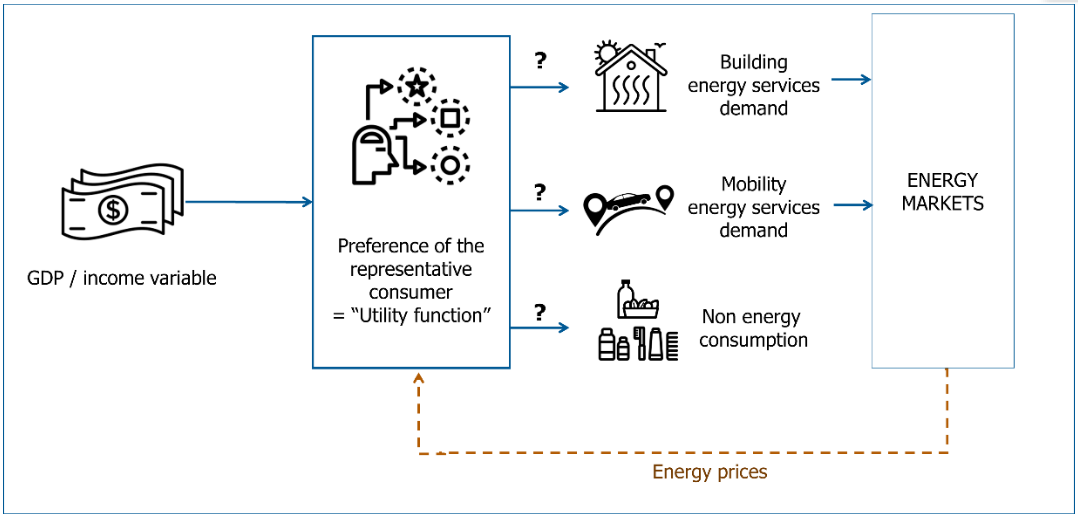

Figure 5: PRIMES model simulates representative consumers which allocate an exogenously fixed income to different consumption activities. Hence if the budget increases, or if energy efficiency increases, or if energy price decreases, the representative consumer spends its extra purchasing power in extra 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.

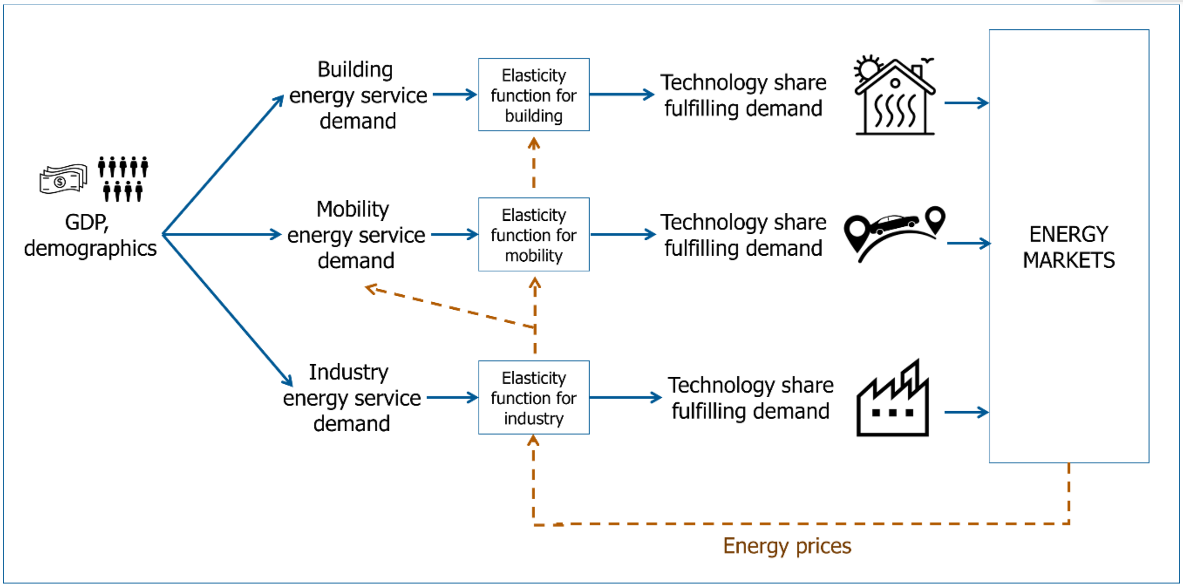

Figure 6: POLES model does not implement specific mechanisms to model rebound effects. However, its structure enables a partial account of price rebound effects, especially in the mobility sector through an elasticity feedback loop between energy price and mobility service demand.

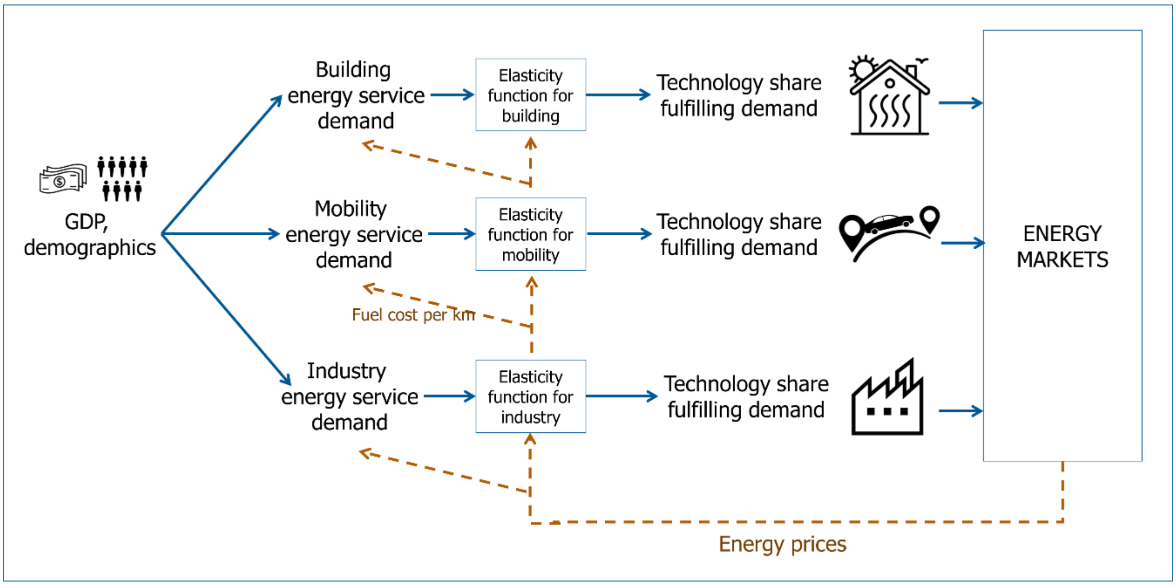

Figure 7: The WEM implements a specific mechanism to model a direct rebound effect in the mobility sector. In other sectors, no specific mechanisms are implemented but price rebound effects may be partially simulated through elasticities between energy prices and energy services demand.

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[11].

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

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 towards sufficiency/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
- 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. Considering climate change impacts on 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. 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 deeper adaptations to the impacts of climate change.

1. Weather sensitive demand

a. In the building sector

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.

b. In the mobility sector

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).

c. In the industry

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 most industrial 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).

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.

2. Adaptations to climate change

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. A modeling difficulty arises in this case, as extreme events are by definition probabilistic in their locations and impacts.

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.

3. Future studies do not consider concrete climate change impacts

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.

[12] From 0.2L to 1L per 100 km (« Heating and air conditioning in cars », 2019)
[13] including demand-side, that is, houses, cars, industries and so on

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 impacts 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 should address the following aspects:

- Climate change level and adaptation storylines.
- Effects of the projected climate change in the geographical perimeter of the study, taking into account the adaptation storyline.
- Extreme events which have been considered and extreme events which could happen but have not been considered. If some probable extreme events have not been considered, a discussion about the impacts of not considering them may be provided.
- 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.

II. 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 energy consumption evolution and the associated levers under a behavior-based approach. This frame is largely inspired by the various studies using this approach, such as (ADEME, 2012; Association négaWatt, 2014; Le Gallic, Assoumou, & Maïzi, 2017).

The behavior-based approach is developed as it better informs the debate about demand evolution by providing details about concrete 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.

We first provide an overview of how levers to reduce energy demand are discussed in future studies, and then present our demand framework.

A. Future studies activate two types of levers to reduce energy demand: energy efficiency and energy sufficiency/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 slightly different meaning, sobriety is sometimes referred to 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* refers to 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).

Several concepts are used in different fields. They are sometimes redundant (sobriety, sufficiency, and *avoid* may be redundant), and often defined through examples rather than through robust, objective, practical definitions. In order to foster collectively efficient discussions about energy demand and the levers to drive it, we now propose a common frame for informing a behavior-based approach.

B. 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 (for example, a given year). 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

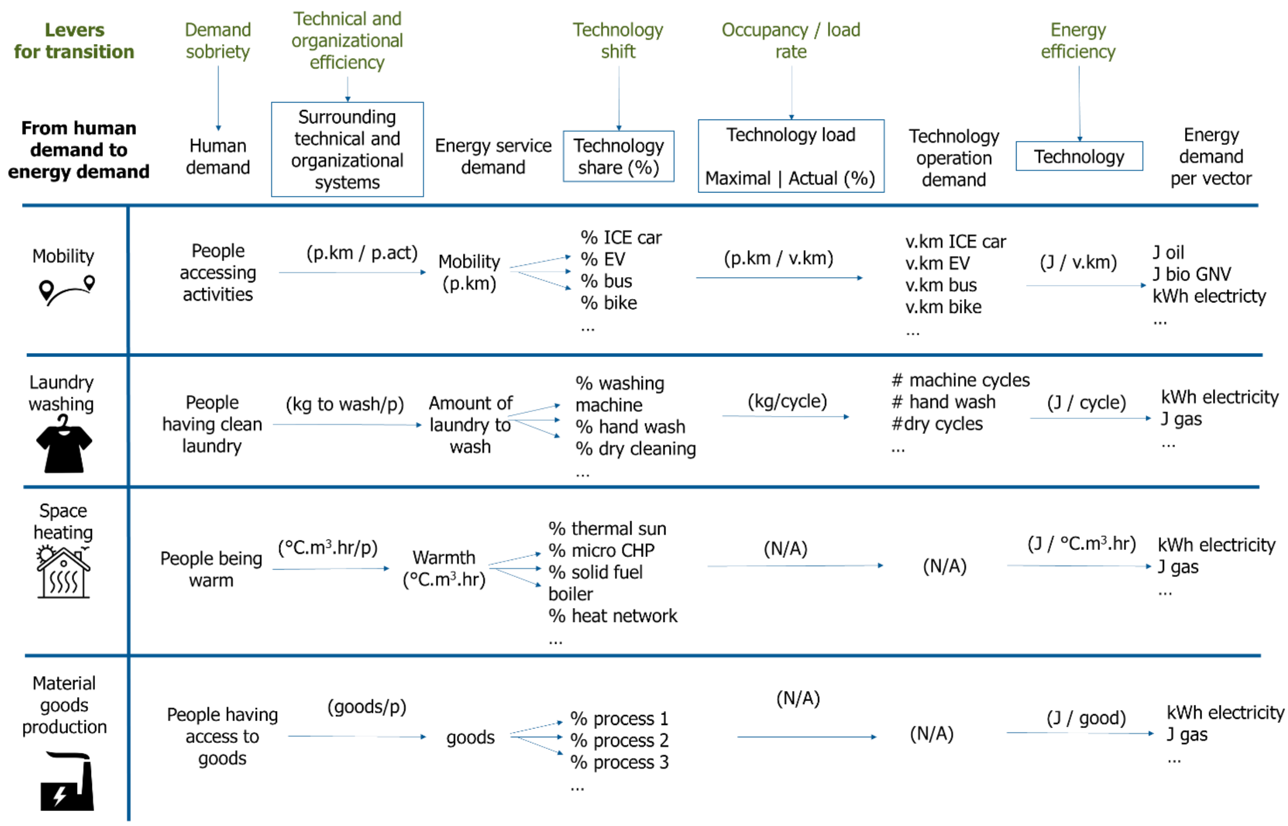

Figure 8: The energy consumption frame for a common behavior-based approach. This frame represents different energy service systems during a given year. It is a snapshot of these systems; as such, it can evolve through a scenario.

There is not necessarily a one-to-one mapping 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.

The different energy service systems which are usually studied in future studies are listed in section G. of this file. We added two systems which can be particularly dynamic in some transition scenarios: Information and Communication (IC) system, and recycling system. The IC system fulfils several types of human demand, such as people being entertained, people having social interactions, people producing things (through organizing one's work or project). The recycling system participates in the "people having access to goods" human demand.

C. 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:

1. 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 successful others using new technologies or having access to new leisure activities, lead to create new, or increase, human demand.

2. Energy service demand

This term is coined by (Le Gallic et al., 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 8, 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.

3. 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.

4. Energy demand per carrier

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 carriers.

D. New concepts to discuss levers triggering evolutions of the energy demand

In Figure 8, 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.

1. 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 sufficiency/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, as reviewed in (Gorge, Herbert, Özçağlar-Toulouse, & Robert, 2015).

In fact, the link between human demand and happiness is highly subjective and depends on each and every one life narrative. For example, reducing one's number of plane trips to distant places for tourism each year may satisfy some people inasmuch they remain there longer (presumably, people who consider that traveling is about spending enough time at a given place to highly benefit from their travel). Reducing one's consumption of plane trips for environmental convictions may also satisfy some people (presumably, people who consider that traveling by plane is detrimental for the world they want to live in). Also see section on behaviors and lifestyles on that topic.

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).

2. Technical and organizational efficiency is a source of efficiency and of interactions within the energy service basket of consumers

The surrounding technical and organizational systems 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.

3. 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 carrier, 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).

4. 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 enables to provide the same service by using the bulb less[14]. Such practices may also apply to heating systems[15].

This use characteristic relates to how long, or how often the technology must be used to provide a service, as opposed to the intensity of use (which corresponds to the following lever, energy efficiency). It does not apply for technologies which can only be used in one fashion (such as TV sets, phones, hair dryers, irons…).

Modifying load rate requires modification of consumer's behaviors, possibly through public incitation or communication campaigns.

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

Each technology used has a specific energy efficiency[16]. 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. Many technologies can be used more or less intensely by choosing their operating points manually (such as for irons, ovens, hair dryers whose temperature can be set). For some technologies though, the operating point is fixed by design.

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 below, and boundary conditions section).

Some technologies might be associated to several energy carriers, which may require to define several energy efficiencies (such as hybrid cars, or hybrid space heating systems).

6. 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".

[14] If the "turning off the light" behavior was automated by a home automation system, then it would become part of the surrounding technical and organizational systems. But in the example where the user does it, it is a change in technology load by the user.
[15] In this framework, if more people live in the same dwelling so that the same use of heating technology heats more people, this is technical and organizational efficiency (TOE). The heating technology per se can be more or less loaded if it is turned on and off manually. If a thermostat is installed, it is a TOE lever.
[16] 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.

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).

7. Sobriety or efficiency? A subjective matter which ought to be replaced by precisely defined concepts

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 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) judgment 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).

The proposed frame goes beyond these subjective uses of the terms by replacing them by precisely defined concepts: demand sobriety, technical and organizational efficiency, technology share, technology load and energy efficiency.

8. 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 emerged 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. The following steps may be followed:

- 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; income level; 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 should be provided about the desirability of the lever (see section on desirability). 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.

For assessing the impacts of the different levers, see sections on impact assessment.

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

A. Levers other than pure energy efficiency may decrease the comfort of use but may lead to side-benefits

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); the 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 (TOE 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). On the other hand, it may be associated with more free time and an improved life balance. Flat sharing enables to lower heating space service demand, but may be seen as uncomfortable. It may also be considered as a source of positive social link.
- Technology shift towards lower consumption technologies may also be associated with some sort of discomfort. 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 for the end-consumer. 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, TOE, technology shift or load rate increase as levers.

B. 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). In addition, as already suggested, energy efficiency apparently goes towards all sustainability goals. As a consequence, **<u>corporations</u> must perform all the transition efforts**, by providing 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 technologies evolutions and corporations enabling them. 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…)** (Le Gallic et al., 2017). 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.

C. 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 fix the 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).

D. Providing a *concretely* substantiated storyline for energy efficiency improvements

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, transformation 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[20].

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 triggered and 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?

IV. 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. We also cover two sectors which may be highly dynamic in many scenarios: information and communication (IC) and recycling.

Note that the sector definitions may differ between studies. For example, tertiary industry is sometimes included in buildings, sometimes in industry (Laurent et al., 2011).

A. 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.

1. Space and water heating and cooling

Space heating/cooling directly depends on level of temperature demand (human demand), building surface and building thermal performance (surrounding 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

[20] 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 carrier demand, through the *technology share*. **District heating, community scale biogas CHP[21], 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 carrier 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).

2. 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, Information and Communication Technologies (ICT), telephone chargers, etc), as well as fans, pumps for ambiance conditioning, vacuum cleaner, iron, hygiene appliances (hair dryer, hair), elevators…

These appliances are very generally thought of as **fueled by power**, as opposed to other energy carriers. 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:

[21] Combined heat and power. These plants produce heat for a heat network and power.

- 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.

B. Mobility sector

1. 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, 2018b):

- 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[22]. 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.

2. 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

[22] Usually called modal share for mobility

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.

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.

C. 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 **TOE** 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, 2012; 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[23] (ADEME, 2012; 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).

D. Industry/agriculture sectors

1. Top-down approach

Energy demand from industrial processes (including energy processes within agriculture) can be assessed through GDP 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).

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

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 carrier to electricity carrier). Energy efficiency evolution is exogenously assumed for each industrial processes.

2. Bottom-up approach

Another method to assess industrial energy demand is to compute the necessary production of goods, materials and services in the scenario, based on the hypotheses in the end-consumption sectors. For example, if more cars are expected in the mobility and freight sector, then car factories need to produce more cars. If more smartphones are bought in the building sector, then more mobile phones must be produced. If smartphones are used more in the building sector, then presumably more data must feed them, leading to extra consumption of the associated data networks.

Also the part of the goods and services demand which is produced in the studied territory must be assumed, for example through hypotheses of offshoring or inshoring behaviors of industries. For example, car factories may be located within the studied perimeter, smartphone factories and data centers located outside of it.

Then hypotheses on demand sobriety and TOE 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) and so on.

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

E. Information and Communication sector

The Information and Communication Technologies (ICT) infrastructure, including data centers and different networks is not yet included in energy demand assessment of future studies, presumably because this infrastructure is new and its consumption is still negligible as compared to total consumption. However, this infrastructure consumes electricity in a fast growing trend due to the fast growing trend of data flow consumption, so that it could represent up to 5% of total energy consumption within a few years (The Shift Project, 2018a).

Data consumption is mainly due to video watching (Efoui-Hess, 2019). Depending on the time of the day when video watching happens, peak power demand could be altered (Morley, Widdicks, & Hazas, 2018).

As a consequence, hypotheses of development of ICT uses, in terms of total quantity and in terms of peak demand, is a key topic for future studies.

Different levers such as TOE (design of websites, distribution platforms and other media), and technology share (what type of data infrastructure are used, such as wired fixed access network, Wi-Fi fixed access network and mobile network) are described in (Efoui-Hess, 2019; The Shift Project, 2018a).

F. Recycling sector

The recycling industry is composed of waste collection, sorting, separation of the different materials within wastes, and transformation into new raw materials which can be used as inputs in industrial processes, as well as transportation between the different activities. Each of these steps consume energy (FEDEREC/ADEME, 2017).

This industry is not considered as a specific sector in future studies. However, some scenarios might suppose a large expansion of this sector to tackle material criticality issues (see section on environmental assessment). In this case, this sector may come to consume significantly more energy over time. As a consequence, specific evaluations of the demand of this sector may be useful.

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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.

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