Energy transition models

Technical file #2

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 a cross-cutting topic, hence it may be linked to all the topics.

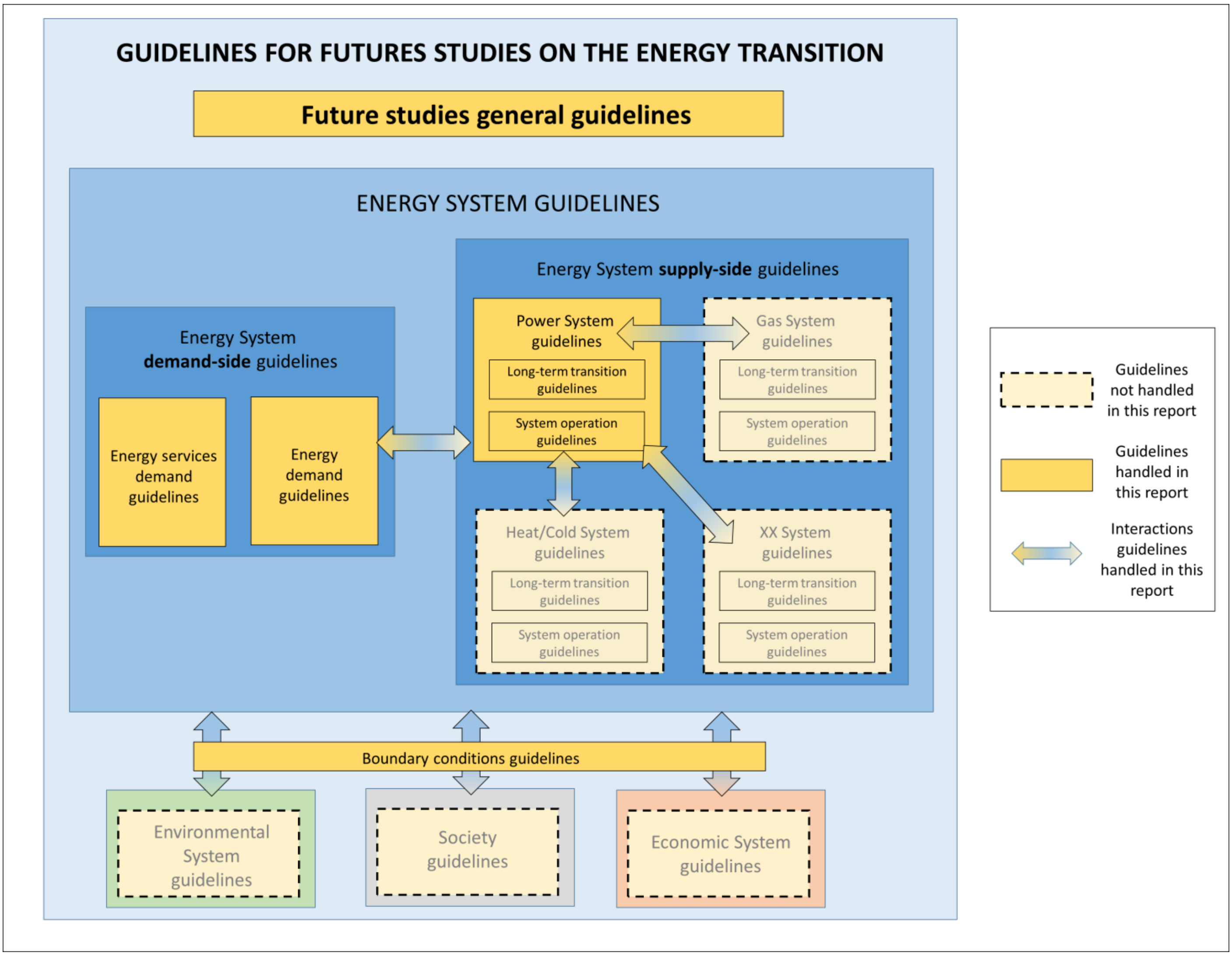


Table of content

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 words which are being defined and will be subsequently used in the framework.

I. Making models understandable

Scenarists are confronted with a wide diversity of models, and scenario readers may misunderstand the role, the assumptions and the limitations of each one. Making models understandable for scenario readers is key to improve trust in future studies.

A. A model is a simplified representation of a real system

A model is a simplified representation of a real system and of the phenomena that occur within it. Simplification is required as describing every aspect of the world at each instant of time is not possible.

An **energy model** is a model which focuses on energy issues. It uses and combines data from different sources to describe the energy system such as energy demand and supply, by determining invariable parameters[1] describing *interactions* between *modeled entities*. Modeled entities are the concepts, objects and actors that the modeler represented in the model. Usually interactions between them are described as equations whose parameters are fixed for all the scenarios of the study. Sometimes they are defined as non-parametric[2] interaction rules. Energy models are used as tools for generating consistent scenarios in future studies about the energy transition (See section on studies). They use inputs (variable parameters[3]) and produce useful outputs (published outputs[4]) to answer the driving questions of the study.

Computer-based modeling for future studies is subject to two main constraints, requiring to simplify the observed world into a simple modelled world (Krakowski, 2016):

- computing constraints such as memory and computing time. These constraints limit the amount of entities which can be modelled and the time resolution at which they can be described.
- radical uncertainty linked to the far-ahead time horizon of future studies.

For future studies taking into consideration power systems and their fine operation, both long-term planning over decades and power system operation at the scale at the millisecond to a few hours are considered. Hence more than 4 orders of magnitude of time scales are considered in such studies. In other words, each modeled entity must be described at 10,000 different time steps at minimum.

In addition, if radical, long-term uncertainty was to be tackled for each uncertain parameter, this number would grow enormously. E.g., uncertainty over which particular weather will occur (which is key for scenario with large amounts of renewables) may be tested by 100 different scenarios. Combined with time resolution, more than 1,000,000 descriptions per modeled entity would be produced, and kept in memory, for tackling these aspects.

Modelled entities interact with each other. Each interaction has to be described the same number of times as the description of the state of each entity. Hence the more interaction, the more computations have to be performed.

Hence choices over which entities are modeled, at which geographical resolution and at which time resolution must be done, as well as choice about which interaction to represent. Several types of simplifications can be performed: the sector scope or geographical scope can be reduced; timeframe can be shortened; the modelled entities can be more aggregated into fewer entities; some interactions can be neglected or simplified; time and space resolution can be lowered.

B. Modeling the energy system is an extremely complex work

Modeling activities may be performed by companies, or university laboratories, specialized in energy system, environment and macro-economic modeling. These entities use their in-house models which can be tuned to the specific questions and data brought by scenario producers after their study strategy activities. For example, the

[1] See section on future studies
[2] That is, not described as equations (for example, they can be described as logic gates).
[3] See section on future studies
[4] Ibid.

European Commission designed scenarios and then contracted the National Technical University of Athens to model scenarios (PRIMES model was used (European Commission, 2011)).

Intense interaction happens between scenario producers and modelers, when they are not the same teams. Scenario-producers might monitor the modeling activities in order to ensure the model is properly tuned and the variable hypotheses can be integrated into the model, or just trust the modelers depending on the modeling experience of the scenario producers. When scenario producers have modeling skills they might even challenge modelers to find the best modeling solution[5]. When they do not, modelers might explain to them as clearly as possible the options and limitations of their models (see section on future studies). They might also clearly phrase the driving questions their model can (or cannot) answer and work with scenarists to determine if the model can fulfil their modeling needs.

Scenario producers may design and implement pre- and post-processing modules to adapt inputs to the model from raw data and to adapt model's outputs to the interpretation and publication of results.

In other cases the same team, or person, performs scenario design and modeling activities (for example associations such as négaWatt or Négatep in France). Big agencies such as IEA or publicly owned companies such as RTE developed their own models (the World Energy Model and the ETP model for EIA and the open source model Antares[6] for RTE).

Modeling activities consist in designing and producing a model, or tuning an already existing one, able to fulfill the needs of a future study. The tuning might be the activation of an option already implemented in the model, or the production of a new module in the model. For illustration purpose, we take the question "What would be the implications of reaching a fourfold decrease of CO_2 emissions in France with more renewable energy sources (RES), energy sobriety and energy efficiency, for the environment, the economy, lifestyles, research activities and energy industry activities? [7]". Modeling activities are composed of:

- Defining the *variable parameters*, which will be part of the exogenous variables in the model and whose values will be controlled by scenarists for each scenario. In other words, the model must offer the possibility to adjust a given set of variables. These variables have been described as levers, social objectives or uncontrollable uncertainties[8]. They are determined by the planning question and brought by scenarists. In the example question, RES installed capacity, final energy consumption and demand-side technologies[9] have to be variable parameters in order to investigate their effects.
- Determining the important endogenous variables. They are those variables which are considered as the main *outputs* to communicate according to the planning question. In the example question, indicators about the environment, economy, lifestyle, research activities and energy industry activities are the important endogenous variables. The model must provide the possibility to extract these indicators, or at least to provide meaningful information about these aspects.
- Modeling the entities brought into play by the planning question and determining the functional links between them, that is, finding out how these entities interact with each other. The example question requires to define the links between CO_2 emissions and the whole energy system, as well as the links between the energy system and respectively, environment, the economic system, research activities, energy industry activities, and lifestyles. It requires in turn to model the energy system, the environment, etc. This step requires a thorough understanding of the whole economy, energy system, or power system depending on the sector scope of scenarios, and data about the parameters defining these systems and the interactions between their elements. These data are often based on external, research sources. This is why this very complex modeling is sometimes performed by specialized teams, composed of experts from various domains.

Once the model is designed and implemented (usually under the form of a computer algorithm), it is run once per scenario, each time producing a set of results corresponding to a set of different *variable parameters*.

[5] A model able to answer the driving questions at the lowest cost and before a given deadline.
[6] https://antares.rte-france.com
[7] This planning question is implicitly asked in ANCRE 2013
[8] See section on future studies.
[9] See section on boundary conditions

C. Scenario readers should be able to understand a model through the story it tells about how a system works

Understanding how a real system is represented in the model is of interest for scenario users and readers, as opposed to understanding how the modeling tool has been designed and implemented. Similarly, a book reader is interested by the story in the book rather than by how the book has been produced or the material it is made of. In this respect, describing a model efficiently for scenario readers is similar to explaining how the described world operates using usual, real-world, concrete concepts. Hence we consider in this framework that the specific computational methodology, programming technique and mathematical logic of models are not of interest for scenario users and readers whenever they do not tell anything about the world they represent. They are rather a diverse set of tools enabling to represent the same systems in different fashions.

II. Describing the represented entities and their interactions

The purpose of this technical file is to make a clear and transparent link between the selected, or designed, model and the driving questions of the study. Indeed scenario producers usually make sure the model they use is suitable to answer their driving questions.

In this section, we seek to determine key characteristics of models which should be made explicit by scenario producers to have the best chance their readers understand the model they used. In addition, scenario producers need a good understanding of the model they use in order to be sure it can answer their driving questions, especially when they use an off-the-shelf model. As noted by (Hülk, Müller, Glauer, Förster, & Schachler, 2018) in their review of transparency in energy modelling, "a profound discussion on the strengths and weaknesses of the existing models and which question can or cannot be answered by them is hampered and it contradicts the general requirements of good scientific work."

We first reviewed models classifications in search for key characteristics.

A. Models classifications might not be the right tool to quickly understand complex models

1. Existing models' classifications are numerous

Many researchers have made attempts to classify models (Bhattacharyya & Timilsina, 2010; Boulanger & Bréchet, 2003; Connolly, Lund, Mathiesen, & Leahy, 2010; Després, Hadjsaid, Criqui, & Noirot, 2015; Herbst, Toro, Reitze, & Jochem, 2012; van Beeck, 1999) that can be aggregated in the following diagram (see Figure 1).

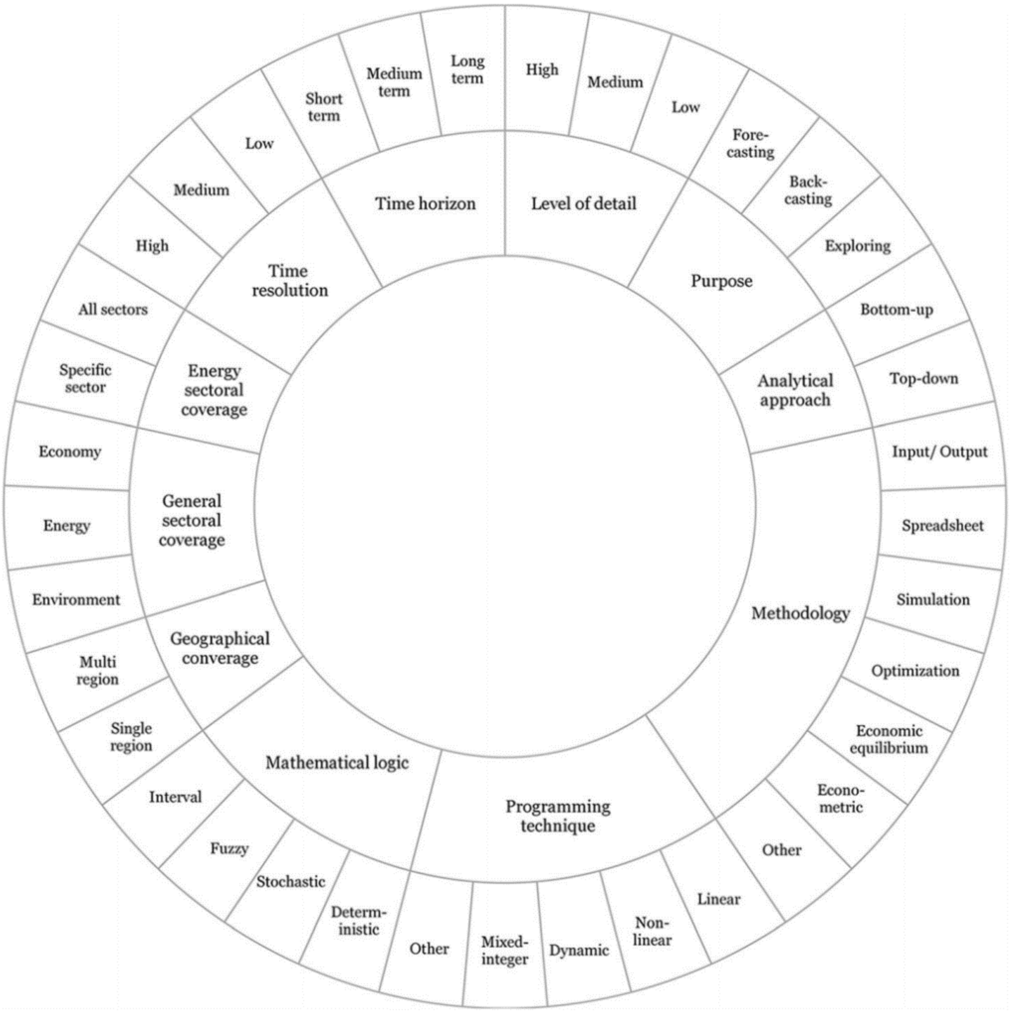


Figure 1 : Classification of models, by (Cao, Cebulla, Gómez Vilchez, Mousavi, & Prehofer, 2016)

Models can be classified by purpose (e.g. to explore the impacts of different levers or to normatively investigate how to achieve social objectives); by analytical approach (i.e. whether technology-based bottom-up, or economy-based top-down); by methodology (e.g. optimization, simulation or equilibrium models); by geographical perimeter (i.e. what regions can be modelled), by level of details (i.e. the level of aggregation of entities represented in the model); by sectoral perimeter (i.e. modelling the whole economy or only the energy system, or power system); by time horizon and by model time resolution.

The goal of this section is to provide keys to scenario readers for a better understanding of how a studied system is represented in models, and to provide recommendations for scenario producers to improve this understanding in their readers. We turn in the following sections on the different ways to categorize models, each time asking: is the categorization useful to understand more profoundly what the model represents of the real world and how it does it, as well as what the model should, or should not be, used for?

2. Scopes of models should be compatible with those of scenarios

Several of the proposed classifications have already been dealt with in the studies section. Indeed, time horizon, geographical coverage, sectoral coverages, and backcasting / exploratory purposes are considered in this framework as characteristics of the study rather than characteristics of the model. In other words, we consider that model design or model selection derive from study design (see figure in studies section).

However this point of view is quite theoretical as in practice strategy design of the study, or even driving questions, are partly model-driven. In other words, the availability of off-the-shelf models may partly determine which questions will be asked by scenario producers, especially when modeling skills, or available resources or time are lacking for the scenario team.

In this respect, scopes of studies and of models (that is, geographical and sectoral scopes as well as time horizon) do not tell how the system is represented but what parts of it are represented and over which period of time. Of course, the scopes of a study and the scopes of the model used by the study must be compatible (either the scope of the model contains the scope of the study, or the model must be completed with modules, or qualitative considerations to fill the gaps).

In particular, scopes of models determine the type of quantitative results which can be produced. Usually, the scope covers the *core system*[10], so quantitative results on the core system such as energy and/or power supply, can by produced by assessing its level, its technological forms and/or its costs. In our framework, other outputs are the evolutions of the *surrounding system* in interaction with the energy system such as the impacts on the economy, society, the environment or the security of supply. If outputs are published about these surrounding systems, most often the associated aspects of surrounding systems are modeled (e.g., some aspects of society, or environment might be modeled). Some other aspects may be difficult to quantify, such as lifestyles, so storytelling approaches can be used in combination to quantitative approaches to produce qualitative results.

By way of examples, ThreeMe (OFCE) can be used to assess GDP, employment or energy bill (Callonec, Landa Rivera, Malliet, Saussay, & Reynès, 2016), ADEME conducted a study on the interplay between energy transition and lifestyle (ADEME, 2014), and Integrated Assessment Models (IAMs) such as DICE, MERGE, MESSAGE also aim at representing the interaction between the environment and the energy system (Després et al., 2015).

3. Models methodologies (optimization, equilibrium or simulation) inform about how transition agent(s) decide

As (IEA-RETD, 2013) puts it, "Human behavior is enormously complex to model. It may be the most uncertain aspect of our energy future, especially when transformative futures are envisioned". A key aspect to understand models is to understand how decisions driving the transition are taken in it.

Models use optimization, simulation or equilibrium methodologies (IEA-RETD, 2013), according to the way decisions are taken about the energy system evolution[11].

Optimization methodology is used to represent a world driven by the search of a global optimality, such as a least cost trajectory under some constraints. METIS model (ARTELYS / European Commission, 2017) or TIMES use such methods (Energy Technology Systems Analysis Programme, 2016).

Equilibrium methodology is used to represent a world driven by balanced markets. This method assumes a unique price equilibrium exists for each market and assumes that decisions by agents are only driven by profit considerations. To make their decisions, these agents take into account information which is available to them. This information may be a complete and perfect knowledge about the future, or only partial information about the future. This leads to biases towards high inertias for key market actors' behaviors (e.g. how consumers value goods relative to each other are calibrated from historical economic data; similarly, use of capital, labor, energy and material to produce goods are calibrated from historical data). PRIMES model uses such a methodology (E3Modelling, 2018).

Simulation methodology is used to represent a world driven by rules applied step by step, year after year, such as investment decisions across competing technologies or plant commissioning/decommissioning decisions. Such rules can be defined by the scenario producer as to produce macro-behaviors which are similar to those observed today or instead they can be defined so as to produce new, "transformational"[12] behaviors. Compared to equilibrium methodology, the emphasis is on representing a system not purely driven by financial costs and profits. For instance, a technology may capture a share of the market even though its life-cycle cost is higher than that of other technologies (Energy Technology Systems Analysis Programme, 2016). POLES (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), or the World Energy Model (International Energy Agency, 2018), use this methodology.

In the section about future studies we introduced the "scenario philosophy" concept. Two philosophies about the *transition agent* which controls the energy system transition in scenarios have been described: simulated agents

[10] See section on future studies.
[11] See section on the long-term transition of the power system
[12] Related to high rates of change within the transition, as opposed to "business-as-usual".

or benevolent planner. In the first philosophy, the evolution of the energy system is driven by agents whose behaviors are modelled and which pursue different objectives. In the second philosophy, energy system evolution is driven by a benevolent planner who follows rules and knows the global energy system.

The benevolent planner representation of the world uses the optimization methodology when the planner seeks global optimality. However, benevolent planners can use different criteria as optimality. They can instead drive the transition following qualitative rules (such as a nuclear phase-out according to a given roadmap with renewable sources in replacement). In this case, simulation methodology is used.

The simulated agents representation of the world can use the simulation methodology if the modeler wants to represent agents' decisions (for example, investments decisions) in a specific way. Or, the equilibrium methodology can be used if the scenario producers wants to represent agents' decisions as if they were in a balanced market world calibrated on today's markets. Some studies implement financing agents whose foresight is perfect; in other words, these agents have a perfect information of all the other agents' behaviors, past of future. These extreme hypotheses produce a cost-optimal emergent behavior for the energy system. In other words, this modeling is equivalent to a cost-optimization by a benevolent planner (also called the invisible hand of competitive markets) (Loulou, 2016).

Transition agent	**Model methodology**		
	Equilibrium	**Optimization**	**Simulation**
Simulated agents	Agents act in balanced markets in a way which is calibrated on today's markets	Agents act with a perfect foresight: equivalent to benevolent planner cost-optimization	Agents control the long term transition following individual specific rules
Benevolent planner	N/A	Benevolent planner seeks to optimize the system as a whole along defined dimensions and under some constraints	Benevolent planner controls the long term transition following system-wide rules

Hence the methodologies can be seen as precisions about how the controlling agent(s) act.

Simulated agents may appear closer to reality than a benevolent planner. However, understanding the way the simulated agents drive the transition in models is not easy, as they are generally much aggregated. Furthermore, their decision behaviors are usually calibrated on past and current actors' behaviors, or on purely theoretical behaviors (also see section on lifestyles and behaviors). Current models implementing simulated agents implicitly assume that the past and current contexts in which actors have behaved cannot change enough to generate changes in the types of actors and in their behaviors. This might lead to overestimating socio-cultural inertias.

On the contrary, the benevolent planner approach does not seek to reproduce past behaviors since the planner decides for the whole system's transition and dynamics. Hence this approach might underestimate socio-cultural inertias.

Note that studies using models with optimization methodology can describe their world either in terms of far-sighted, long-term financing agents (such as in (RTE, 2017)), or in terms of global system optimization (such as in (ADEME / Artelys, 2018)).

4. Model foresight informs about how far ahead transition agent(s) perfectly see

Some models assume an intertemporal foresight which means agents in the model (benevolent planner or simulated agents) make their decisions knowing in advance the whole trajectory up to the time horizon. Hence the whole trajectory is solved in one step (such as D-CAM model for a benevolent planner (CGDD, 2016) or TIMES for simulated agents (Energy Technology Systems Analysis Programme, 2016)).

Other models assume a myopic foresight, which means agents in the model make their decisions at each time step having some, but not all information about how the future will unfold, or having perfect and compete information but only for a given window of time.

For instance, PRIMES represents actors of the demand with a myopic foresight and actors of the supply with a perfect foresight. PRIMES usually "assumes a perfect foresight over a short time horizon for demand sectors and perfect foresight over long time horizon for supply sectors." (E3MLab, 2017)

Furthermore, having these information, simulated agents make investment decisions based on a preference for the present, that is they discount the future (modeled by a discount rate which is more or less disaggregated by sector, type of agent, etc). Similarly, the benevolent planner might optimize the transition with a given discount rate (such as in TIMES (Loulou, 2016)).

5. Top-down *versus* bottom-up categorization would be usefully replaced by a description of the modelled entities and their aggregation levels

Abundant literature divides energy modelling between two main categories: bottom-up and top-down models. Definitions differ according to modelers (Després et al., 2015), but some prominent points seem to be unchanging.

In **top-down** models, information is descending from aggregated to disaggregated levels (Després et al., 2015; Djemaa, 2009); they therefore provide an **aggregated** description of the system, which is represented in monetary units. Top-down models are also referred to as **economic models**. They can be categorized into three main categories: optimal growth models whose principle is to perform an intertemporal maximization of profit for a unique aggregate agent; macroeconometric models, which simulate the evolution of economic variables based on their past interactions; general equilibrium models which represent the markets for each good and service, their interdependence as well as the budgets of representative agents (Guivarch, 2011).

They rely on few aggregated variables – K: capital, L: labor, M: raw material, E: energy – which link the technical sphere to economic activity and technologies are implicitly represented *via* elasticities.

In **bottom-up** models, information is ascending: the description of the system is **disaggregated** and described with numerous technological variables. They are therefore referred to as **technological, or engineers models**. Unlike top-down models, technologies, energy flows and technical characteristics are explicitly represented. Consumption and production of each technology are then summed from the bottom to the top. Two types of bottom-up models can be found, corresponding to the benevolent planner approach or simulated agents approach.

Nevertheless, despite being one of the most common distinction between models, it seems to lose relevance over time with the emergence of **hybrid models** in which these descriptions are mixed together in such a way that some models tend to be "mostly bottom-up" or "mostly top-down" but cannot be purely classified as one or the other (IEA-RETD, 2013). Boulanger even questions this distinction as economic models are simultaneously "ascending" and "descending" regarding the interaction between volume (descending) and price (ascending). Moreover, he notes that macroeconomic models (as Corelli model) can adopt a highly disaggregated description as well as a bottom-up methodology (Boulanger & Bréchet, 2003).

This historical distinction is actually more fundamentally described in terms of which actors and objects are represented in the model and at which aggregation level. In other words, no need to say a model is bottom-up or top-down if one knows what technological objects and what deciding agents are represented in the model.

B. Describing the actors and objects represented in scenarios (the modeled entities)

The energy system and its surroundings feature not only complex interactions between elements at a large scale, but also complex behaviors of the elements themselves (Grandjean & Giraud, 2017). At the same time, modelers face technical limitations such as computing times, limited knowledge of the components of the system and of the way they behave, not to mention data deficiency and inaccuracy (Bhattacharyya & Timilsina, 2009). **Simplifications** of the system are thus needed, which is what defines the modelling approach.

Modelled entities must be selected taking into account those limitations. They belong to the sector scope and behave within the geographical scope and time horizon of the study.

These entities can represent physical assets (such as power plants, grid elements, storage equipment, consuming devices such as light bulbs etc), human beings or organizations (for example markets, finance decision-makers, households), or environment elements (for example CO_2 in the atmosphere) in the real world.

1. Chossing the proper resolutions and aggregation levels of modelled entities

It would be unfeasible to represent the energy system and all its surroundings electron by electron, cent by cent or $kgCO_2eq$ by $kgCO_2eq$, hence the need to **aggregate** some agents and define a **level of resolution** for each considered phenomenon. Some parts of the system are then described with more details than others, resulting in a **specialization of models** that the reader must be aware of since it can significantly affect the interpretation of results (such specializations appear in the bottom-up *vs* top-down distinction).

a. Aggregation level

Compared to the real world, entities can be represented in an aggregated way in the model. Here are examples of aggregation levels for different entities.

Power grid can be represented with different aggregation levels. For example, the European power grid may be represented as a set of interconnected copperplates, one per represented country. The copperplate is an aggregate of the power grid as if it were condensed in a single copperplate to which all the country's power plants and electric devices would be connected (Després et al., 2015). The power grid may be represented more finely with more regions and with more detailed equipment (different types of lines per level of voltage, equipment ensuring grid stability…).

The power generation has many representation possibilities too. Conventional productions can be described at the power plant level or aggregated by technology types. Several similar technology types can be aggregated (such as different technologies of wind turbines).

Economic agents are usually aggregated per sector (such as the iron and steel sector generating energy demand in PRIMES), or per technology (such as finance decisions for different power plant technologies).

The atmosphere is aggregated into a single figure when it comes to measuring GHG emissions.

Research and development (R&D) departments, industrialization departments or strategy departments of companies within a technology sector may be said to be aggregated when a "technology learning rate" is chosen. This rate usually represents the rate at which costs of a technology decreases with commercial experience. Even though most often no concrete explanation is provided about why the costs decrease, one might assume that they decrease because R&D and industrialization engineers lead to cost reduction, or because some parts of the activity are offshored to lower labor cost regions. In other words, making the explanation concrete reveals what actors are actually modeled, and how they behave.

b. Space resolution

Geographical resolution is the minimal space step between two modelled locations. Space resolution might be important for simulating renewables production (PV and wind), by precisely determining wind or sunlight levels for different locations.

It might also be important for representing highly deconcentrated power systems in which the specific place where electric device and equipment as well as production plants need to be precisely known to ensure a local power-supply balance (IEA-RETD, 2013), and a proper voltage control (see section on power system operation).

c. Time resolution

Depending on the goal of the model, time step can vary from less than 1 s to several years. Typically, long-term transition models run on 1-year to 5-year time-steps whereas power system operation models typically run on sub-hour to 1-hour time-steps (see box hereunder).

A higher resolution enables to represent interactions with a higher dynamics between the represented entities. Several types of inertias can interact within a year in reality but could not be captured in a 5-year time-step model. For example, workforce structure evolution (such as the amount of available workforce in a given sector and the time it requires to modify this amount through training programs in a transition context), industrialization rates per technology, growth of material availability (such as rare earth magnets within wind turbines, or certain materials for photovoltaics) etc, need to be represented at a sufficient resolution to bring insight on the resulting inertia, especially within transformational scenarios (IEA-RETD, 2013).

Resolution adaptation for studying high shares of variable renewables in power systems

As explained in (IRENA, 2017) two different time steps are used in energy system models, to account for different processes happening at different time scales.

The first time step corresponds to the **development of capital stock and investment decisions**, happening on the long term. This is generally a 1 year to 5 year time step, which is precise enough to account for the long-lived capital stock evolution (whose lifetime ranges from 15 to 40 years or more) (see section on long term transition of the power system).

The second time step corresponds to the **operation of the power system**, taking into account the simulation of flexibility needs and how the proposed power supply system fulfils them, as well as other ancillary services (see section on power system operation) (IEA-RETD, 2013). Usually, modelers define time slices over which system operation is studied. They are chosen in order to represent the power demand and supply variabilities in order to study some aspects of flexibility. With few variable RES in the power system, these time slices account for demand variability[13]. With more RES, supply variability must be taken into account, which changes the time slices' definitions. Neglecting the variability of supply of variable RES could lead to a sub-optimal power mix, or to a power mix which is not operational. Hence scenario producers studying high power RES scenarios use hour time step models over whole years.

Similarly, geographical resolution has to be adapted for the study of RES supply, as supply largely depends on the precise location of the production plants. Typically, long-term models are not precise enough as they represent the power system through national nodes ("copperplates") interlinked by interconnections. Hence in these models, RES generation would be the national average generation as if RES were evenly distributed over the whole territory. This can lead to sub-optimal power supply mixes. Furthermore, local grid structure cannot be modelled, hence the costs of its adaptation to more RES cannot be estimated finely, especially in case of deep restructuring. Finally, local phenomena such as voltage control cannot be modelled with such low resolutions.

Choosing the aggregation level and time/space resolutions depends on the needed precision, and the computation time. The more disaggregated entities are, the more entities must be individually modelled and the number of interactions between them might grow exponentially[14]. The higher space resolution, the more locations need to be modeled, and the higher time resolution, the more computational steps need to be performed to reach a given time horizon. Hence a tradeoff needs to be solved between these resolution aspects and precision needs. These choices also depend on data availability: if more entities are modelled, more data are required to calibrate them at first time step and to model their interactions between them. Similarly, to model PV and wind production at a high space resolution, weather data need to be available at the same, or a higher space resolution.

[13] For example, one week day and one week-end day for each season are represented, each of them being divided up in four 6-hour slices.
[14] n entities interacting together represent factorial n (n !) interactions.

2. Describing how entities behave and interact in scenarios

Represented entities interact with each other in the model. In that sense, each entity can be said to participate in different functions.

For example a coal power plant can have a CO_2 emission function, a power production function, power reserves and flexibility functions, a coal consumption function, a cost function, meaning that it is represented as emitting CO_2, injecting power in the grid, participating in reserves and flexibility services for the power system, consuming coal and inducing costs respectively.

A market might have a price function as well as a supply and demand function, as it determines the clearing of the three variables. A financial decision-maker has an investment allocation among technologies function. Households may have a workforce function as well as a consuming different energy commodities, different goods and services functions and so on.

Among those functions, some might only be **output functions** (for example CO_2 might just be counted each year to produce an output, as opposed to being an input for a climate change feedback loop; cost might just be counted for total system expenses each year and so on) whereas others are interaction functions (injected power is consumed by other entities), and others are only **input functions** (for example the cost function of oil or gaz – their prices, or the power production of wind turbines depending on their location, etc).

Each function requires to characterize the entity which has this function through **key characteristics of entities**. For example, a coal power plant might have a coal consumption function, a power production function, and a power reserve function. Each of these functions need to be characterized: the plant consumes a given amount of coal per hour enabling it to produce a given amount of power per unit of consumed coal; the plant can increase its power by a given amount within a given amount of time to participate in reserves services etc. In the present framework, key characteristics of entities are dealt with in section about long-term transition of the power system.

Understanding the basics of a model requires to understand the main entities and main interactions between entities. As hundreds of different entities can be modelled, a simpler description can be provided by aggregating entities into meaningful groups sharing the same interactions with entities outside their groups. For example, all fossil fuel power plants may be grouped together in the simplified description of the model.

Key interactions between key entities can be represented within an interaction matrix, or with a graph. They can also be textually described.

	Coal power plants	Transport	Households	Total expenses	Power	Fossil fuels	…
Coal power plants				X	X	X	
Transport			X	X	X	X	
Households					X	X	
Total expenses							
Power consumption							
Fossil fuels							
…							

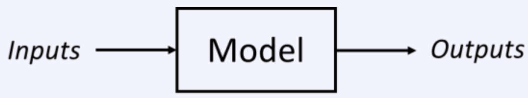
Table 1: Interaction matrix between modelled entities for a fictive model.
Reading key: coal power plants participate in total expenses through their CAPEX and OPEX, they produce power, the consume fossil fuels; transportation is consumed by households; it participates in total expenses (in this fictive model) through vehicles production; it consumes power and fossil fuels, and so on.

Understanding the interactions between key entities of a model does not imply understanding the overall system behavior (so-called emergent behaviors may happen in complex systems). Hence such a matrix could be used as a help to properly and concretely tell the stories the model participates in writing along the scenario production process. Writing the story requires to be able to translate in real world terms what the model simulates (which entity did what, and why it did so in interaction with the other entities) and integrate the elements of narrative it provides to the overall story composed of the storyline, hypotheses, model mechanisms, model results and their interpretations.

Recommendations for scenario producers:

Future studies should be transparent about how the model(s) they used represent the real studied system. Explaining a model requires transparency and a simplification of it. The modeled system as well as its similarities with the real system should be described, including the following aspects:

- The geographical perimeter and time horizon used in the model(s). A substantiation of **compatibilities of the geographical perimeter and time horizon used in the model(s) with scenarios' needs** (including the driving questions) should be performed.
- The sector scope of the model(s). A substantiation of **the compatibility of the sector scope of the model(s) with scenarios' sector scope and published results** should be performed. *E.g., if scenarios talk about lifestyles, or purchasing power, does the model enable to compute lifestyle changes, or purchasing power of households? Otherwise, how are these questions handled by the study?*
- Geographical resolution of the model(s). A substantiation of the compatibility between **geographical resolution of the model(s) and the main published results** should be provided, in line with the driving questions. *For example, if the lowest level of resolution is the country level, no results can be provided on a country's regions level. Typically, if PV resources are evaluated based on a country average, their repartition across the different regions within the country cannot be provided from model's results.*
- Time step of the model(s). A substantiation of the **compatibility between time step of the model(s) and the main published results and their interpretations** should be provided, in line with the driving questions. *E.g., infra year dynamics cannot be described by a one-year time step model. For power system (see section about power system operation), infra hour to hour time-steps may be required to provide results on the power system stability, depending on the structure of the proposed system and its share of variable renewable energy sources.*
- The inputs and outputs of the model. A very simple diagram should be provided to **show the inputs and outputs of the model** (Cao et al., 2016).



- **The main entities which are represented in the models**. These entities are objects and agents existing in the real studied system. *E.g., technology learning rate cannot be seen in the real world; however, they may represent the decisions from the aggregation of R&D and industrialization departments of a sector's companies in the real studied system.*
- **The level of aggregation for each entity, and its consistency with the main published results** and their interpretations, in line with the driving questions. *E.g, all nuclear power plants may be aggregated in a single object in the model. This would not be compatible with describing in the scenario a precise nuclear phase-out schedule.*
- The **main interactions of the described entities**. The links (or absence of links) between the *modeled* interactions and those *observed in the real system* should be described. These interactions can be described using interaction matrices, or graphs, and/or through text, or any other mean suiting the scenario producer. This representation should clearly show what entities are inputs and what entities are outputs. *E.g., R&D and industrialization departments of the wind turbines sectors may interact with wind turbines through time to decrease their costs and improve their load factors by 2% every time 1000 wind turbines are installed. These entities, through their technology learning rate, can be an input.*

Bibliography

ADEME. (2014). *Visions énergie climat 2030/2050—Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060—Synthèse*.

ARTELYS / European Commission. (2017). *METIS Technical Note T6—METIS Power System Module* (p. 43).

Bhattacharyya, S. C., & Timilsina, G. R. (2009). *Energy Demand Models for Policy Formulation—A comparative Study of Energy Demand Models* (Nº 4866). The World Bank.

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management*, *4*(4), 494-518. https://doi.org/10.1108/17506221011092742

Boulanger, P.-M., & Bréchet, T. (2003). *Une analyse comparative des classes de modèles*.

Callonec, G., Landa Rivera, G., Malliet, P., Saussay, A., & Reynès, F. (2016). Les propriétés dynamiques et de long terme du modèle ThreeME. Un cahier de variantes. *Revue de l'OFCE*, *5*(149), 47-99.

Cao, K.-K., Cebulla, F., Gómez Vilchez, J. J., Mousavi, B., & Prehofer, S. (2016). Raising awareness in model-based energy scenario studies—A transparency checklist. *Energy, Sustainability and Society*, *6*(1). https://doi.org/10.1186/s13705-016-0090-z

CGDD. (2016). *Trajectoires de transition bas carbone en France au moindre coût*.

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, *87*(4), 1059-1082. https://doi.org/10.1016/j.apenergy.2009.09.026

Després, J., Hadjsaid, N., Criqui, P., & Noirot, I. (2015). Modelling the impacts of variable renewable sources on the power sector : Reconsidering the typology of energy modelling tools. *Energy*, *80*, 486-495. https://doi.org/10.1016/j.energy.2014.12.005

Djemaa, A. (2009). *Modélisation bottom-up, un outil d'aide à la décision long terme pour les mesures politiques en matière d'énergie et d'environnement : Le modèle TIMES appliqué aux industries grandes consommatrices d'énergie*. 417.

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017—Detailed model description*.

E3Modelling. (2018). *PRIMES MODEL VERSION 2018—Detailed model description* (p. 221).

Energy Technology Systems Analysis Programme. (2016). *Documentation for the TIMES Model*.

European Commission. (2011). *Energy Roadmap 2050—Impact assessment and scenario analysis*.

Grandjean, A., & Giraud, G. (2017). *Comparaison des modèles météorologiques, climatiques et économiques : Quelles capacités, quelles limites, quels usages ?*

Guivarch, C. (2011). *Évaluer le coût des politiques climatiques : De l'importance des mécanismes de second rang*. Paris-Est.

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics*, *148*(2), 111-135. https://doi.org/10.1007/BF03399363

Hülk, L., Müller, B., Glauer, M., Förster, E., & Schachler, B. (2018). Transparency, reproducibility, and quality of energy system analyses – A process to improve scientific work. *Energy Strategy Reviews*, *22*, 264-269. https://doi.org/10.1016/j.esr.2018.08.014

IEA-RETD. (2013). *Re-assume—A Decision Maker's Guide to Evaluating Energy Scenarios, Modeling and Assumptions*.

International Energy Agency. (2018). *World Energy Model Documentation—2018 Version* (p. 82).

IRENA. (2017). *Planning for the Renewable Future—Long-term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies*.

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

Krakowski, V. (2016). *Intégration du renouvelable et stratégie de déploiement du réseau électrique : Réconciliation d'échelles spatio-temporelles dans des exercices prospectifs de long terme*. PSL Research University.

Loulou, Ri. (2016). *Documentation for the TIMES Model—PART I* (p. 151). Energy Technology Systems Analysis Programme.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

van Beeck, N. (1999). *Classification of Energy Models*. 25.

Authors

Nicolas RAILLARD

Project Manager – nicolas.raillard@theshiftproject.org

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

Quentin MINIER

Intern

Quentin Minier joined *The Shift Project* for a two-month internship on energy models, as part of his Engineering and Political Science graduate training at Mines de Nancy (France) and Science Po Paris.

The Shift Project

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

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

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