Economic evaluation of energy transition scenarios

Technical file #11

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.

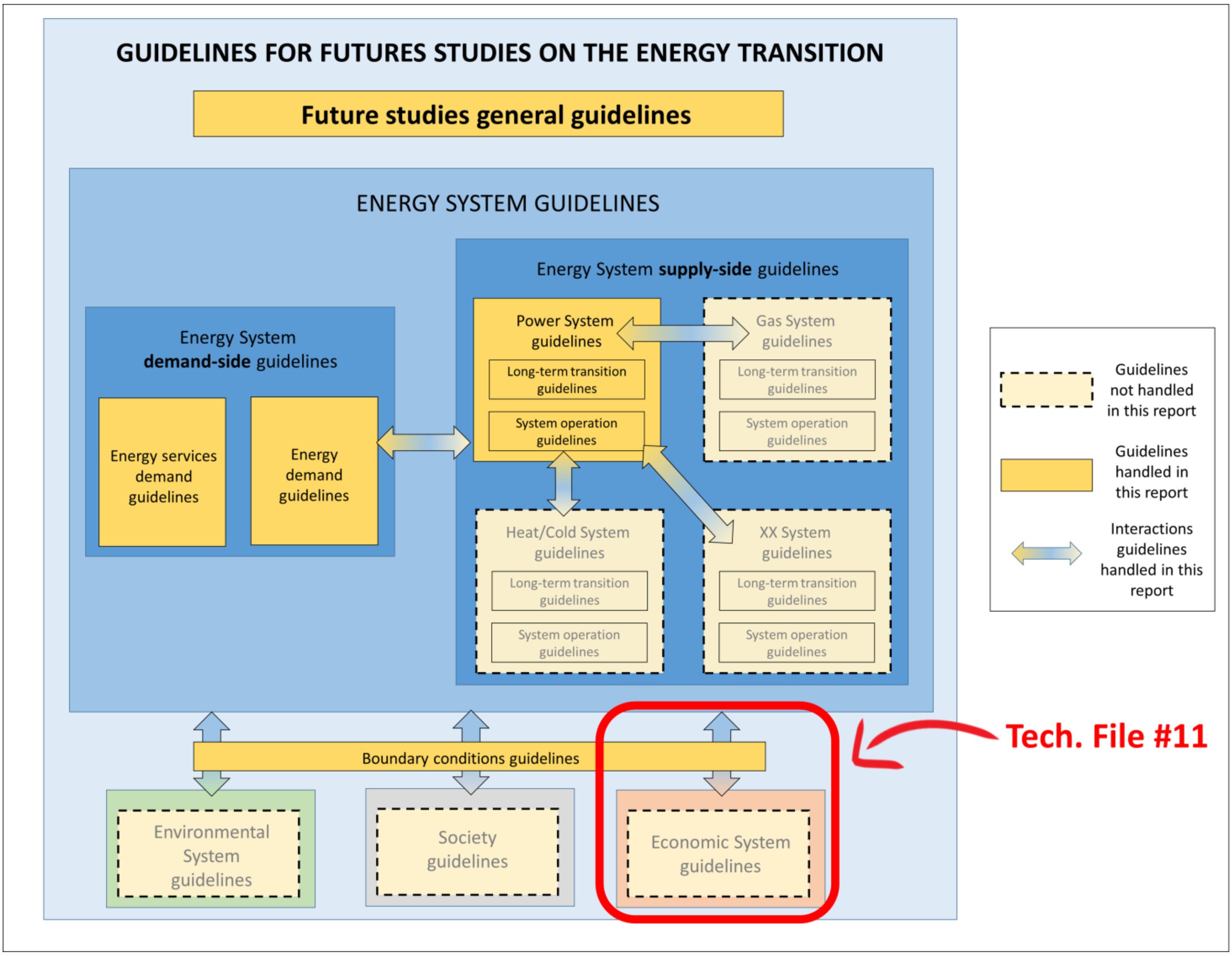
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project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

A. Two types of costs to assess and compare scenarios: technical, and macroeconomic

The notion of cost is not straightforward, even though cost is extensively used to assess and compare different scenarios, or even to drive energy transition in scenarios (such as scenarios driven by a cost-minimizing benevolent planner).

The cost of an action can be defined as **the difference between the cost of a Business as Usual (BAU) scenario and a scenario in which the action is performed**. In this definition, who bears the cost is not defined. Intuitively, a cost is incurred by some economic agent (a household, a company, the State…). However, in our context, we seek to characterize the cost to *make the system work*, as opposed to a cost for such or such agent.

Concretely, the cost of a transition (defined as the cost of all the actions involved in the transition) is an indicator which may be useful to inform some decisions regarding the energy transition. The information this indicator provides depends on how it is computed.

Practically for future studies, the cost of an action or of a set of actions is usually computed in **two ways**, each way transmitting a **different meaning**, and each of them being associated to a **different types of modeling** (Guivarch, 2011).

The first type of cost is called ***technical cost***. Technical cost is the difference between two scenarios (one of them considered as the Business as Usual) of the investment cost, or of the total operating cost (investment and operation cost) incurred by the technical systems (power plants, vehicles, house insulation, cement production technologies and so on), sometimes discounted over the scenario timeframe. This indicator does not take into account the interactions between the described technical systems and the rest of the economy: it is a partial economy indicator, as its computation includes only some sectors of the economy.

The second type of cost is called ***macroeconomic cost***. This indicator takes into account all the interactions between the sectors considered for the transition and the rest of the economy. In a word, this indicator takes into account the propagation of technical costs into the whole economy, through wages of the technical sectors being spent in the rest of the economy, or through the effects of the evolving offer on consumers, who reorganize the way they spend their money (for example in case of electricity price evolution).

This indicator accounts for a number of macroeconomic effects such as eviction effects, or rebound effects. Eviction effects happen when an actor invests in domains she would not have invested in without the transition, at the expense of some other domains. Rebound effects happen for an actor when she saves money due to some efficiency, or sobriety measures, leading her to spend her savings in other domains she would not have spent her money in otherwise.

This indicator can be computed as a GDP difference between two scenarios. It is a general economy indicator, as its computation includes the whole economy.

Computing technical costs requires **technology-rich models** (see section on consumption). Most often those models either do not consider economic variables, or consider only the economy of the energy sector. As a result, those models do not compute macroeconomic costs.

On the other hand, computing macroeconomic costs requires a **macroeconomic model**. Macroeconomic models are not technology-rich enough (their level of technological aggregation is too high) hence they cannot properly compute technical costs.

B. How should those indicators be used? Are they sufficient to inform energy transitions?

Technical costs inform about the overall expenses involved by changes on the energy system, and incurred by all the actors involved in the financing of this sector. Concretely, a lower technical cost means that the changes on the considered energy system have required less human work or capital[1], and/or cheaper human work or capital. In a way, technical cost represents the amount of human effort to perform the energy system transition. It is an indicator of cumulated effort along the transition. That is, a transition involving less technical costs leaves more available workforce and capital for other economic activities (assuming demography is unchanged between the two compared scenarios).

Macroeconomic cost as a GPD difference at a given time during the transition represents the effects of the transition actions on the overall size of the economy, as measured by GDP. GDP per inhabitant represents the average consumption volume of each inhabitant, without taking into account the quality of this consumption.

Note that those indicators do not automatically include information about the physical limits of the planet[2]. They do not include neither any consideration on the evolution of lifestyles and cultures. Hence **those indicators have to be completed by other indicators and narratives** in order to provide a more complete view of the proposed transition.

C. Other economic variables can also be assessed through technical, or macroeconomic indicators

Generally speaking, economic variables such as purchasing power, employment or balance of trade can be assessed by a technical approach or by a macroeconomic approach.

The **technical approach** consists in assessing the implications **within the energy system perimeter** of the actions to change the energy system.

A technical assessment of job employment during the transition and as compared to a BAU scenario, would be to assess the evolution of jobs directly involved in the energy transition (on the supply-side and demand-side of the energy system).

For assessing balance of trade, the trade with other regions of goods and services directly involved in the energy transition would be taken into account, such as the trade for cars, for energy, for power plants and so on.

Similarly, a technical assessment of purchasing power during the transition would be to assess the direct effects on households' expenses of the energy transition, such as energy savings from house insulation and electric cars, more expensive electricity and so on.

This approach does not provide the full picture though, because macroeconomic effects are not taken into account (see Figure 1). For example, employment rate could increase during the transition, which could raise wages and hence affect the balance of trade. Such an effect would not be taken into account with the technical approach. Technical purchasing power does not take into account the fact that people will be employed for house insulation, raising the employment rate, hence raising GDP and raising the average purchasing power.

[1] The price of a good or service (without tax) is the sum of the wages and rents that have been transferred to workers who participated in producing, transporting, installing, selling etc. this good or service, and owners of production tools or land involved in that good or service (Jancovici & Grandjean, 2009).

[2] In the reviewed studies, cost indicators do not include information about the physical limits because those limits are neither endogenized nor taken into account via boundary conditions. If they were, then prices would likely reflect such limits.

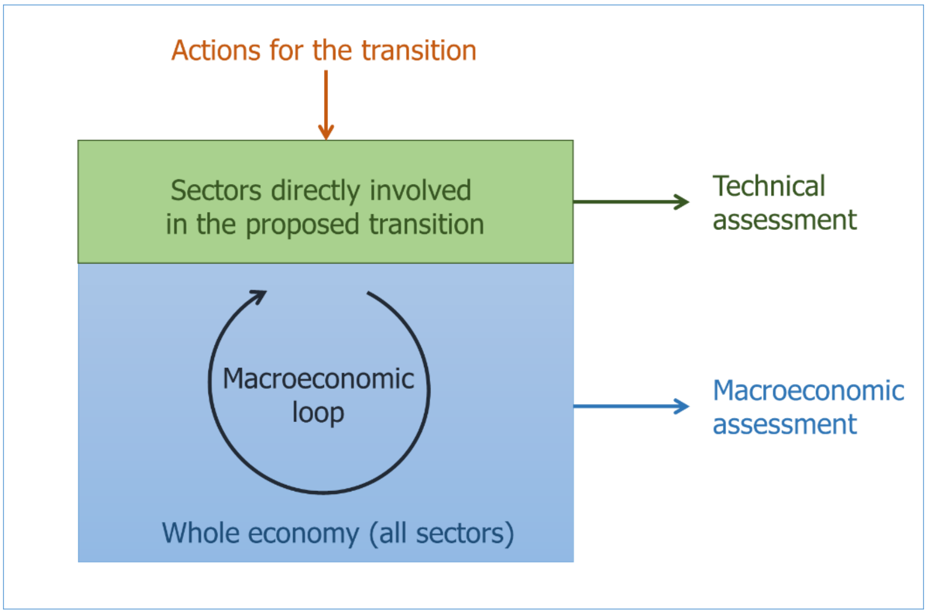


Figure 1: Illustration of the economic sectors which are included in technical assessments and in macroeconomic assessments.

These sectors evolve, as compared to a BAU scenario, under some actions for the transition. These actions can be investments, regulations and bans, taxes and subsidies, or actions undertaken by the modeled benevolent planner.

These macroeconomic loops are simulated in the macroeconomic approach. However, this approach is based on complex models which can hardly be understood by people who do not work on a daily basis with them, which are based on different macroeconomic theories with no clear account of why such theory should be used for such case and which are too aggregated to be concrete enough in explaining the results to stakeholders.

The future studies we reviewed compute no cost indicator, or they compute technical costs. We propose in the following section a framework aiming at fostering transparency when it comes to technical cost computation.

II. Evaluating technical costs of transitions in future studies

This framework explores a methodology enabling scenario producers to carry out an **economic evaluation of a *technical* nature**. Therefore, the further presented power system (PS) inventory and technical system indicators table are only viable for technical evaluation (consideration about possible perspectives do apply both for technical and macroeconomic evaluation). As previously explained, a technical evaluation focuses on the energy system whereas a macroeconomic evaluation focuses on the entire economy. Therefore, in the case of a macroeconomic assessment, the use of a model is necessary, the inventory becomes the whole economy, and the indicators used are not technical ones but rather macroeconomic ones such as GDP gaps. Next paragraph introduces a distinction between three types of studies that drives this kind of choices.

Then the three main parts of the methodological framework are presented: possible perspectives, power system inventory, and cost indicators.

A. Selecting the economic evaluation approach depending on the levers activated in the future study

We define here **three main categories of studies**, which determine certain choices related to economic evaluation, particularly concerning the inventory and the main indicators used.

These three categories are distinguished according to **the levers activated** to ensure the balance between supply and demand.

1. Studies activating supply-side levers only

Some studies activate levers on the supply-side only. Most of them assume an identical demand level across their scenarios and explore different ways to fulfil this demand (Agora Energiewende, IDDRI, 2018; Agora Energiewende/Öko-Institut, 2017; ECF, 2010; RTE, 2017; Barton et al., 2018). Some test several different levels of demand, but in any case no action that could affect the demand system is possible to ensure the supply-demand balance (ADEME, 2015; ADEME / Artelys, 2018).

For this type of study, **both a technical and a macroeconomic evaluation are viable**. If a technical approach is selected, the inventory focuses on the PS supply-side. As a consequence, technical indicators and methods described in this framework can be used, including those designed for the supply-side (such as the s-LCOE indicator[3]).

2. Studies activating supply-side levers and energy efficiency on the demand-side

Some studies activate levers on the supply-side but also on the demand-side, without however giving the possibility to introduce demand sobriety. Thus, the construction of pathways includes options that can affect the demand system, such as different energy efficiency measures. Such studies typically explore the trade-offs between reducing demand and increasing supply in order to achieve a supply-demand balance.

This is the case for some studies using the PRIMES model, or for (Fraunhofer ISE, 2015) for example. The importance of taking into account the consumption side, and in particular the reduction of energy consumption, is increasingly recognized (CEDD, 2013).

[3] S-LCOE is a system-wide LCOE, as opposed to a LCOE applied to a single technology and used by investors to make investment decisions (called here i-LCOE).

For this type of study, **both a technical and a macroeconomic evaluation are viable**. If a technical approach is selected, the inventory focuses on the PS (or energy system) as whole (demand-side and supply-side). As a consequence, technical indicators and methods described in this framework can be used.

3. Studies activating supply & demand-sides levers (including demand sobriety)

A few studies[4] activate levers on the supply and demand-sides, including the demand sobriety lever. We call *demand sobriety* a reduction of *human demand* (see Demand section for a precise definition). This type of lever is used in studies such as those conducted by négaWatt Association (Association négaWatt, 2014; Association négaWatt, 2017).

For this type of study, a technical approach in the economic evaluation has serious limitations because it does not allow certain important phenomena to be taken into consideration.

Indeed, we believe that there is **a strong causal link between energy consumption and GDP**. This thesis, which can seem quite obvious to intuition, is discussed and supported by a whole part of the literature (see studies such as (Belke, Dobnik, & Dreger, 2011) or (Giraud & Kahraman, 2014), which also present literature reviews on the subject). This means that a decrease in energy consumption via a decrease in human demand (i.e. a decrease of in 'overall' activity, see Demand section) logically leads to a decrease in economic activity and therefore ultimately to a decrease in GDP, all other things being equal.

In other words, scenarios exploring the effects of demand sobriety may show significant de-growth effects[5] which deserve to be discussed as they may affect lifestyles.

Recommendations to scenario producers

A study strategy about cost assessment should be defined and justified with regards to the driving question. It should include considerations about whether or not cost of the transition is assessed.

If costs are assessed, the following aspects should be considered:

- Type of study: supply-side only, whole system with no demand sobriety levers, whole system with demand-sobriety levers
- Type of indicator and methodology used to assess costs: technical and/or macroeconomic. In case the study includes demand sobriety levers, considerations on macroeconomic effects should be provided, either through a quantitative macroeconomic analysis or through qualitative elements.

B. Selecting adapted perspectives to discuss costs: system perspective to inform public decision

1. Several perspectives can be adopted to assess power system cost

Costs can be looked at from different perspectives. We will distinguish in the present framework two main types of points of view: **system perspective** and **specific actors' perspectives**.

[4] See section on energy consumption about the lack of such studies.

[5] Demand sobriety can at the same time lead to an increase in free time, happiness, etc. We do not believe that the demand sobriety lever should be neglected, quite the contrary. It is indeed a demand lever very rarely used in scenario studies which makes it possible to introduce non-technological measures. Moreover, given the urgency of the situation about climate issues and in order to monitor emission reduction trajectories in line with Paris Agreement, it may seem relatively logical to activate a variety of possible levers. **Introducing demand sobriety lever in addition to other usual levers can therefore be a very appropriate approach**.

On the one hand, **system perspective** relates to costs *to make the system work*, and only those costs. More precisely, it relates to the costs incurred for the proper providing of energy services based on electricity[6]. System perspective seeks to assess the cost as a PS aggregate actor, considering only the necessary expenses for the PS (both on supply-side and demand-side) to operate as opposed to any other monetary flow between specific actors within the system (such as taxes, power expenses, etc.) These costs are ultimately paid by society as a whole (i.e., by final consumers, tax payers, etc.).

On the other hand, there are **three main different perspectives of specific actors** related to power system that can be usually found in future studies:

- **The State**, when it deals with PS affairs.
- **Power system supply-side actors**, such as power producers, transmission system operators, electricity suppliers, etc.
- **Power system demand-side actors**, usually called final electricity consumers. They can be subdivided into households and industry. These actors seem representative of the system perspective, as the system provides a service to them. However, for considerations on expenses and costs, these actors may not directly pay for the whole PS costs, as taxes, subsidies and other market mechanisms may distort the cost they see compared to the pure PS costs.

Other actors can of course be considered.

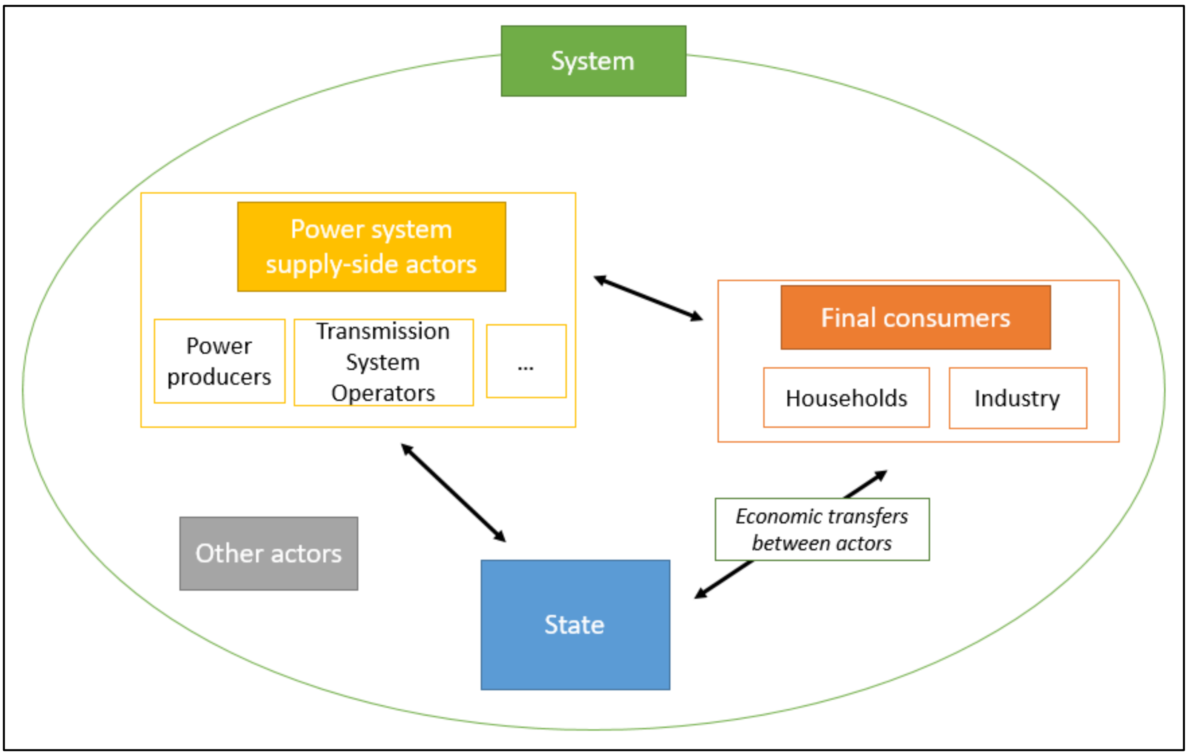


Figure 2: The diversity of perspectives from which costs can be looked at. This is not a representation of how the economy works but rather a way to represent the several perspective from which costs can be looked at. For example, energy and raw material flows are not represented here: they implicitly appear in costs (either costs from a specific actor's perspective or system perspective).

As explained in the section about impact assessment, system perspective covers the PS as a whole (supply-side and demand-side). Hence, supply-side studies do not usually inform this perspective. Rather, they inform the perspective of the power system supply-side actors. However, under some specific conditions they can inform the

[6] See definition in the section about impact assessment.

system perspective, namely when the evolution of the demand-side is the same along all the proposed scenarios[7]. This is why we include in this section some considerations on the s-LCOE, an indicator about the supply-side only.

The chosen perspective is very important in an analysis: the same element can be been seen as having negative or positive impact according to this choice. Here is an illustration from (Agora Energiewende, 2015):

"As in any other market, entrance of a new producer tends to have a negative impact on the return on investment of existing producers. From the perspective of consumers, who do not have to pay for capital invested into existing power plants, the new entrant may appear as a positive effect if it induces lower power prices on the market. From the perspective of the owner of an existing power plant, reduced utilization will be a negative effect, leading to lost revenues and reducing the plant's value. From the perspective of an environmental agency, a change in power plant structure that reduces, for example, the utilization of lignite power plant and their emissions represents a benefit, not a cost."

Thus, it may be interesting to study costs but also revenues from different perspectives, especially for specific actors (since one actor's expenses are another's revenues).

2. Being unclear about the chosen perspective is a classic reason for misunderstandings

According to (RTE, 2017), the diversity of possible points of view is a **classic reason for misunderstandings**.

Firstly, one economic evaluation can require the use of several perspectives. Indeed, it can be interesting to analyze the results of a study from different angles. However, not being precise about the chosen perspective make these results unclear.

(Fraunhofer ISE, 2015), for example, is presenting results from a system perspective first, and then makes some assumptions on taxes to evaluate the costs from households perspective in a second time, with a clear distinction. Another example can be found in (ADEME / Artelys, 2018): one paragraph describes the consequences of an evolution of market prices first on revenues evolution for nuclear power producers, and then on savings for the State. The chosen perspectives are well clarified; it enables to easily understand the objective of each analysis.

Secondly, some analyzes fall into the trap of **trying to compare several studies that are using different perspectives**. However, these are **not comparable**. Some studies themselves may fall into this trap too when presenting their results. It can of course lead to incorrect conclusions.

3. Society perspective is a vague concept in future studies: system perspective should be preferred

Many future studies refer at some points to 'costs to society'. Some of them sometimes claim to evaluate these costs and to provide indicators informing society as a whole. However, **what is meant by this term is never defined**: 'cost to society' does not relate to any specific perimeter.

The underlying idea behind the 'costs to society' concept would be that these are the 'global' or 'ultimate' costs when 'everything' has been included. It would be representing the 'real overall effort', costs that it would be 'right' to minimize. Sometimes, it even seems to refer to 'non-monetary' costs, as if the concept would go beyond a sum of expenses and revenues. If we try to translate this into a definition, the costs of "something" for society would be the sum of all 'costs' (in the broadest sense) that all the stakeholders related to this thing would have to bear. As we can see, **this is a very vague definition which deserves to be clarified**.

For example, the approach to the evaluation (technical or macroeconomic) which would enable to measure these costs to society needs to be clarified. Indeed, the meaning of an indicator emerges from the way it is calculated.

Whether externalities should be included in the cost perimeter or not should be discussed too. The concept of 'costs to society' is used in many other fields than future studies, and externalities can be included or not (De Clerck et

[7] In this specific case, the assessment of the demand-side evolution is the same for all scenarios hence it cancels out when scenarios are compared.

al., 2018). In the case of illnesses for example, 'costs to society' may include the direct costs paid by patients and hospitals, the absenteeism costs paid by companies, and it is not clear whether costs related to mortality (which are not real costs but the internalization of an externality, see Externality paragraph) are part of the definition (Wang et al., 2016).

The concept of 'costs to society' is sometimes used to designate the overall costs within the assessed system as opposed to costs from a specific actor's perspective, with the idea that this perspective better informs public decision.

This idea leading to a precise definition, we use the term *system perspective* for this purpose: once the assessed system is clearly defined, the 'total' costs are the costs from a system perspective. In this context, 'society as a whole' (i.e. final consumers, tax payers, etc.) have to pay for these system costs.

In this framework, we go even further by focusing on a system providing a macro-service, that is, a service provided to society as a whole (energy services, or energy services from electricity).

4. Selecting system perspective to inform public decision

As previously defined, system perspective relates to costs incurred by the proper operation of a system which provides a macro-service[8]. In simpler terms, this perspective covers the costs *to make the system work*.

A perspective refers to which components are looked at, that is, which components are included in the assessed system. The perspective directly translates into the inventory of the assessment. Assessing costs from a system perspective means that the inventory includes the system providing a service *as a whole*.

With such an inventory, it is possible to choose different system costs indicators. For example, studies in which a benevolent planner drives the power system transition compute costs as a cumulated system cost (with or without discounting). Other studies use other indicators, as will be developed later.

(RTE, 2017), (Agora Energiewende, 2015) or (OECD, 2012) defend the idea that system perspective is a better way to compare policy options.

For example, after discussing about the limitations of an indicator such as the i-LCOE, the study (OECD, 2012) states: "[There is] an increasing awareness of a need for a system approach to cost accounting also at the level of decision-and policy-makers." (Agora Energiewende, 2015) explores this idea under the term 'Total system cost approach'. The underlying idea of this approach is that public decision is better informed when studies are focused on system as a whole rather than on specific technologies, and from a system perspective rather than a specific actor's perspective.

The present framework on economic evaluation is specifically designed for studies using a system perspective.

Recommendations for scenario producers

Transparency should be achieved when it comes to the perspective taken when reporting study's results. For example:

- For each result analysis, the chosen perspective should be transparent.
- When results are compared, the common perspective should be transparent.

[8] See section on impact assessment.

If results are claimed to represent society's interests, this claim should be justified. In doing so, the following aspects may be considered:

- Selected inventory: how does the selected inventory reflect society's views and interests? Does this inventory correspond to a system perspective as defined in this framework?
- Selected indicator and computation methodology: how does the selected indicator reflect society's views and interests?

Here are described some key characteristics of system perspective:

a. Total system costs is a reflection of the real overall effort and should therefore not include economic transfers between actors

Total system costs seeks to represent the real overall effort, that is, **the amount of time spent and resources mobilized to build and operate the assessed system**. It could be approximated with the sum of all the wages, rents and annuities involved[9] in these activities.

Therefore system costs do not include economic transfers between actors, such as taxes and subsidies (see Economic transfers paragraph for more details). These are indeed expenses and revenues that do not reflect an effort or a number of hours of work, but rather a money transfer between actors. They should not be taken into account in system costs. Note that if the two "sides" of an economic transfer are taken into account (i.e., both the expenditure of an actor and the corresponding revenue of the other actor), it get canceled in the sum. To avoid counting errors, not counting them remains the simplest option.

b. System perspective as opposed to specific actors' perspective

System costs effectively makes it possible to understand **which option is optimal for the system** under consideration rather than for particular actors composing it or interacting with it. The several possible perspectives do not offer the same understandings. When it comes to enlighten public decision, a specific actor's perspective is incomplete. More precisely, results obtained with a specific actor's perspective does not bring enough information to inform the debate for a proper public decision. Typically, analyses about the bankability for a type of technology in the mix cannot inform the overall performance of the global mix. As explained in (RTE, 2017), the same measure can have both a positive impact on some actors and a negative impact on others. Therefore the best way to evaluate this measure is by choosing to **focus on the system as a whole**.

Yet, specific actors' perspective can of course provide **further useful insights**. Some specific questions cannot be tackled by a 'pure' system approach. Specific actors' perspective can for example enlighten issues such as bankability for particular power system supply-side actors or purchasing power for final consumers. However such evaluation requires greater computation work and hypotheses, such as the integration of economic transfers between actors. This aspect is developed in the Cost indicator part.

c. System perspective as opposed to a focus on specific technologies

The system perspective, as a way to evaluate the evolution of the system, influences the way the system develops in scenarios. Indeed, in order to determine what is cost-optimal at the system level, using a system approach is much more appropriate than focusing on specific technologies. For example, even if it was possible to determine what the «cheapest technology of all» is, the cost-optimal mix would probably not be 100% composed of this technology, especially because each installation provides a different set of "services" to the system (see Power system Operation section). Hence, with a system perspective, decisions that drive the PS are more likely to be made at the system level rather than by comparing technologies.

[9] Thus this cost can change according to the country because the same wages differ from one country to another.

Here is a summary of Agora Energiewende's stance about this issue:

Summarized description of the total system costs approach as opposed to a technology focus as described in (Agora Energiewende, 2015)

The questions for policymakers in charge of long-term power sector development is **"What are the implications of choosing path A or path B?"** (rather than "How can different power generation technologies be compared?" for example)

For political decision-making, the comparison of total system costs in different scenarios can be a more appropriate tool. A comparison of the cost and benefits of certain components of the system, such as renewables or nuclear power plants, may be additionally performed, but is not required.

The key insight informing this approach is that society as a whole must bear the costs of the power system, regardless of redistributive effects and how costs are defined.

Total system costs approach has been used - in different variations - in a large number of studies including ECF Roadmap 2050 (ECF, 2010), the European Commission Roadmap (European Commission, 2011) and all the studies based on PRIMES model.

C. Defining the power system inventory: what activities are included in the assessed system

As previously explained, the presented framework is designed for economic evaluation of a technical nature. Thus, the following section about system inventory is not adapted for macroeconomic evaluation (in such type of economic evaluation, the inventory is the economy as a whole).

1. The power system inventory should be explicit to enable inter-study comparison in cost assessment

The power system is composed of several subsystems. Taking all these subsystems into account is a complex task. This is why most studies only focus on one or several subsystems but not all of them: production part only, production and transport, etc.

From one study to another, the **choices are different**. For example (ECF, 2010) takes into account generation, transmission, distribution, interconnections, and part of consumption costs through energy efficiency ; (Lappeenranta University of Technology / Energy Watch Group, 2017) assesses generation, transmission and storage. One can easily understand that the economic evaluations of these two studies **cannot be directly compared**.

However, some studies are not explicit about what they consider. In these cases, what is in and what is out of the assessed system cannot be clearly identified by study users. **This makes the use of a diverse set of studies complicated**.

2. Properly defining and reporting the PS inventory

The system perspective relies on an inventory which includes the set of activities enabling the PS to properly provide the macro-service it is intended to provide. This complete inventory is called in this framework the "power system inventory". The same logic could be applied to the overall energy system and would require to add some elements such as inter-carrier conversion systems.

Here is a sketch of the power system inventory:

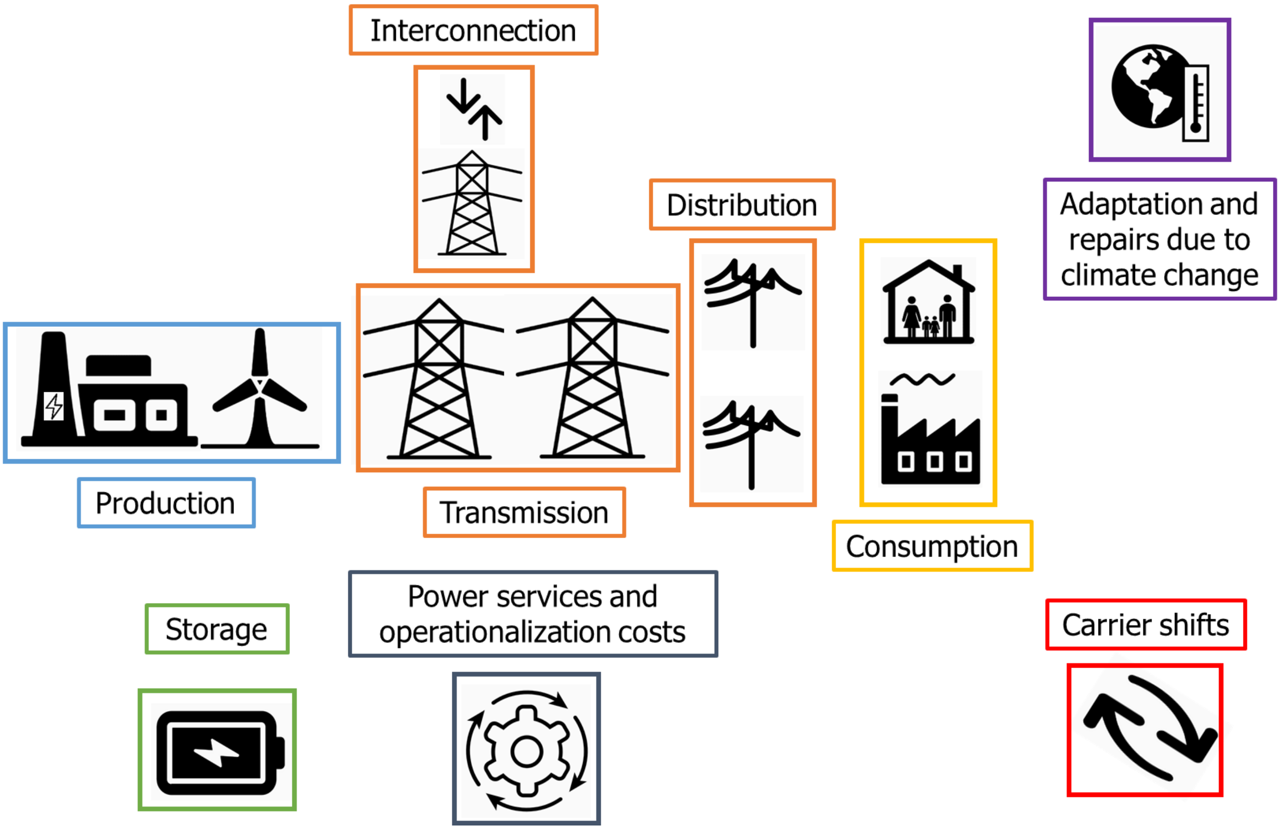


Figure 3: The power system inventory is composed of all the activities required to build and operate a power system. We use the term "activity" to insist on the fact the PS properly operates because past and present activities have been, or are performed. For example, the transmission grid has been designed and built in the past. The design and the building are activities which involved costs.

All these activities are described below.

a. Production costs

It covers all costs required to effectively produce electricity:

- Investments related to the development and the end-of-life of new generation capacities and the extension and end-of-life of already-existing ones, including financing costs (i.e. capital costs).
- Fixed and variable operation and maintenance costs needed to run the infrastructures such as maintenance costs, fuels costs or waste and pollution management like fumes treatment for example.

b. Network costs

It covers all the costs needed to transport electricity from its production place to its consumption place. It also includes costs needed to ensure a proper security of supply and quality of supply (frequency, voltage control and so on).

Electricity transport and security of supply is managed at grid level through three components in real time interaction with production and consumption sectors: transmission network, distribution network and interconnections. Each part requires significant investments and operation and maintenance costs, especially for the creation of new lines and the renewal of already-existing ones so as to increase the capacity, for the connection of new power plants to the grid, and/or for demand-supply balance. This last element requires control equipment and specific mechanisms (see System Operation section) which costs are borne by transport and distribution sectors but also implicitly by all other sectors[10].

Furthermore, network development is often subject to strong social and environmental acceptability constraints. Therein lines can possibly be buried instead of being aerial at an approximately 5 to 8 times higher cost (Brown et al., 2018).

c. Storage costs

Storage systems such as pumped-storage hydroelectricity or batteries enable to decouple electricity production and consumption periods. It requires both investments and operation and maintenance costs.

Note that storage devices may be useful for the proper PS operation, as described in file about PS operation.

d. Power services and operationalization costs

We include in this category all the costs that are required to make the system work in practice and that enable to improve it. It includes:

- New systems costs for real time load management through demand flexibility such as load shifting and shedding. Compensation costs to remunerate lost production for industry after load shedding are economic transfers between PS actors and thus should not be counted here (see Specific actors' perspective paragraph).
- Costs related to the wholesale and retail electricity markets functioning (aggregators, etc.)
- Commercialization costs related to the sale of produced electricity. It includes advertising, marketing and customer management costs. Some other costs can be borne by electricity providers depending on the rules of a specific country such as the purchase of energy savings certificates, but these are also economic transfers and thus should not be counted here.
- Transaction costs required for the changes to actually happen, that can appear at local scales for example such as costs for consultations, costs of transmitting information.

e. Carrier shifts

Some uses can be transferred from the electrical system to another system and vice versa thanks to carrier shifts.

For example, some of the mobility previously provided by the oil system can be transferred to the electrical system via the introduction of the electric vehicle. This translates into an increase in demand for electricity and equipment such as electric cars and associated infrastructures in the power system inventory which may already appear in production and consumption sectors. At the same time there is a decline in fuel consumption and in the need for equipment in the oil sector. In order to count the net effect of this carrier shift, these savings in oil sector can be taken into account by allocating the savings to the PS or by enlarging cost perimeter to the oil sector.

f. Consumption costs

The use of electricity requires its production and on-time delivery, but also the presence of all the appliances actually consuming it in order to deliver energy services[11], such as light bulbs, heat pumps, electric vehicles, etc. Integrating the costs of power system demand-side implies to count the costs of every new consuming equipment as in PRIMES model (E3Modelling, 2018) or (Association négaWatt, 2017). It doesn't matter if each equipment comes in replacement of another old one or for a new usage; and it doesn't matter either if each equipment is

[10] For example there can be a tradeoff between investing into more transmission capacity and paying producers to increase/reduce their production or use more storage and demand flexibility, as reducing demand is equivalent to increasing the supply from a supply-demand balance perspective.

[11] Electric appliances convert final energy (electricity) into useful energy (light, movement, heat…).

more efficient. This way, investment in energy efficiency, appliances, heating systems, and related infrastructure (buildings, factories) throughout the economy are all taken into account.

As previously explained, including the demand-side in the assessment perimeter (and hence consumption costs) enables a proper assessment of energy efficiency measures.

g. Climate change impact on costs

Climate change impacts require both adaptation work (e.g. the construction of dikes to protect infrastructure from rising water) and repair work (e.g. reconstruction of a high voltage line after a hurricane). Such impact can occur both for supply and demand-sides. All these costs can be distributed over the subsystems presented above (e.g. repair costs can be considered as investments in the production subsystem, transmission grid, etc.) For considerations about climate change impacts on demand and production, see also Energy consumption file and Long-term transition of PS supply-side file.

NB: other impacts on costs may also be taken into account, such as potential costs linked to acceptance issues.

Furthermore, we chose **not to include externalities** in the inventory. Indeed, we argue externalities are better counted when expressed in physical quantity rather than in costs (see Externalities paragraph).

3. Selecting similar and sufficient inventories to compare scenarios

Once an explicit inventory has been described, scenario comparison becomes possible. Comparisons must be performed between scenarios sharing the same inventory. In addition, as explained in section about impact assessment, comparisons are meaningful if their inventory covers all the elements which evolve differently between the compared scenarios. An example of insufficient inventory would be the comparison of the overall costs of two scenarios based on a similar inventory focused on supply-side only while there are significant changes on the demand-side in one scenario.

Recommendations for scenario producers

When performing an economic evaluation (and especially when comparing several scenarios), the evaluation perimeter (inventory) should be clearly stated and described, through an inventory containing all the activities which are part of the evaluation (see Table 1 in the annexes).

Special care should be taken not to double count some activities which participate in different services. For example, some components of the power system supply-side bring several different services to it (batteries can bring reserve services and storage services).

Before presenting a cost comparison between several scenarios in a result section, scenario producers should make sure all the compared scenarios are based on both **similar and sufficient inventories**: inventories should be the same, and should cover all the subsystems evolving differently from a scenario to another. Otherwise it should be explicitly stated, so that the comparison can be analyzed with special care.

The inventory should be compatible with the driving questions and with the conclusions drawn from the results, as discussed in the section about impact assessment. This holds when assessing costs in case of carrier shifts altering demand of the electricity carrier (inventory should include the corresponding parts of demand-side).

D. Transparently defining and computing cost indicators, and explaining their meanings (why we can conclude what we conclude from them)

The adapted choice and use of cost indicators for a consistent economic evaluation is the last element of this framework. This choice depends on the type of economic evaluation, the chosen perspective, and the system under study. Thus, if the evaluation is of a macroeconomic nature, indicators such as GDP gaps should be used. The next part explores the possible range of indicators in the case of an economic evaluation of a technical nature.

Once a clear system inventory has been defined, there is several ways to compare and evaluate costs of the defined system depending on how and what scenario producers want to enlighten.

We propose here a table categorizing the diversity of possible cost indicators of a technical nature (as opposed to macroeconomic indicators) that can be used to assess costs from a system perspective (as opposed to indicators designed from specific actors' perspective)[12] on the entire scenario timeframe (see Figure 4 below).

WACC if any

Social discount rate if any

	Actual expenditures cost items			Cost items for fairer comparisons	
	CAPEX ***with or without capital costs***	**+ OPEX**	**+ Electricity trade balance**	**+ Future costs**	**+ Past costs**
Cost trajectory *Cumulated value*		s-LCOE	Expenses shape		Absolute costs
Total cost value ***with or without social discounting***				Comparative costs	

Figure 4: System technical cost indicators table. This table is composed of five cost items (columns) and two types of indicators (raws). Discounting operations are represented as yellow arrows. The use of WACC for simulating economic agents' decisions and integrating capital costs in CAPEX is described in the section about long-term transition of the PS. The use of a social discount rate for comparing costs of various proposed transitions by a benevolent planner is described in this section.

Cost indicators can be composed of one to five cost items. The five cost items and the methodologies to compute them are presented in detail in annex p.30.

There are two types of cost items: *actual expenditures*, composed of CAPEX, OPEX and electricity trade balance, are expenses that actually have to be paid each year during the scenario whereas *cost items for fairer comparison*, composed of future and past costs, enable to integrate 'edge effects' for fairer comparisons (future costs enable better comparison between scenarios and past costs enable better comparison of a scenario with today's situation).

- *CAPEX* (Capital Expenditure) gathers all the investments for building, extending the life of, or dismantling infrastructure.
- *OPEX* (Operational Expenditure) gather fixed costs (workers' wages, maintenance…) and variable costs (fuel purchase…).

[12] Depending on the system that is defined, it may happen that the system perspective matches a specific actor's perspective, such as the final consumers' perspective in the case of the s-LCOE indicator for example.

- *Electricity trade balance* is the net cost or revenue due to electricity imports and exports with neighbors.
- *Future costs* are the costs and savings that happen after the end-date of a scenario due to choices that occur within the scenario timeframe.
- *Past costs* are the costs to be paid and the savings realized during the scenario timeframe which are due to expenses or decisions made before the start year of the scenario.

Cost items are presented in an additive way in the table (e.g. electricity trade balance adds up to OPEX, which adds up to CAPEX), going from the simplest indicator (CAPEX) to more and more comprehensive indicators, that is, indicators containing more and more information. However, each cost item could be presented alone for studying specific aspects of the PS (e.g. a fuel costs trajectory as in (Greenpeace, 2015) or an electricity trade balance trajectory as in (RTE, 2017)).

So as to express system technical costs, **two types of indicators are distinguished: cost trajectories and final cost values**. In both cases, indicators can be presented as an outcome for a single scenario or as a difference between two scenarios to compare scenarios.

1. Cost trajectories for visualizing expenses through time

Cost trajectories describe the **evolution over time of one or more cost items**. It is represented by a curve or a bar graph with a value for each time step (every year, every five years, etc.) Cost trajectories can be represented for a single scenario or be expressed as a difference trajectory between two scenarios as in (Fraunhofer ISE, 2015) (see annex A for some examples), or be represented for several scenarios in the same graph to easily compare them such as in (RTE, 2017).

s-LCOE or the further presented *expenses shape* and *absolute costs* (see box below) are cost trajectories.

Most of the time, trajectories are used to visualize cost indicators based on *actual expenditure* cost items (CAPEX, OPEX, and Electricity trade balance), in order to show the evolution through time of the expenditures for society or for specific actors. This is useful to detect situations of important financing needs. Most of the time, cost trajectories allow to visualize costs ***as observed within the scenario timeframe***.

However, trajectories integrating future costs and past costs may also be used to compare several scenarios, such as in (RTE, 2017).

As applying a social discounting to a cost trajectory 'flattens' the costs and thus distorts the trend, costs included in trajectory indicators are not discounted[13].

Expenses shape to show the transition financing effort

Expenses shape indicator is a cost trajectory showing the time evolution of a scenario expenses *as observed within the scenario timeframe*[14]. It enables to visualize the actual financial effort that will have to be made year after year.

This indicator provides interesting information about **the overall effort repartition**. It can reveal key information such as **expenses peaks** during the scenario timeframe. Furthermore, expenses shapes from two different scenarios can be compared, for example to see which one has the highest maximum annual cost value.

When each of the three cost items appears distinctly within the expenses shape (i.e. when the indicator is clearly subdivided into CAPEX, OPEX and electricity trade balance) it provides information about which specific actor will bear the costs. For example the CAPEX part of the shape is useful to measure the overall financial effort that has to be performed to develop and extend capacities, and possible difficulties related to the corresponding fundraising.

As the three considered cost items can differ significantly from a scenario to another, we believe expenses shape is an important indicator to inform public decision.

[13] Except in rare cases (e.g., when highlighting the effect of a discounting over time, as in (Fraunhofer ISE, 2015))

[14] This indicator is based on actual expenses displayed through time

Absolute costs for storytelling

Absolute costs indicator is a cost trajectory of one scenario. It is **a trend that enables to understand cost evolution of the assessed system from today's situation.**

Unlike the expenses shape, this indicator does not represent the costs that will actually have to be paid each year by system actors. It rather represents the cost of the assessed system including 'edge effects' by adding past and future costs to the three other cost items. This indicator takes into account the costs of assets used within the scenario timeframe that were already in place at start year.

Such an indicator enables to properly compare the cost of a future situation with today's situation. However, as explained in the section about future studies, only future situations can be compared for decision making. Therefore absolute costs indicator should not be used for public decision but for storytelling purposes only.

For example in can help to understand how the importance of the assessed system (e.g. electricity sector) is changing over time from today compared to other sectors (in terms of share in the aggregated cost) and explain why such evolutions happen in the scenario.

2. Total cost values to describe the sum of costs over the whole timeframe

Total cost values are unique values (i.e., a number) representing **the cost of the assessed system over the entire scenario timeframe**.

This category includes indicators commonly referred to as "total system cost" (European Commission, 2011; European Commission, 2016), "total cost of a pathway" (ADEME, 2015; ADEME / Artelys, 2018), "cumulative total cost" (Association négaWatt, 2017; Fraunhofer ISE, 2015). It is even sometimes referred to as "cost to society", as in (ECF, 2010). These studies seek to compute and present total technical costs of the studied system of a scenario. However, inventory and cost items differ across studies.

Indicators such as the total CAPEX/OPEX of a scenario, or the further presented comparative costs (see box below) indicator belong to this category.

The total cost value of a system for a given scenario is obtained by summing all the costs taken into account, that is, by calculating **the sum of the associated**[15] **cost trajectory over the scenario timeframe**.

A social discount rate can be included in the calculation. The obtained total cost value is thus modified compared to a calculation without discounting[16], typically downwards in the case of a positive discount rate (which is the case most of the time). This value represents the total cost from a benevolent planner perspective, as opposed to cost *as observed within the scenario timeframe*.

Benevolent planner perspective and social discounting

Some future studies explore scenarios in which social welfare is maximized given some constraints (such as reducing GHG emissions). Social welfare is generally assumed to be correctly represented by the inverse of total cost. Hence scenarios are driven as by an omnipotent benevolent planner seeking to minimize total cost of the proposed transition.

A few future studies discount the costs with time according to a "social" discount rate[17]. The use of such a rate and its meaning are debated, and several studies do not discount total costs (such as the studies using PRIMES model

[15] The cost trajectory of the same inventory and same cost items

[16] Or with a 0% discount rate.

[17] See note on discounting (in French)

(E3Modelling, 2018)). The value of this rate is also debated and is said to reflect ethical choices. Some economists argue this value should contain three additive components (Percebois, 2012):

- an impatience component, reflecting a "natural" bias of humans towards granting a lower value to the future than to the present, following an exponential de-growth curve.
- A wealth component, reflecting the general belief that future generations will be wealthier than todays' so that current generation should not perform efforts at any price to solve future problems: future generations will have more means to solve them. The value of this components directly reflects imagined future growth values.
- A precaution component, reflecting the growing uncertainty about the previous component with further time horizons. This component reduces the wealth component when time horizon is far. It actually reflects a new belief future generations will not be as wealthy as was previously assumed.

Using this method leads to similar values across future studies (from 2 to 5%), meaning that the value of the future is divided by 2 compared to todays' within 15 years to 35 years (respectively for rates of 5% and 2%).

As discussed in the section about PS long-term transition, discounting is also used for simulating decisions from private project holders through WACC values which integrate a "risk" component to ensure a satisfactory average rate of return for project financers given the risks and uncertainties the project faces.

Total cost indicators are mainly used to **compare the results of several scenarios**, to inform the public decision once the final results are obtained. The comparison can be explicit (values are compared on the same graph, or mentioned in the same paragraph for direct comparison) or implicit (values are presented in the report in such a way the reader can easily compare them, but they are not explicitly compared by scenario producers).

Including future costs in total cost indicators allows to correct comparison biases due to the horizon effect but is too often neglected in future studies.

In addition, as for cost trajectories, final cost values can be represented for one single scenario or as a difference between two scenarios.

Comparative costs to fairly compare several scenarios

Comparative cost indicator is a total cost value **enabling a fair comparison between several scenarios.**

To that extent, comparative cost is composed of four cost items, namely **CAPEX, OPEX, electricity trade balance and future costs.** Adding future costs enables to make a good comparison by handling the "horizon effect," as this effect is very likely different across the compared scenarios. Past costs are not included because they are the same for the compared scenarios.

The difference between the comparative cost of a scenario to that of a BAU scenario is sometimes interpreted[18] as a 'cost of transition' indicator, as it contains all the extra-costs induced by a transition compared to a "no-transition" situation.

Comparative costs can include a social discounting to express costs from a benevolent planner perspective[19].

[18] This is the case in (IRENA, 2018).

[19] In this case, comparative costs between two scenarios can be calculated from the expenses shapes of these two scenarios through four steps: discount each expenses shape, add the corresponding discounted future costs, make the sum of both resulting cost trajectory, and finally compare them (see more explanations in Future costs paragraph).

3. When comparing two systems, the chosen cost indicator should be sufficient

As for inventories, a cost indicator needs to **cover all the changing elements between two systems** so as to compare them fairly. To do so, all the cost items evolving differently from a scenario to another should be included in the calculation of the chosen indicator.

This is particularly true with **future costs**, which are costs and savings that will happen beyond the end date of a scenario due to choices that occurred within the scenario timeframe. This cost item should be included so as to take horizon effect into account for fairer comparisons.

Comparing scenarios using a differential value (the difference of costs between two scenarios) enables to neglect elements with little or no cost difference between scenarios (that is, elements which evolve in the same way in both scenarios). Indeed, if the possible evolution of the costs is the same from one scenario to another, then the value in difference remains unchanged and the comparison remains fair. In this way, (RTE, 2017) for example neglects part of the commercialization costs when comparing several scenarios.

Recommendations for scenario producers

Scenario producers should transparently describe the cost indicator(s) they selected and the reasons for their choices. The following aspects should be handled:

- Type of indicator: cost trajectory or total cost values. The reason for this choice should be justified with regards to the study strategy on the narrative elements to produce. Doe the study seek to inform about financing needs through time, or about total costs for society?
- Composition of the indicator, based on the different costs items presented in this framework: CAPEX, OPEX, electricity trade balance, future costs, past costs. The reason for this choice should be justified with regards to the study strategy on the narrative elements to produce. Des the study seek to compare several scenarios, or to tell a story on the evolution of the PS, or to explore the evolution of CAPEX and OPEX, etc.?
- The link between the selected indicators and the conclusions drawn by the scenario producer should be thoroughly substantiated. Each indicator should be used depending on what needs to be explored about the assessed system. *Which cost use is being explored? To what extent the proposed conclusions emerge from the chosen cost indicators?*
- When a social discount rate is used, the chosen value should be justified with regards to the projected economic growth in the given the scenario (whether explicit or implicit). Scenario producers could simulate a low or negative economic growth case though low or negative social discount rate values. In the case of non-monotonous growth, it may also be interesting to explain the methodology used. *Is the chosen social discount rate value linked to economic growth projections? What are these forecasts and their level of certainty?*
- The chosen cost indicator for comparison between two scenarios should be **sufficient**: it should include all the cost items evolving differently from a scenario to another. It should typically include the often neglected '**future costs**' cost item so as to correct comparison biases due to horizon effect. Otherwise it should be explicitly stated, so that the comparison can be analyzed with special care.

E. Assessing costs from specific actors' perspectives to bring complementary insights

As previously explained, assessing costs from a system perspective should be preferred to inform public decision, but specific actors' perspective also bring **useful complementary insights**. It may be indeed interesting to assess costs from an electricity producer perspective, from the government perspective, or from the perspective of households or industries so as to enlighten issues related to **bankability or purchasing power**. As explained here, assessing costs from a specific actors' perspective requires to take extra elements into account.

It should be noted that in particular cases, **system perspective can be very close, or even match a specific actor's perspective**. It happens only with indicators describing costs *as observed within the scenario timeframe,* that is, cost indicators that do not include any social discounting in the calculation and which are based exclusively on *actual expenditures* cost items (CAPEX, OPEX, and/or electricity trade balance). In addition, capital costs should be included in CAPEX. For example, a PS cost from a system perspective can match the final consumer's perspective if taxes, subsidies and market mechanisms are excluded.

1. Economic transfers needs to be added when assessing costs from specific actors' perspective

Costs from a specific actor's perspective includes money transfers between actors. These transfers do not appear in the system inventory.

We present here some of these economic transfers. This list in not comprehensive: many other economic transfers between actors can be added to the analysis, depending on the imagined legal and tax frame (such as the purchase of energy savings certificates within commercialization costs or electricity trade balance between countries within scenario geographical scope for example).

a. Taxes and subsidies

Taxes and subsidies are money transfer between actors, as they are expenditures for some actors and revenues for other actors. For example some taxes are paid by the end consumers to the State. They do not constitute a real cost from a system perspective.

b. Internalized externalities

This term designates externalities that are actually paid (see next part, p26). This is currently the case, in some States and for a few externalities only. Furthermore, the price paid does not necessarily reflect the real damages to the economy.

However, internalized externalities represent a real cost from a specific actor's perspective: in Europe for example power producers pay the State for each tons of CO_2 they emit at the price of the EU ETS (Emissions Trading System) market[20] which can represent a significant part of their OPEX. This is a money transfer only since it is not associated with any additional jobs[21] or wages (it is thus not a real cost from a system perspective).

Introducing an internalized externality such as a carbon pricing mechanism in a scenario can have several direct, very significant macroeconomic impacts such as a decrease of purchasing power for households. Indeed, the amount of money transferred by concerned actors – often from activities generating the externality and paid to the State – may be significant, especially for transition scenarios: this money is then recycled and may have various impacts on consumption (rebound effects), inequalities, etc. This extra money can be recycled in several ways so as to balance the negative direct effects (ANCRE, 2013).

Some studies try to evaluate the macroeconomic impacts of such internalized externalities. But the use of revenues from such mechanism is sometimes forgotten in the evaluation.

c. Sunk costs burden sharing

Even though sunk costs are taken into account when calculating future costs (see Future costs paragraph), it does not indicate who is going to pay for it. This information is not important from a system perspective, but is needed

[20] This price has fluctuated between 0 and 35 €/tCO_2 approximately since EU ETS creation.

[21] These are not the job-creating investments driven by the tax signal to reduce emissions.

to understand interactions between actors (e.g. some scenarios might put into play States compensating for sunk costs).

d. Curtailment costs burden sharing

Curtailed electricity is also already included implicitly in the power system inventory: it appears indeed in production costs, network costs and storage costs, often as an optimization (the choice to curtail a part of the production can typically increase production costs while decreasing network and storage costs even more). However the same question of "who will pay for it?" can help to understand the actors' perspective. It can be particularly true in high renewable share mixes.

Recommendations for scenario producers

When assessing costs from a specific actors' perspective, money transfers seen by these actors should be taken into account. Their list should be provided and justified. This list should be the same for each scenario which is compared, and remain the same through the scenario timeframe, including start year.

The following money transfers should be considered, and the associated extra hypotheses should be transparent (when are the transfers made compulsory? Under what precise rules? For what reasons?):

- Taxes and subsidies
- Internalized externalities. A description of internalization implementation should be performed:
  - Internalization mode. *Regulation, tax, market?*
  - For a tax or market, the associated price evolution. For a cap regulation, the evolution of the allowed quantity.
  - Reuse of the revenues for a tax or market.
- Sunk costs burden sharing
- Curtailment costs burden sharing

2. Final consumers perspective: discussing costs rather than prices

a. Price and cost do not contain the same information

Price may be seen as an important criteria **for households** from a social desirability and energy poverty perspective, as for **industries**, which consume energy[22] for their production. Thus, it is often argued that the price of energy plays a major role in our economy: all things being equal, an increase in energy prices in a country reduces the purchasing power of households and the "competitiveness" of companies.

However, households and industries are actually impacted by the cost of energy in their final bills (average unitary price times the amount of consumed energy) rather than by the (unitary) price of energy per se. Energy cost variations really inform **the evolution of purchasing power or competitiveness** of economic actors, unlike price variations on the long-run[23]. In turn, these impacts may lead to desirability issues, as explained in the section about desirability.

[22] This paragraph deals with the price and cost of *energy* for final consumers as opposed to price and cost of *electricity* since the reasoning is valid in both cases.

[23] However, on the short run price variations directly represent cost variations because economic actors do not adapt their demand-side at this time scale. Rather, demand-side takes several years to decades depending on the equipment.

For example, if an energy efficiency measure that increases the price of energy reduces consumption enough to make the final cost decrease, then it may be judged as a good measure[24]. In that respect, minimizing cost may be seen as more important than minimizing price.

Usually, supply-side studies[25] provide price indicators as their demand-sides are fixed. In that case, price and cost strictly co-evolve.

On the contrary, (Fraunhofer ISE, 2015) – a whole PS study – calculates the "yearly cost for end consumer" as a whole (not per person) which consists in the **sum of total system costs plus some taxes**. This is the global common effort to share between all end consumers.

b. Carefully comparing prices and costs to today's

As any other indicator, energy price and cost indicators can be used to compare several future options. However in practice, these indicators are often used to compare energy price/cost of a given scenario to today's energy price/cost (implicitly or explicitly) because these indicators are closely related to people's daily life.

When comparing prices/costs to today's (for instance via a graph showing its evolution through the scenario timeframe), the cost inventory must remain the same along the timeframe, and the actor's perspective must remain the same, including taxes and subsidies (e.g., one third of the electricity bill for households in France is composed of taxes).

A fair comparison of costs including taxes with today's requires to make assumptions on future political decisions such as taxes and subsidies systems. Thus, price or cost of energy can be more influenced by choices in the Storyline than by evolution in the scenario itself.

Alternatively, it is possible to compare a scenario price/cost of energy *before tax* with today's price/cost *before tax*.

Recommendations for scenario producers

When taking the final consumer perspective, the choice between price and cost indicator should be justified with regards to the studied system perimeter and activated levers. The conclusions should be in line with this choice.

When using an energy price/cost indicator in an economic evaluation to provide insights from a specific actor's perspective, the assessed perimeter behind these indicators should be clearly defined and the integration or not of economic transfers should be made explicit.

Is the given energy price/cost indicator based on the overall supply / supply and demand system? Or do they only refer to a fraction of the overall system? Which fraction? What assumptions are made about taxes or subsidies taken into account?

When an energy price/cost indicator is used to make a comparison with today's situation (explicitly or implicitly), it should be made explicit that such analysis is only viable for storytelling purposes (as opposed to informing public decision). In addition, the used indicator should be based on the same inventory as the one used to assess today's situation. Justification on how conclusions are drawn from this analysis should be provided with regards to the chosen inventory.

[24] Energy efficiency does not imply a reduction in energy service demand. It reduces energy consumption with a constant energy service demand (see Energy consumption file)

[25] See paragraph p10 for a definition of the three categories of studies according to the levers activated to ensure the balance between supply and demand.

III. Concretely describing externalities through physical quantities rather than prices

Externalities are all the elements resulting from an activity that do have impacts which are **not taken into account** in the agents' economic calculations and therefore in their decision-making. They can be positive but are more easily noticed when they are negative because of acceptability issues.

Externalities perimeter can possibly be very wide. Indeed, all environmental and sociopolitical aspects may be concerned: GHG emission (climate change), premature deaths, injuries, and illnesses (human health), loss of biodiversity, land use change, nuisance from noise and odor, congestion, or visual blight, impacts on energy security, geopolitical relations, family values, etc. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012)

A. Externalities and internalization mechanisms in the real world

There are several mechanisms for "reintegrating" an externality into decision-making. The main mechanisms are taxes (associated to generating the externality), quota markets (quotas are associated to a maximum amount of externality generation), regulation (such as setting standards for generating less, or no, externality) and subsidies (to foster activities generating less, or not, externality).

Their role is to foster investments leading to reduce the externality by associating a cost to generating this externality. Hence they direct the economy towards activities generating less and less externalities. We say these mechanisms "internalize" the externality.

However, in practice it is very complicated to fully internalize externalities. The enforcement scope must contain all the activities generating the considered externality (e.g. the EU ETS mechanism only takes into account CO_2 emissions by some activities but not all of them) and the associated price, or quotas must reflect "the true value" of the damages caused by the externality[26] (the current price of CO_2 on the EU ETS market is much lower than this "true" value).

We distinguish here "**externality"** and **"internalized part of externality"**. The first one is the externality as a whole, while the second one is the price actually paid in the real world (or in scenarios) by the concerned actors for the given externality.

Internalized externalities are only money transfers from a system perspective, but real costs for the enrolled actor's perspective[27].

B. Giving a value to externalities is a controversial approach

The calculation of a "shadow price" to reflect the true level of damage caused by each externality has many components that are subject to debate, such as the assessment of the expense a community is willing to assume to avoid a death or the choice of an appropriate value of discount rate. (CEDD, 2013)

Furthermore, putting a price on an externality suggests that the related impact is linear: if a plant emits 50 tons of CO_2, the total damage is supposed to be 50 times the damage of one ton. However there is a consensus among scientific community on the concept of "environmental thresholds", which is strongly incompatible with a linear way of thinking. (« Assessing "Societal Costs" in Order to Choose the Economic Models of Tomorrow », s. d.)

Despite these caveats, some projects have tried to give a value on electric supply-side system externalities, such as European Commission's CASES project, ExternE project and NEED project (see annex VI.C). They suggest that CO_2 and other GHG (climate change) and air pollutant (human health) are the two main externalities of power plants.

[26] This is called a "shadow price"

[27] However, the investments triggered because internalization mechanisms are enforced in the scenario

C. Keeping externalities outside published cost indicators so as to foster concreteness

Among the studies which consider economic indicators, here are the practices we observed with regards to considerations on carbon values in total costs indicators:

- The only externality which is internalized in final cost indicators is a carbon value. No other externality is included.
- Some studies are not clear about whether or not their final cost indicators include the carbon value.
- Some studies do not attempt to compute total cost indicators. Instead, they compute costs for a few sectors only, or only capital costs.
- For the studies which compute total cost indicators and which are clear about how they consider carbon value with respect to their indicators:
    - Some studies "artificially" integrate a carbon value in their final total cost indicators to compare their different scenarios once they are written (such as (Fraunhofer ISE, 2015)). For these studies, the carbon value is a pure mathematical artefact having no meaning in the scenario storyline (as economic agents in the scenario do not see this value and do not take into account in their decisions). This artefact is used to integrate an externality value into the final cost indicator. It is not a carbon tax, or carbon price which emerged from a carbon market in the scenarios. Indeed, if such a value was submitted to economic agents in the scenarios, the obtained results would be different from those exposed in the reports.
    - Studies about the power system supply-side integrate the carbon value in final results by taking a specific point of view: the point of view of electricity supply-side actors (such as in (Agora Energiewende, IDDRI, 2018; Agora Energiewende/Öko-Institut, 2017; RTE, 2017)). In these studies, power supply-side economic actors are subject to a carbon price. This price influences their decisions, and comes as a cost for them. Hence the selected total cost indicator includes the carbon price.
    - Studies using PRIMES model (about the whole energy system) integrate the carbon prices and taxes in their total cost indicators. Indeed their indicator includes what final energy services consumers have to pay, including carbon price and taxes which are passed on to them (E3Modelling, 2018).

Recommendations for scenario producers

The study strategy about the integration of externalities in total cost indicators should be made explicit and substantiated with regards to the study strategy. The following aspects should be considered:

- Substantiation of the choice to integrate externalities in cost indicators instead of assessing pure costs and impacts aside, as suggested in section about future studies.
- Methodology used for the integration, and meaning of this methodology with regards to the conclusions drawn from the final cost indicators: *does the integration of externality values in cost indicators correspond to a specific point of view (such as final consumer, or energy producer)?*
- Substantiation of the choice for the externality value with regards to the meaning of the methodology: *what does the value represent: a cost seen by economic agents in the scenario (such as a carbon tax or carbon market price), a mathematical artifact representing the value of the future damages for the economy (shadow price), etc?*

IV. Annexes

A. Inventory of the activities included in the cost assessment

Here is an illustrative table scenario producers can base their assessment on and use to transparently show their inventory related to power system cost assessment, by declaring for each item if it is included in the inventory and substantiating their choice.

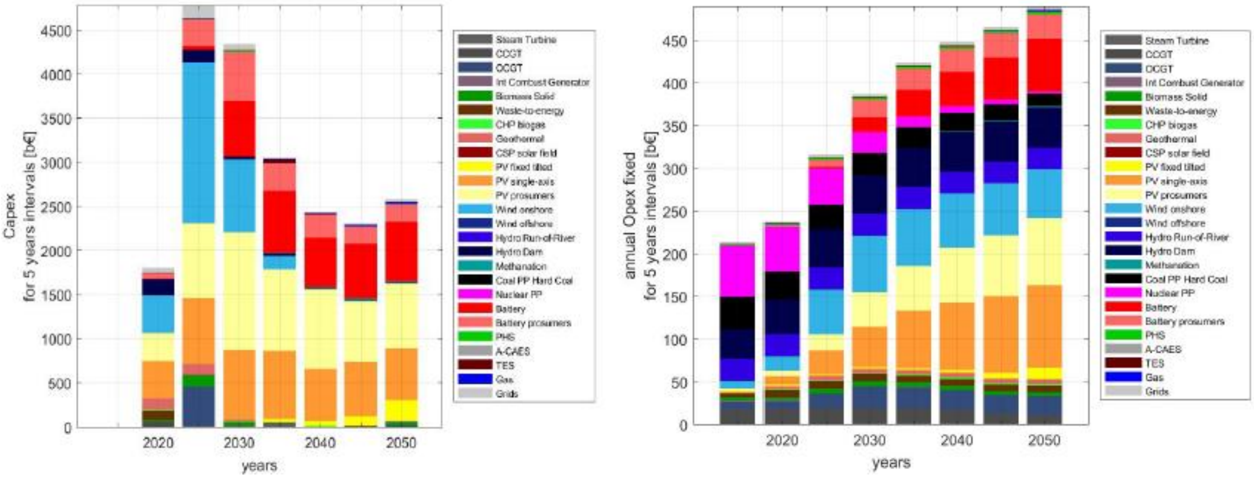
<table>
<tr><th>System component</th><th>Activity</th><th colspan="2">Cost item</th></tr>
<tr><td rowspan="8">Electricity supply</td><td rowspan="6">Production costs</td><td rowspan="4">CAPEX</td><td>New generation capacities</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td>Dismantling costs</td></tr>
<tr><td>Others</td></tr>
<tr><td rowspan="2">OPEX</td><td>Fixed O&M costs</td></tr>
<tr><td>Variable O&M costs</td></tr>
<tr><td rowspan="2">Commercialization costs</td><td colspan="2">Publicity, marketing, customer management</td></tr>
<tr><td colspan="2">Others</td></tr>
<tr><td rowspan="9">Electricity transport and storage</td><td rowspan="3">Transmission costs</td><td rowspan="2">CAPEX</td><td>Investments</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
<tr><td rowspan="3">Distribution costs</td><td rowspan="2">CAPEX</td><td>Investment</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
<tr><td rowspan="3">Interconnection costs</td><td rowspan="2">CAPEX</td><td>Investment</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
<tr><td colspan="2" rowspan="3">Control systems</td><td rowspan="2">CAPEX</td><td>Investment</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
<tr><td colspan="2" rowspan="3">Electricity storage
(no conversion)</td><td rowspan="2">CAPEX</td><td>Investment</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
<tr><td rowspan="6">Electricity consumption</td><td rowspan="2">Appliances production costs</td><td colspan="2">Investment</td></tr>
<tr><td colspan="2">Capital cost</td></tr>
<tr><td>Sobriety costs</td><td colspan="2">Investment</td></tr>
<tr><td rowspan="3">Load management</td><td rowspan="2">CAPEX</td><td>Investment</td></tr>
<tr><td>Capital cost</td></tr>
<tr><td colspan="2">OPEX</td></tr>
</table>

Table 1: Inventory table

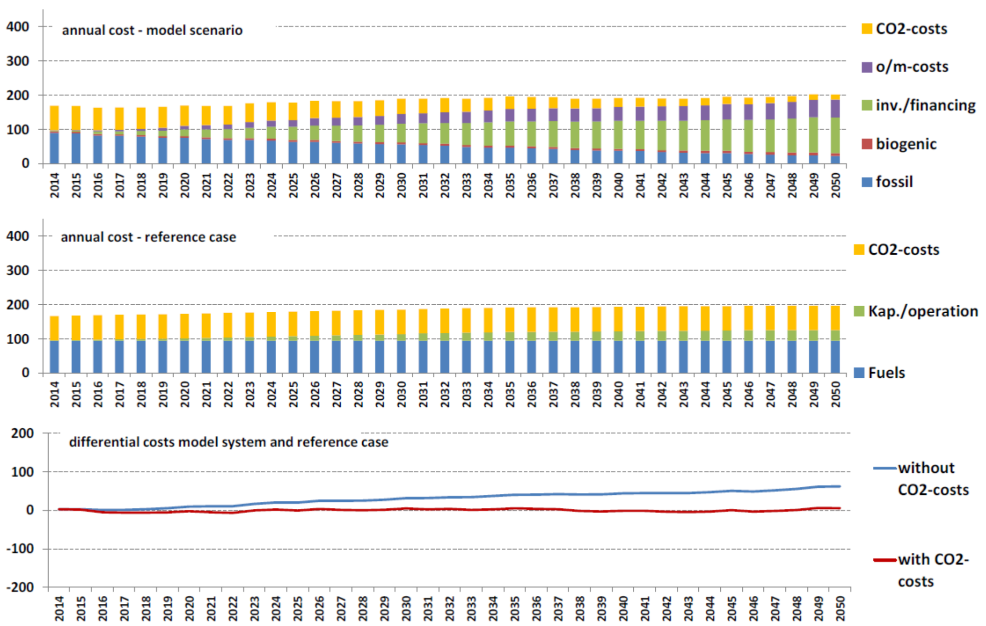
B. Some examples of cost trajectories indicators

The following figures are two cost trajectories from (Lappeenranta University of Technology / Energy Watch Group, 2017). They respectively show the evolution of CAPEX and OPEX of one scenario during the whole timeframe with a five year interval:

Figure 41: Global - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).



These three figures are cost trajectories from (Fraunhofer ISE, 2015). The first two show the respective cost evolution of two different scenarios, while the third one shows the differential evolution between the two scenarios:



Analysis of the 85-% Scenario

Fig. 40 The chronological cost development for the 85-% scenario (top), the fuel costs as well as CO_2 costs for the reference scenario (center), and the difference costs between model system and reference (bottom) are shown. The chart applies for constant costs of €100 per ton charged for CO_2 emissions.

C. The five cost items to build system technical cost indicators

This section describes the several cost items than can be used to calculate system technical cost indicators:

1 – CAPEX
2 – OPEX
3 – Electricity trade balance
4 – Future costs
5 – Past costs

The following description of the five items is designed to assess costs from a **system perspective**.

To build specific actors' cost indicators, the same five cost items can be used, but new elements should be added, as explained in the Economic transfers paragraph.

These costs items actually **refer to activities taking place during the evolution and operation of the power system**: CAPEX refers to the costs incurred by the activities of building power system assets; OPEX refers to the costs incurred by the operation of these assets; electricity trade balance refers to costs incurred by activities taking place in neighbor countries; "future costs" refers to costs incurred by activities on the power system happening after the time horizon of the study; "past costs" refers to costs incurred by activities on the power system happening before the start date of the study.

CAPEX and OPEX are almost always accounted in future studies while the other items are often neglected. **We explain in next paragraphs why electricity trade balance and future costs are particularly important to consider and how future costs also enable to take sunk costs into account**.

The five cost items can also be divided in **two categories**: CAPEX, OPEX and electricity trade balance are what we can call ***actual expenditures***, i.e. expenses that actually have to be paid each year during the scenario; whereas future costs and past costs are cost items enabling **better comparisons** by integrating edge effects.

In addition, calculations of some of these cost items may require to annualize them, that is, to allocate a one-time cost over several years. Several annualisation methods exist. For example, a 20M€ expenditure useful for 10 years can be distributed "on average": 2M€ per year over 10 years. But it could also be progressively discounted and/or indexed on inflation.

Recommendations for scenario producers

The chosen annualisation method should be explained for more transparency.

What is the reference period for annualisation? Is it the technical service life of a plant? Are cost equally distributed over the period? Are costs also discounted in the same time? Is inflation taken into account?

The five items presented here are designed to assess costs from a **system perspective**. Therefore, **no economic transfers between specific actors** should be included.[28] For example, all cost items should be tax free to avoid distortions due to different tax levels for different products or services. Note that all those costs depend ultimately on labor costs which depend on local tax, environmental and social regulations, and on import and export costs.

Here is a summary of how to assemble the cost items to calculate the three previously described system technical cost indicators:

[28] Or both 'sides' of each economic transfer has to be included so that the value is cancelled in the sum.

	Expenses shape	Differential costs	Absolute costs
CAPEX	Y	Y	Y
OPEX	Y	Y	Y
Electricity trade balance	Y	Y	Y
Future costs	N	Y	Y
Past costs	N	U	Y

Y : Yes N : No U : Useless

Figure 5: Cost items composition of the three presented system technical cost indicators

Reading key: expenses shape must include CAPEX, OPEX and electricity trade balance and must not include future and past costs. Past costs can be accounted for differential costs but are useless: it would not change the result.

1. CAPEX

CAPEX (Capital Expenditure) is composed of **all the investments**, such as investments to build new capacities, extend the life of already existing capacities, or spare money (provision) for future expenses as dismantling or waste management.

Depending on the scenario producer choice, **capital costs** may or may not be included. Capital costs are **the financing costs** of the investments. They are included in the calculation whenever a WACC is used (see section on long-term transition of the PS)

2. OPEX

OPEX (Operating Expenditure) comprises all costs required to **make the system operate**. It includes fixed costs such as worker wages and regular maintenance operations of infrastructures, and variable costs such as the purchase of fuel to make power plants run. Carbon quotas on EU ETS market, taxes, and other economic transfers should not be included as these are not costs from a system perspective: they are not needed to make the system operate and should therefore only be considered when assessing specific actors' perspective (see dedicated paragraph, p23). Considerations on how to handle externalities in economic evaluation, can be found in the next section.

3. Electricity trade balance

Electricity trade balance is the **net cost or revenue due to electricity imports and exports with neighbors**[29].

As it can be significantly lower than CAPEX and OPEX, it may be justified to neglect its value in some cases. However, as pointed out in (RTE, 2017) it can also be an important item, that can vary significantly among scenarios (going from a positive to a negative value in some cases and going from the same positive value to a tripling in others).

What must be taken into account here are the **exchanges between countries within the geographical scope of the scenario and the countries outside**. Exchanges among countries within the geographical scope are indeed only an economic transfer in the scenario and do not have an impact on the overall costs or revenues. It would enable to provide insights from specific actors' perspectives but should not be accounted as a system cost. Thus, in the proposed framework, electricity trade balance does not need to be assessed in worldwide scenarios since there is no neighbors "outside the geographical perimeter".

[29] It should not be seen as the overall trade balance of the electrical system (it does not contain imports of equipment for example).

a. Calculation method

Cost of imports and revenues from exports have to be calculated separately as the electricity price is not the same in the two situations. This is the case because imports and exports does not occur in the same time while the electricity price can significantly vary over time. One possibility used in (Fraunhofer ISE, 2015) is to set one unique purchase price for electricity import and one unique selling price for electricity export (expressed in €/MWh). Conservative values can be chosen so as to be sure the scenario remains robust. Hourly electricity price variation can also be taken into account for more accuracy.

b. Precaution of use in scenarios

A few elements should be borne in mind when planning to introduce electricity trade balance in a scenario, as described in Boundary Condition section. Countries' electricity trade balance should be justified to several extend:

- Import-export previsions must be **consistent with the neighbors' own previsions** (two neighboring countries cannot decide to be net exporters toward the other during the same years).
- Thus **geopolitical aspects** are involved since neighboring countries or regions have to accept to be structurally importers or exporters, sometimes for several decades. This can be reported in the storyline.
- **Time repartition of electricity exchange** should be taken into account. For example if two neighboring countries have an important wind capacity, correlation in time between their electricity productions should be assessed. Moreover, if one of the two countries plans to import electricity during its peak hours, the real time ability of the neighboring exporter country to export electricity should be checked since it can be facing its peak hours at the same time. Annual import-export means are therefore not enough: hourly exchange capacities are needed. It implies to take a look both at supply and demand time repartition (especially in high RES mixes for supply).
- **Interconnection capacities** must be available so as to physically transport the electricity exchanges

(Fraunhofer ISE, 2015) takes electricity trade balance into account and handles some of these elements. This results in setting a maximum exchange power value in each of its scenarios (15GW in one case, 40GW in another, etc.)

4. Future costs

Future costs are the **costs and savings that will happen beyond the end date of a scenario due to choices that occurred within the scenario timeframe**. This is sometimes called the "horizon effect".

As we will see, integrating future costs enables both to properly compare scenarios and to take sunk costs into account.

a. What are future costs?

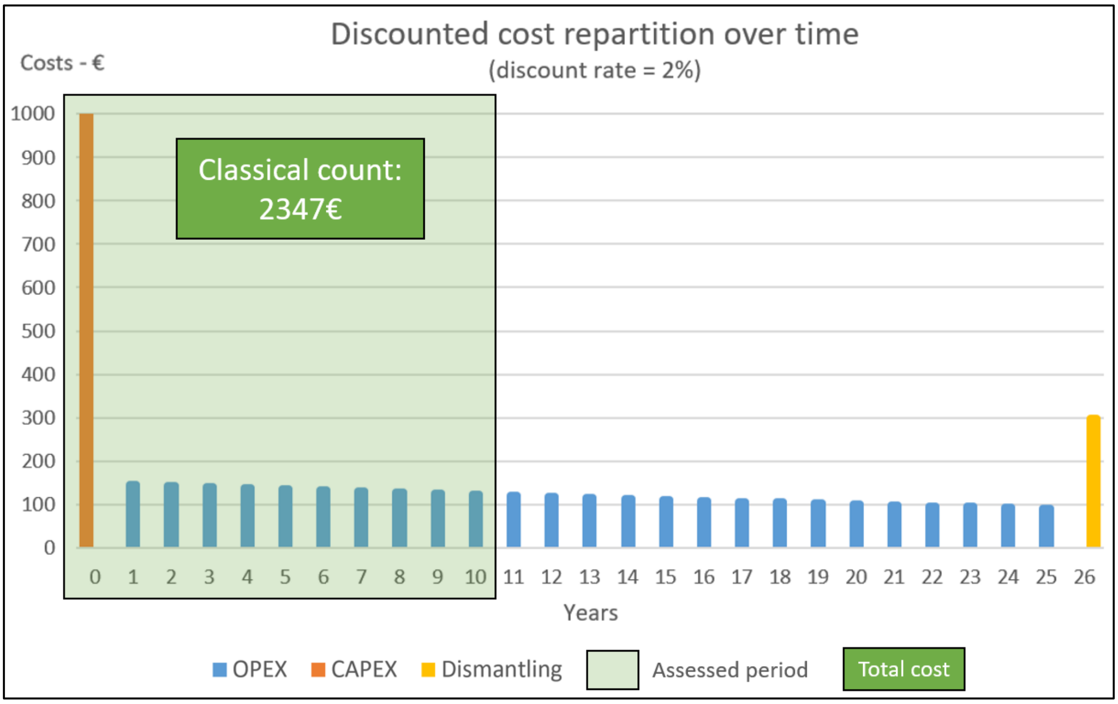
Let's take the example of a scenario A where a new hydropower plant is built one year before the scenario end date (let's say in 2049). All the CAPEX are paid in 2049 and the plant is used only one year in this scenario. But in fact it will produce low cost electricity long after 2050. Thus, all this 'unused CAPEX' can be seen as future savings. All these futures savings must be accounted so as to properly compare costs of scenario A with costs of a scenario B where the new hydropower plant is not built. **Indeed, a *fair* comparison requires to look at 'useful' CAPEX** (i.e. CAPEX which is actually used within the scenario timeframe) **rather than total CAPEX**. This is particularly important when comparing a BAU scenario with a transition scenario where big amount of high CAPEX and low OPEX decarbonized production units are deployed.

A *fair* comparison also requires to look at undervalued or unaccounted costs like dismantling or waste management costs that are due to choices occurring during the scenario timeframe but that will have to be paid after the end date of the scenario. Again, only the **'useful part'** of those costs must be taken into account. In this case, these are not savings but costs.

This is why this section could be named "future costs and savings" but we will keep the shorter "future costs" designation.

Since future costs **will not have to be paid during the scenario period** they should not be included in cost indicators aiming at describing costs *as observed within the scenario timeframe* such as the expenses shape indicator (see Expenses shape paragraph). Future costs are indeed not *actual expenses.* However they are required to compare several scenarios properly so as to get a fair comparison. They enable indeed to take "horizon effects" into account. This is why it is included in the differential costs indicator (see Differential costs paragraph). For example, the comparison between (RTE, 2017) four scenarios is better informed thanks to the integration of future costs according to RTE.

Here is an illustrative example: a 25 years lifetime asset has a 1000€ CAPEX with 150€ OPEX each year and a 500€ dismantling cost. The costs are discounted with a social discount rate of 2%. The scenario ends after the 10th year. Each of the two graphs illustrate a way of counting: classical way and including future costs.



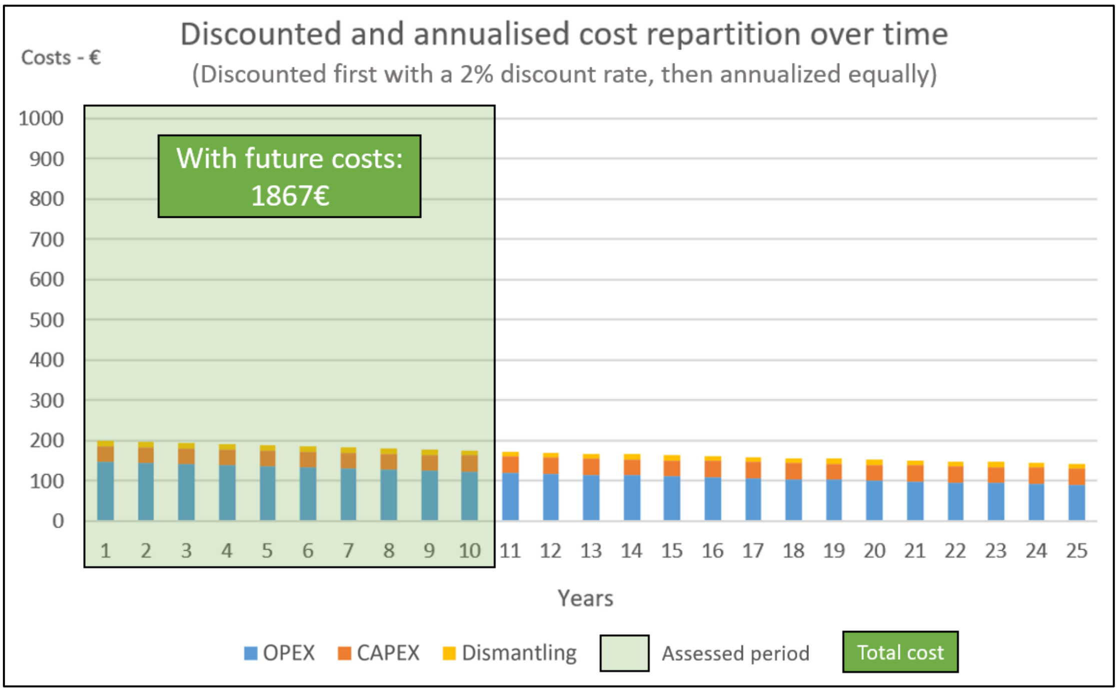


Figure 6: Illustrative example of counting with future costs

We can see that in the first case all the CAPEX are counted while dismantling costs are not taken into account. In the second case, future costs are added (and savings are removed): only the useful part of CAPEX is accounted, and the useful part of dismantling cost is added. The first method reflects the real discounted evolution of expenditures over time while the second method enables fairer comparisons.

b. Calculation method

Integrating future costs due to CAPEX still useful after the end date of the scenario consists in ***removing* the discounted 'unused' CAPEX**. Integrating future costs due to undervalued or unaccounted costs due to choices during the scenario timeframe that will cause costs after the end date of a scenario, such as dismantling costs, consists in ***adding* the discounted 'useful' part of those costs**.

<u>Evaluating the 'unused' or 'useful' part of a cost: rule of three</u>

RTE suggests two methodologies to evaluate the 'useful' part of a cost. Both examples are based on CAPEX, but the reasoning is the same for investments like dismantling costs.

The first one is the most simple and we believe it is efficient enough. It consists in counting only the CAPEX part used during the scenario period, thanks to an elementary rule of three. For example, if a wind turbine farm with a 30 years lifetime and 120M€ CAPEX was built in 2040 in a scenario that ends in 2050, only 10 years upon the 30 years should be counted which means that only one third of the CAPEX is counted. In this case, the CAPEX value of the wind turbine farm would be 40M€. More specifically, integrating future costs would consist in *removing* an 80M€ cost from the scenario total costs.

The second method consists in evaluating an "end-of-period value" for each type of capacity. This value reflects the real value the asset will provide between the final date of the scenario and the end of their lifetime. While the first method was a *time* pro rata, this one is a *real use* pro rata and would require specific additional hypothesis.

<u>Introducing the discounting: discounting before adding</u>

As any other costs, future costs have to be discounted. In order to properly add future costs while using a discount rate, these future costs must be discounted **before** being added.

Indeed, if they are added to other costs (for example to an Expenses Shape) without a discounting and then the resulting trajectory is discounted, no difference in value will appear between the future costs occurring at the beginning or at the end of the trajectory.

Thus, it is necessary to **first discount future costs, then to distribute them year after year, and finally to add them to an already discounted cost trajectory**. The discount rate used must be the same, and it has to be a social discount rate.

To sum up and give an example, going from two expenses shapes of a scenario A and a scenario B (see Expenses shape paragraph) to a differential costs between the two scenarios (see Differential costs paragraph) consists in:

- calculating and discounting future costs separately, with a social discount rate (let's say 2%)
- discounting each expenses shape with this same social rate (2%)
- adding future costs A to expenses shape A, and future costs B to expenses shape B
- summing the costs over the entire resulting cost trajectories, for A then for B
- subtracting these two values. The resulting value is the differential costs including future costs.

c. Future costs handle sunk costs

Integrating future costs enable to implicitly **take sunk costs into account**.

Indeed, if a plant is closed and replaced n years before its economic lifetime, the plant coming in replacement will arrive n years in advance and will therefore lose the value of these n years in the future costs account.

Let's take the example of a scenario A where a still-usable gas power plant is replaced by a new gas power plant in 2030 against a scenario B where the same replacement occurs in 2040. Without the integration of future costs, both scenarios have roughly the same costs over the period up to 2050 (i.e. gas purchase for the same number of years and CAPEX for the same new gas plant). But when the future costs are included (i.e. when only 'useful' CAPEX is accounted) scenario B becomes less expensive than scenario A since the new gas plant is 10 years "younger" in scenario B and will therefore be able to produce electricity 10 more years after the end date of the scenario. The cost difference between the two scenarios is **the value of the sunk costs**.

Another effect with lower impact is that the new gas power plant in scenario B benefits from a 10 years technology improvement with the associated cost reductions compared to the scenario A plant. This effect is also implicitly taken into account.

This method to include sunk costs into a comparison is efficient from a system perspective. However assessing the cost from specific actors' perspective also requires to identify who is going to pay for these sunk costs (see Sunk costs paragraph in Desirability section).

5. Past costs

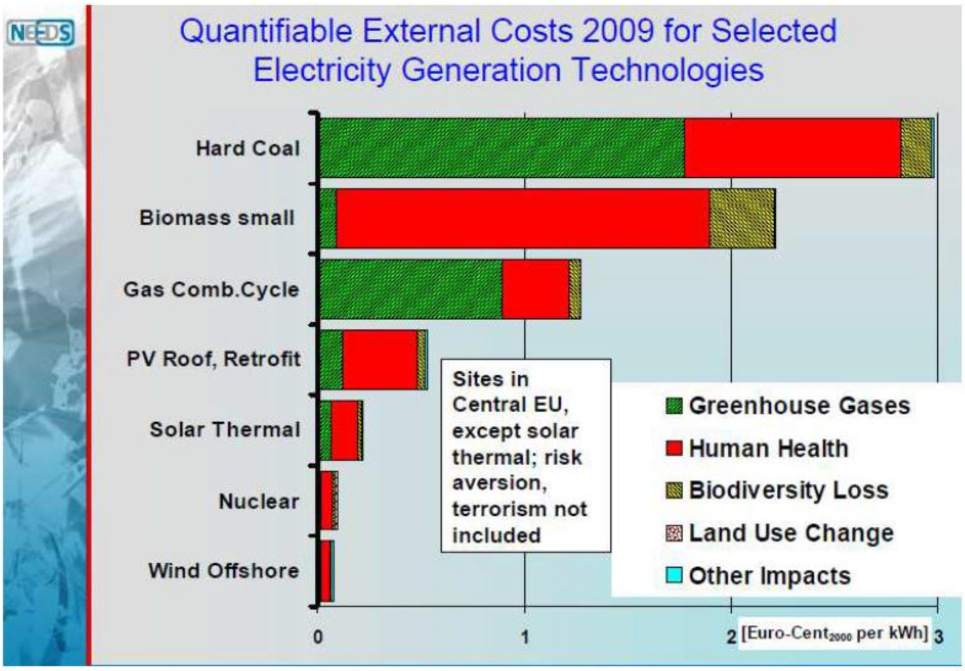
Past costs follow a similar philosophy as future costs: they are the **costs to be paid and the savings realized during the duration of the scenario that are due to expenses or decisions made in the past** (i.e. before the starting date of the scenario).

It includes costs such as the dismantling of power stations or waste management, but also and mainly **all the CAPEX of already existing infrastructures**: we usually count the OPEX of these assets but not their CAPEX. As for future costs the idea is to integrate the 'scenario-useful part' of these CAPEX, which are not *actual expenses* (nobody will pay today for CAPEX already paid in the past). Therefore, past costs should not be integrated in cost indicators aiming at describing costs *as observed within the scenario timeframe.* Furthermore, past costs are a consequence of decisions that happened in the past, therefore they are the same for every scenarios using the same cost inventory. Thus, it is not useful to introduce these costs when comparing two scenarios since it would not change the differential value.

In the end, this cost item is only needed when trying to compare the costs of a scenario to today's cost, as with the absolute costs indicator (see Absolute costs paragraph).

Past costs can be calculated the same way that future costs with a time pro rata, but this time by *adding* the useful part of the past CAPEX. However it requires some specific assumptions with potentially high uncertainty.

D. Examples of externality assessment for some power supply-side components



Source : Needs, R.Friedrich, 2009

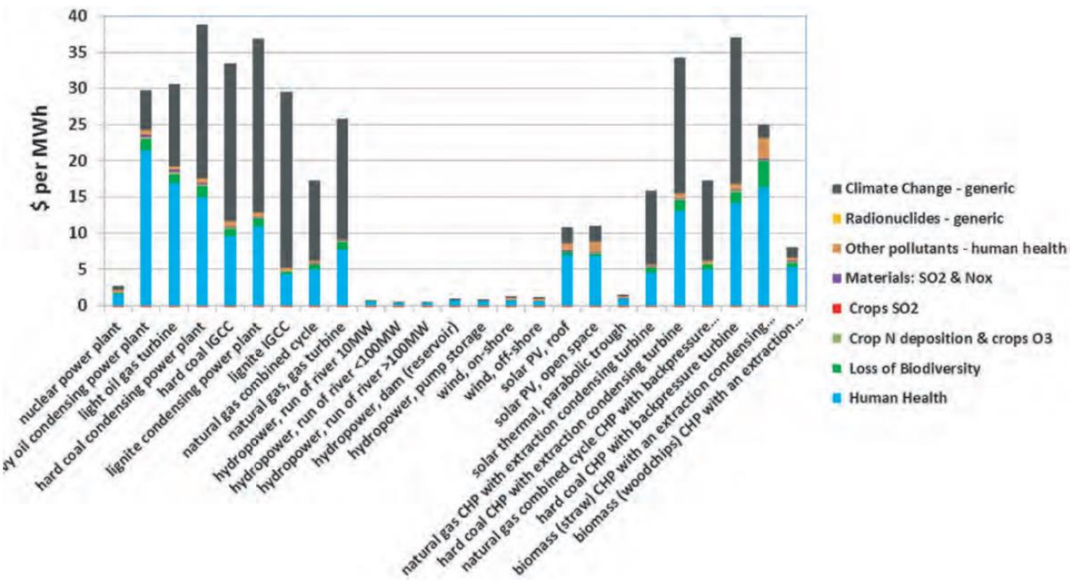


Figure 6.7 | Average external costs for the European Union. Source: Markandya et al., 2010.

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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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