Chapter 4
Economics of Concentrating Solar Power Generation

4.1 The Value Chain of the Sector

The CSP value chain comprises many activities ranging from the development, civil works, solar field, tower, receiver, control, piping/valves, steam generation, turbine, cooling system, electrical system, auxiliary system, assembling, and research [15]. As of today, Europe is still the technological leader in the CSP sector and, given that one of the priorities of the Energy Union is to “become world leader in renewables”, Europe is making efforts to preserve this status.

As demonstrated by various studies [6, 12, 19, 35, 67, 77], having industrial leadership brings multiple socioeconomic benefits in the form of employment and economic stimulation across many sectors. Besides the reduction of environmental externalities, the socioeconomic benefits of CSP deployment are important reasons that justify CSP support in many sunny belt countries.

As shown in Table 4.1, technology manufacturers along the CSP value chain are found in more than ten countries in Europe [15] and, out of the fourteen activities that comprise the CSP value chain, Spain ranks first, with a participation in thirteen of those.

However, and in line with what has happened in the wind power and PV sectors, the European leadership may quickly vanish due to the ambitious initiatives recently launched in other world regions and, in particular, China [47: 76–83, 81]. According to consulted experts, the growing threat on EU technology leadership comes from non-EU companies which have bought the industry’s know-how holders and RD&D infrastructure at low cost.

Lilliestam [39] argues that the most critical aspects of the construction of a CSP project can be grouped into four main categories of the value chain: (i) the engineering, procurement and construction (EPC), (ii) the development of a project, including design and planning and also the plant components, (iii) the solar collector assemblies (the mirrors), and (iv) the receivers (heat collector elements, HCEs). Figure 4.1

P. Mir-Artigues et al., *The Economics and Policy of Concentrating Solar Power Generation*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-11938-6_4

Table 4.1 European participation in various activities of the CSP value chain

	Member state	Germany	Denmark	Czech	Spain	France	The Netherlands	Italy	Portugal	Belgium
Activity	Development	v			v	v		v		
	Civil works				v			v	v	
	Solar field	v			v	v				v
	Tower				v			v	v	
	Receiver	v	v		v		v			
	Storage	v			v					v
	Control	v	v		v	v	v	v	v	
	Piping/valves	v			v	v		v	v	v
	Steam generation	v	v		v		v	v		
	Turbine	v		v				v		
	Cooling system				v			v	v	
	Electrical system	v	v	v	v	v	v	v	v	
	Auxiliary system				v			v	v	
	Assembling				v			v	v	
	Research	v			v	v		v	v	

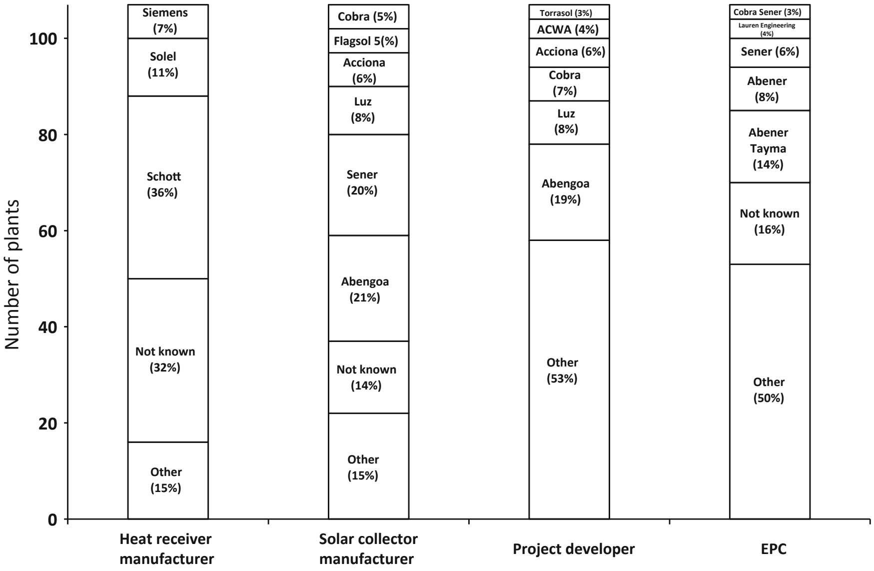


Fig. 4.1 Active companies in the EPC, developer, heat receiver, and solar collector manufacturer phases. *Source* Lilliestam [39]

shows the most important participating companies (for 107 CSP plants) for each of those categories.

To have a better understanding of the past, current situation, and future trends, a detailed breakdown of the country origin for the different supply chain phases is provided below[1]:

- As shown in Fig. 4.2, the EPC market is highly concentrated and dominated by Spanish companies. The market share of companies like Abener/Abengoa, SENER, Acciona, and Cobra (with 16, 14, 9, and 9 projects, respectively) is remarkable. However, since 2012, most Spanish EPCs have reduced their activity. In this regard, all but three projects under construction are built by EPCs without experience from previous projects. As highlighted by Lilliestam [39], whereas this is beneficial for new actors entering the relatively undiversified EPC market, there is also a considerable risk that the know-how acquired in the last decade is lost if the previously dominant companies exit the market [41].

---

[1] The data and figures presented here have been abstracted from [39], who conducted a very comprehensive analysis of a dataset of all CSP stations of 10 MW or larger in operation and under construction during the period 1984–2020 (csp.guru 2018).

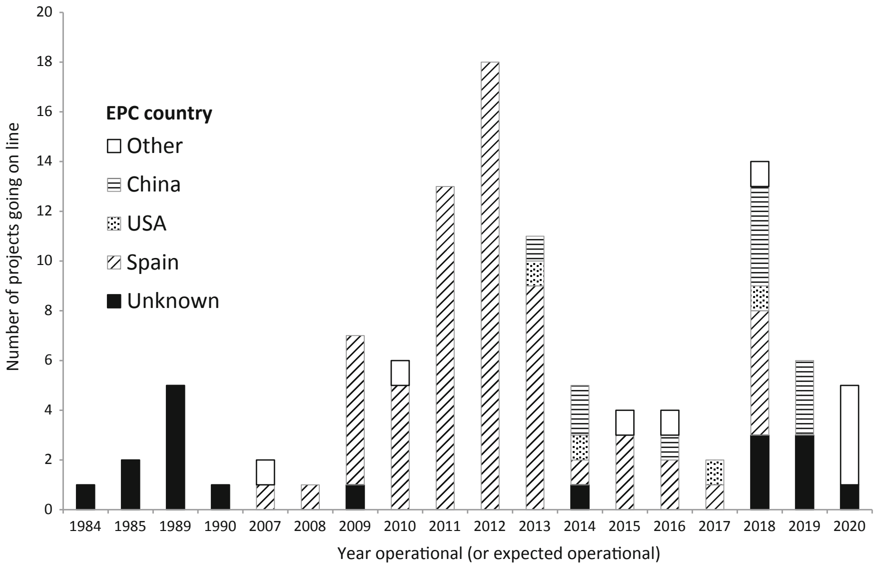


Fig. 4.2 Country of origin of the EPCs of CSP projects (1984–2020). *Source* Lilliestam [39]

- The market of developers is dominated by almost the same companies as in the EPC market, and as it can be observed in Fig. 4.3, After an initial leadership of American first and Spanish developers next, the market is currently experiencing an increase of Chinese and other Asian developers. As documented by Lilliestam [39], the Saudi developer ACWA has won bids for all three Noor stations in Morocco and for Bokpoort in South Africa and also won the bid for the 700 MW DEWA IV station in Dubai.
- In the market of heat receivers (HCE), Schott (bought by Rioglass in 2015) has dominated the market. Schott/Rioglass is active in at least two projects under construction, whereas all other known HCE suppliers are new (including, again, new Chinese market entrants) (Fig. 4.4).
- As in the EPC market, the production of solar collectors (SCAs) is dominated by the same companies which supply components to 60% of all projects. However, for the new projects, most SCA manufacturers are new. Contrary to the previous phases, the Chinese companies have not yet taken over the market [39] (Fig. 4.5).

The results from the analysis by [39] presented above seem to indicate that, after an initial industrial leadership of North America and Spain, new actors are entering the various phases of the CSP value chain. Among the newcomers, the emergence of Chinese companies is remarkable. According to [81], China's industry faces both great opportunities and challenges. The same authors argue that China has several positive features which could lead this country to achieve an industrial global leadership in CSP: It has large areas with excellent solar conditions for CSP, strong basic capabilities in traditional manufacturing activities which are important to CSP, and,

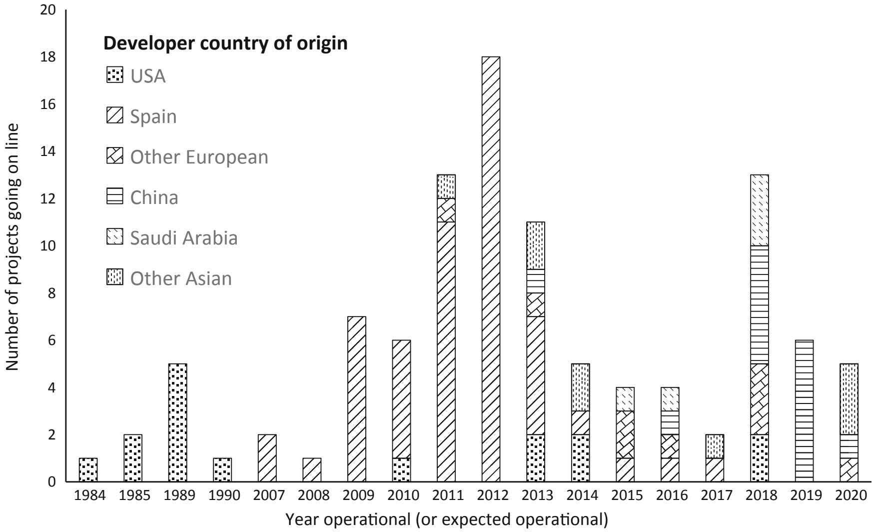


Fig. 4.3 Country of origin of the developer of CSP projects (1984–2020). *Source* Lilliestam [39]

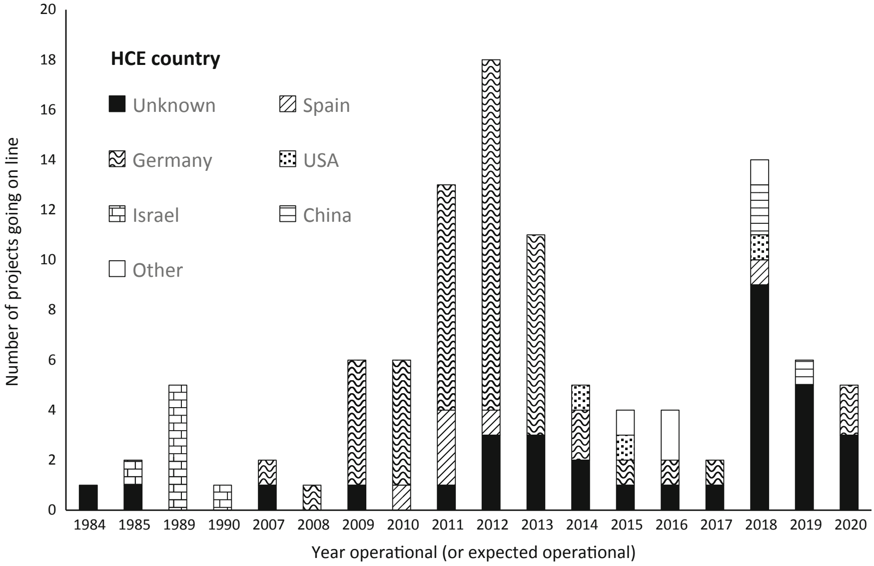


Fig. 4.4 Country of origin of the HCE manufacturer (1984–2020). *Source* Lilliestam [39]

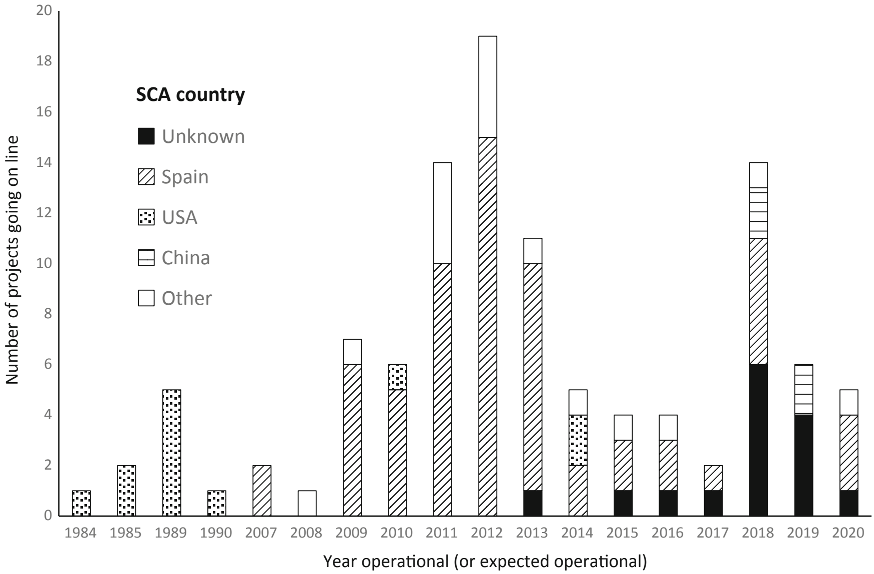


Fig. 4.5 Country of origin of the solar collector assembly manufacturers (1984–2020). *Source* Lilliestam [39]

also to some extent, know-how in CSP technologies. China would also profit from stronger international collaboration in the field, standardization, and international property rights legislation and management.

Regardless of the country of origin, the entry of new industrial players may have positive effects in terms of innovation as well as less dependence and vulnerability on the support scheme of a few countries. Furthermore, this will, in turn, contribute to ensure the continuity of the CSP industry in case the dominant firms leave the market [40]. According to the same authors, continuity in the industry is essential and support policies must be designed in order to address two risks: (i) Larger firms leave the market, and (ii) project developers and operators fail to take advantage of innovations and, as a result, fail to push costs down.

4.2 Design of Plants and Economic Analysis

The development of economic models for solar thermal generation, supported in their corresponding technical base, is an issue of some complexity for the following two reasons:

- Beyond the four main types of solar thermoelectric plants (i.e., parabolic trough, solar tower, linear Fresnel, and dish/stirling), there is a large number of particular configurations, each with their own technical and economic specificities. Some particularities are related to the resources of the place where they are located (DNI, water for cooling, etc.), to the goals of the public authorities in energy matters and to the willingness of the developers to improve previous designs (secondary innovations).
- The different energy transformations which were carried out in CSP plants are subject to several technical requirements which lead to numerous trade-offs, with the levels of energy efficiency being the key indicator of the quality of the process. The goal to reduce the cost of generation requires, then, carrying out very careful calculations. The issue is often to estimate to what extent the savings in one element (with respect to a reference point, probably a previous project) is not offset by the increase in the expenditures in another. However, such an increase may be a requirement in order to achieve the final reduction in the costs. It is not surprising that the process of economic optimization of CSP plants is arduous, given the dense network of technical and economic variables involved, as well as the uncertainty on the evolution of the later, which has kept generations of technicians and engineers busy since the middle of the nineteenth century.

The economic models proposed in this section are merely conceptual. Their aim is to highlight the basic technical and economic interrelationships which are present in the design process of thermo-solar plants, taking parabolic trough plants as the reference, since they are the most common design. There is no doubt that the identification of the technical and economic details of a specific plant is an issue which entails considering and fitting many relationships and optimizing a large amount of variables. Therefore, it is a process with many feedbacks.[2] Furthermore, it is likely that the definition of the project has to include the requirements suggested by planning and simulation models used by the system operators (SOs) in order to determine the least cost electricity dispatch generation mix (subject to given transmission grid constraints). Addressing such complexity goes well beyond the objective of these pages, although it inspires the models proposed. These models are built based on the following assumptions:

- The plant operates under a normal functioning regime (or steady-state conditions).
- The plant is only dedicated to the production of electricity. Complementary activities such as industrial steam production or water desalination are excluded.

---

[2] However, as it is obvious, the greater the experience of engineering firms, the greater the diligence in carrying out this activity.

- The plant has heat storage tanks and can operate under a hybridization regime.

In this context, two main issues will be highlighted: the discussion on the solar multiple (SM) concept and an approximation to the cost of generation per MWh.

Before addressing these issues, however, the economic process of a solar thermoelectric project should be briefly described. Although it is obvious that there might be many legal and financial variants, its main aspects are worth describing. To start with, given the large investment that a CSP plant represents (tens or hundreds of millions of € or $), a specific firm is created. There might be institutions which provide financial resources (such as economic and technology development agencies) to this firm. If it is a demonstration plant, public support is usually massive.

The next step is to contract an engineering firm which elaborates the first technical project and its business plan. These documents are then sent to financial institutions, which analyze the financial needs of the initiative and their risks and communicate their financial proposals to the firm, which will have to assess them. The accepted proposal is developed until there is a complete financial plan, which requires the approval of the financial institution, once third parties have revised the technical project and their regulatory and legal requirements.

If they are not shareholders, the financial institutions usually provide loans up to 70–80% of the funds needed, according to corporate finance or project finance schemes (the project itself is the collateral which secures the debt). In this last case, the cash flow coverage ratio is between 1.3 and 1.45 times the debt service. The amortization period of the loan is usually between 18 and 20 years. Sometimes, it is possible to cancel it after 7 or 8 years, with the shareholders assuming such liquidation, or the possibility to renegotiate the debt and its guarantees. Insurance companies cover unexpected events (delays in the execution, coverage of the loss of profit, and civil liability).

Next, the design of the definitive project, the setting up of the schedule for the completion of the project, and the subcontracting of the construction and purchase of the needed components and systems are awarded to a firm (probably through an invitation to a tender). They are engineering, procurement and construction (EPC) contracts, in which the main contracting party has to assume upward deviations, whereas it benefits from savings with respect to the awarded budget. Contractual formulas regarding the management of the plant by third parties during a trial period are also common. If the management firm anticipated part of the investment, this period may entail several years of operation until this investment is recovered. After such period, the management of the plant is transferred to its owners. O&M operations are usually subcontracted to a specialized firm, according to a fixed price which is periodically updated.

This institutional and financial scheme may be complicated with several issues: payment for the hiring of the land to the landowners where the plant is placed, bond issuance by the firm which owns the firm, etc.

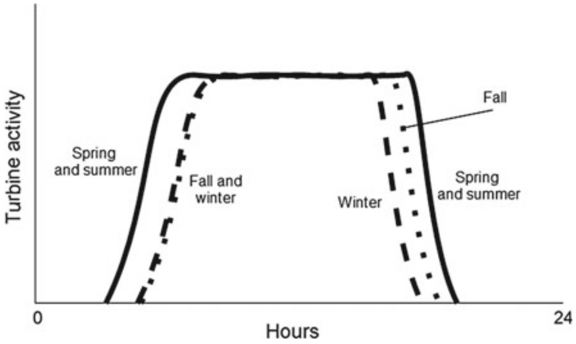
4.2.1 Design Point and Solar Multiple

It should be mentioned first that solar thermal plants, as it is the case of other electricity generation plants, have to operate a maximum number of hours per year. Although there might be breakdowns and maintenance activities which lead to interruptions in their operation, CSP plants should operate during the night hours and when the impact of atmospheric circumstances reduces the DNI. Again, this leads to the storage of heat in order to operate at nighttime or to opt for hybridization. On the other hand, it should be mentioned that the capacity of thermoelectric generation grows with the intensity and persistence of direct solar irradiation (which represents 80–90% of the solar energy which impacts the earth crust). The minimum intensity values are between 1900 and 2100 kWh/m^2/year, whereas the persistence requires avoiding locations which are cloudy or have frequent mists, since those drastically reduce the DNI.[3] Although steam, aerosols, and ozone which are present in the atmosphere have a very small impact on the reflecting surfaces of the solar field, the dust carried away by the air requires their periodic cleaning [75: 58].

It should also be mentioned that the power block and the HTF/steam exchanger may operate in a wide range of partial load. This is an unthinkable attribute if the plant operates only under solar mode. However, for economic reasons, it should operate at its nominal (or full, or rated) power. This is why it may need the temporary recourse to the stored heat and/or hybridization. Furthermore, the number of daily hours of activity of the turbine changes depending on the season of the year. The more differentiated are the seasons, the more differentiated will be those activity intervals (assuming an only-solar without TES operation mode) (see Fig. 4.6).

With clearly differentiated seasons, the daily operation interval of the plant is greater in spring and summer, given the higher number of sunny hours. The opposite occurs during the winter and autumn. However, during the daytime hours, the operation of the power block is very stable and the closest possible to its nominal power.

Fig. 4.6 Seasonal turbine activity. *Source* Own elaboration



---

[3] Once the clouds have gone by, it will take some time for the plants to recover their full level of activity.

As it is well known, the capacity factor (L) is a relevant indicator of the performance of an electricity generation process. Since generation can undergo interruptions (breakdowns, night hours in the case of solar plants) and oscillations (insufficient wind, cloud passing, etc.), the capacity factor indicates how many hours, taking the natural year as a reference, would have been needed if the plant had operated at full capacity, in order to generate the electricity that it really has generated. Or, in other words, in the case of CSP it indicates the equivalent amount of hours that the power block has been operating at full power in a year. The capacity factor is a technical indicator, although it has profound economic implications: The higher its value, the better the installed capacity will be used and the faster the investment will be recovered. The capacity factor of a solar thermal plant (defined without hybridization, i.e., only the solar generation) can be expressed as follows (adapted from Izquierdo et al. [29: 6216–6217]):

$$L = \frac{q}{\Lambda \cdot H}$$

where q is the electricity generated in a year (MWh), Λ is the nominal power of the turbine (MW) and H is the number of hours in a year (8760 h). As it was indicated, L is the relationship between the effective and the maximum generations.

In order to illustrate the underlying factors, this expression can be rewritten as follows:

$$L = \frac{\varepsilon \cdot \psi \cdot S}{\omega \cdot \Lambda_{\text{th}} \cdot H} \tag{4.1}$$

where ε $(0 < \varepsilon < 1)$ denotes the collector system performance, Ψ refers to the solar direct irradiation captured by the solar field, S is the solar field collector surface,[4] ω represents the conversion factor between thermal energy and electricity,[5] and Λ_{th} is the capacity of the power block in thermal units. The numerator, thus, shows the quantity of energy delivered by the solar field (MWh), which is below the incident energy due to losses, whereas the denominator is the rated power cycle.

Leaving aside the technical details, the solar energy available is defined by the multiplication of the DNI and the collector surface, including losses. The latter depends on the type of plant. For example, in the case of a trough collector it is the aperture area of the parabolic reflectors, whereas, in a Fresnel plant, it is the overall surface of the flat mirrors. Inevitably, there are optical losses of the solar concentrator and receiver devices, as well as thermal losses of the HTF. The total addition of the losses of the solar field due to optical and geometrical reasons can represent more than 60% of the incident solar energy.

---

[4] The capturing surface of the collectors (S) is only a fraction of the total land area occupied by the plant. Izquierdo et al. [29] assumed that this is 27.5% for parabolic troughs and 12% for solar tower heliostats.

[5] This conversion factor is 1 kWh = 3.6×10^6 Joules (J), since 1 J = 1 W s.

A brief discussion on the relation between the thermal units (which are used to measure the capacity of the solar field, as well as the capacity of the power block) and the electrical units (which are much more common to measure the capacity of the power block) follows. The use of thermal units does not entail major challenges, although the different sources of heat which feed the power block, as well as unavoidable energy losses, have to be taken into account. Thus, given a sufficiently long time period (a year, for example), the thermal energy required in the process (E_{th}) is the addition of the energy provided by the solar field and used immediately $\left(\alpha_1 E_{\text{th}}^F\right)$, or the energy charged/discharged by/from the storage system $\left(\alpha_2 E_{\text{th}}^F\right)$, $\alpha_1 + \alpha_2 = 1$, and the one corresponding to hybridization $\left(E_{\text{th}}^Y\right)$. Therefore, we can write:

$$q = \omega\left[\left(\alpha_1 \varepsilon \Lambda_{\text{th}}^F + \alpha_2 \varphi^+ \varphi^- \Lambda_{\text{th}}^F\right) H^F + \chi \Lambda_{\text{th}}^Y H^Y\right]$$

where the electricity generated (q), given a conversion factor ω between thermal energy and electrical energy, is associated with the aforementioned thermal contributions. These result from the sum of the nominal thermal power of the solar field (Λ_{th}^Y) multiplied by its hours of activity (H^F), which is divided by a fraction α_1 immediately used and a part α_2 stored for a later use, plus the thermal rated power of the gas turbine (Λ_{th}^Y) which is used in a hybridization regime[6] multiplied by its hours of operation (H^Y). The right-hand side of the expression contains two additional parameters whose meaning is as follows:

- χ ($0 < \chi < 1$) represents the performance of the hybridization generation process.
- φ indicates the performance of the process of heat transfer from the working fluid to molten salts (φ^+) which is in the storage tanks, or the recovery from these tanks (φ^-). In both cases, yearly average values and $0 < \varphi < 1$ are considered.

The electricity self-consumption of the plant should also be taken into account. The annual electricity production, q, is a gross amount (MWh), since the plant consumes part of its own electricity given the needs of the pumps which operate in the plant, in order to feed the solar tracking devices and to maintain the cooling equipment active. Thus, in a parabolic trough plant, the HTF should be boosted within the solar field and the collectors should be moved to left/right. In the case of a solar tower, the heliostats have to strictly follow the transit of the sun. This is also the case with the dish/stirling collectors. As a result, the plant usually consumes between 5 and 10% of the electricity that it generates. Thus, differently from other renewable technologies, CSP plants consume a non-negligible amount of electricity when they are in operation. Thus, the annual quantity of electricity fed into the grid (MWh), which is remunerated at a given price p, is $q^* < q$.

Assuming the existence of an energy policy which promotes thermo-solar generation, as well as a sufficiently detailed plan for the deployment of new-generation

---

[6] Assuming that the plant is hybridized with natural gas simplifies the expression. Indeed, it is directly burned in the corresponding turbine whereas, if the aim is to use the gases from coal or biomass combustion, they should be channeled to a heat exchanger in order to obtain superheated steam.

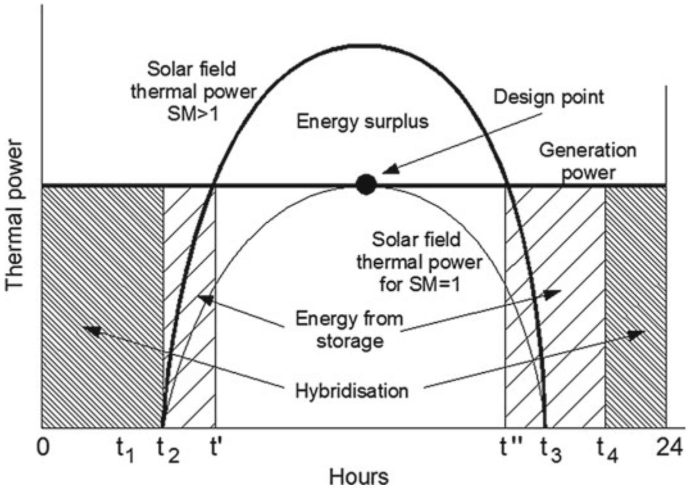


Fig. 4.7 Design point, solar multiple, storage, and hybridization. *Source* Own elaboration

capacity and grids, the first step of project developers of a new CSP plant, within the regulatory framework, is to set the electricity capacity, that is, the nominal capacity of the power block. These data are essential for the later design of the solar field and the rest of auxiliary systems of the plant.

The goal is to adjust the thermal capacity of the solar field to the thermal needs of the power block, with the aim to sustain its electricity generation capacity. However, the thermal energy delivered by the solar field is not constant, and there are hours (and even days, depending on the latitude), in which this can be lower than the required thermal power of the turbine. In other moments, the volume of thermal energy exceeds the needs of the power block. In order to solve this mismatch, a first step is to calculate the so-called design point or operating point under steady-state conditions, that is, the size of the solar field which delivers a sufficient amount of thermal energy to run the power block. Figure 4.7 (based on Palenzuela et al. [56: 106]) illustrates this discussion.[7]

The design point is obtained by considering a wide array of factors, including the following for a parabolic trough: the orientation of the axis of the collectors, the geographical location of the plant, with a special attention on the irradiation and climate of the place, the incidence angle of the direct solar irradiation on the collectors, the difference of the temperature of the HTF when it enters and leaves the solar field, the type of collector, and the type of working fluid and its optical and thermal losses, respectively [56: 92–106]. All this has to be adjusted to the incident irradiation in a given moment of the year, for example, the one corresponding to the summer solstice at noon. With all this, the size and technical features of the solar

---

[7] The asymmetry of the figure is worth noting: The energy stored is higher in the afternoon than in the morning.

field which allow meeting the thermal power required by the generation system are obtained. This is the so-called solar multiple (SM) which takes the value of 1 (in Fig. 4.7 SM = 1 curve).

Generically, the SM is the existing relationship between the nominal thermal power collected by the solar field and the surface necessary for the turbine to work at its rated power or, also, its needs of thermal input [7: 682, 25: 14, 29: 6215]. Therefore, according to expression (4.1),

$$SM = \frac{\psi \cdot S}{\Lambda_{\mathrm{th}} \cdot H} = \frac{\omega}{\varepsilon} \cdot L$$

The SM is closely related to the capacity factor. If SM increases, the capacity factor will also increase, taking into account that the level of energy losses of the plant and the thermal energy/electricity conversion factor do not change.

In Fig. 4.2, the thermal power corresponding to SM = 1 is only the starting point in order to expand the size of the solar field. SM = 1 corresponds to the sizing of the solar field so that, then, it is enough to replicate the technical unit, thus obtained in order to meet the thermal requirements of the power block only by using the energy from the solar field, during the annual number of hours which the managers of the plant deem appropriate (see the SM > 1 curve of Fig. 4.7). This resizing of the solar field allows meeting the thermal requirements of the power block during the daytime hours. This barely changes if the plant is in the appropriate latitudes (see Chap. 1). Otherwise, the seasonal variations in the solar irradiation need to be carefully considered and offset through other ways to generate steam. Setting a SM > 1, however, leads to an excess of thermal energy in the middle hours of the day, as shown in Fig. 4.7. Since the alternative to change the focus of some collectors does not have economic sense, another solution will have to be looked for.

The value of SM is between 1.1 and 1.5 in plants without heat storage or hybridization. In this case, all the energy captured by the solar field is transformed to electricity although, as it is obvious, this may lead to periods in which the turbine/generator operates below its nominal capacity. The activity of the plant will be null at night and cloudy days. The economic efficiency of the generation process is, thus, seriously jeopardized. In order to improve the capacity factor, the excess heat provided by the solar field, that is, the volume of thermal energy which is above the needs of the power block, can be stored and converted into steam at night hours. With an SM which has values in the range between 2 and 4, the plant is close to its objective to operate at its rated power the maximum number of hours in a day and the maximum number of days in a year. The surplus of thermal energy provided by the solar field is not a problem, but rather the opposite is true: It allows increasing the capacity factor and, then, the economic efficiency of the plant. The fact that storing heat is relatively cheap (compared to storing the electricity directly) allows spreading out the size of the solar field, despite the additional investment that it requires,[8] since it

---

[8] As it is obvious, increasing the SM value also increases the land area required by the plant. If a plant is located in an arid zone, then this aspect is irrelevant.

is offset by the greater capacity factor [72: 8–11]. The storage achieved by adding solar fields with a size of SM = 1 avoids having to change the focus of the collectors in case of surplus. It also allows extending the hours of electricity generation since there is sufficient thermal energy. If storing heat had been an expensive operation, CSP generation would never have taken off, as warned by some of its pioneers (see Sect. 3.1).[9]

In reality, the process of adjustment of the size of the solar field, the capacity of the power block, and the hours of storage are carried out through simulations whose output is the cost of the MWh generated by the plant. The accumulated experience suggests that, as a general rule, the optimal values for the SM are between 2.5 and 3, both for parabolic trough plants and for solar towers, whereas the hours of thermal storage are usually 4, 8, 12, or 16 h. The greater the number of hours of TES which are added to the indicated SM values, the lower is the LCOE, although the advantage from 8/10 h of storage is negligible [50, 51: 62]. On the other hand, the capacity factor increases with the value of SM and the hours of storage, although proportionally less with a higher number of hours of storage. This result clashes with the increase of the investment that the heat tanks involve. At the start of the current decade, the simulations carried out indicated that, in the case of parabolic trough plants, the lowest costs (i.e., €cts 16/kWh) were associated with a multiple of 2.5 and 8 h of storage. For solar towers, the SM has a secondary role, however. The lowest cost (€cts 10/kWh) corresponds to the combination of SM = 4 and 16 h of storage, although for SM = 2.5 and 8 h of storage, the cost of the MWh only increased by 1 €cent. It should be noted that, in principle, the solar towers had costs of the MWh which were comparatively lower than those of the parabolic trough plants, whatever the number of storage hours (see Izquierdo et al. [29: 6219–6221], Jorgenson et al. [31, 32], Mehos et al. [45]).

Figure 4.7 also shows that the storage capacity, measured as hours of operation of the power block at its nominal power, does not have to be used in a continuous manner. Thus, it has been assumed in the figure that, after sunset, the plant uses the heat accumulated during the day, a fact which allows it to meet the likely high electricity demand at sunsets. Notwithstanding, when the night advances, and assuming a limited storage capacity, the plant uses generation by hybridization (with its alternative being to stop its activity of the power block). At dawn, the stored heat is used again in order to guarantee a normal operation of the power block, while the DNI increases as the sun goes up in the sky. It should not be forgotten that the losses of the tanks are negligible and, thus, the suggested time distribution of use is perfectly possible. Finally, when the quantity of heat collected in the solar field exceeds the capacity of the thermodynamic cycle, part of the fluid is deviated to the TES, where it is stored until sunset. It has been assumed that after both lapses of activity from the storage (the one at sunset and the first daytime hours), its capacity has gone down

---

[9] The positive economic effect of storing heat was taken into account at the start of the twentieth century (see Chap. 3). It was clear at the end of the past decade that the increase in the investment per installed MW, related to the increase in the fraction of solar in generation, would lead to higher capacity factors and, then, to a gradual reduction in generation costs [76: 125].

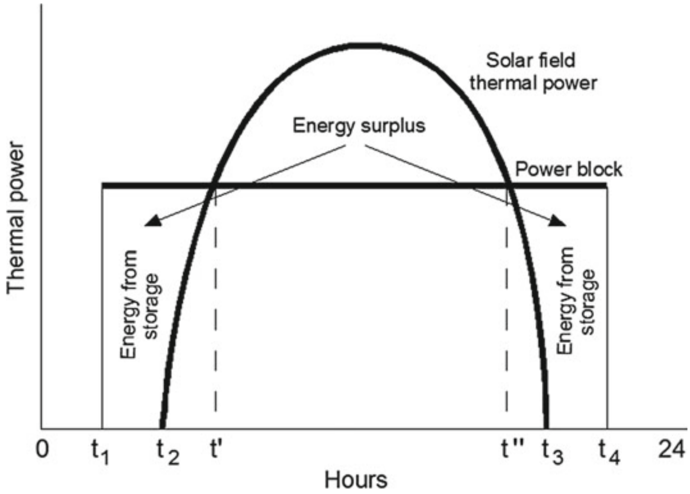


Fig. 4.8 Thermal energy surplus in daily central hours of the day. *Source* Own elaboration

to the minimum level, and thus the surplus which is accumulated will allow a new activity cycle.

It should be mentioned that the analysis carried out so far does not contain any assumption about the use of the plant. This use is associated with the desired time lapse of the activity. Let us start from Fig. 4.8, which represents an already known situation: There is an interval of daytime hours $[t', t'']$ in which the solar field provides more thermal energy than needed by the power block. This surplus is stored in order to be able to generate electricity when there is not any solar light, i.e., in the intervals $[t_3, t_4]$ and $[t_1, t_2]$ or, which is more common, adding to these intervals those in which the irradiation being captured is not enough anymore to feed the turbine, that is, $[t''$, $t_4]$ and $[t_1, t']$. This regime of operation does not rely on hybridization, as shown in the figure.

However, the case shown in Fig. 4.9, albeit opposite to the previous situation, could also occur since it makes economic sense. There could be a plant whose only objective is to cover the electricity demand in hours with high consumption, that is, at midday in hot days. Therefore, the heat produced is stored in the first and last hours of the day in order to reinforce electricity generation at times of peak demand. In this case, the thermal needs of the power block are above the maximum direct thermal contribution of the solar field. In order to avoid an oversized generator with respect to the solar field, the heat produced in off-peak hours is stored. Of course, a careful calculation has been required in order to adjust the surplus and deficit of thermal energy. As it is obvious, the profitability of this design assumes a high price of electricity in the midday hours (demand peak load) [25: 14–15]. It all seems to indicate, however, that this possibility has vanished due to the competition with photovoltaic generation.

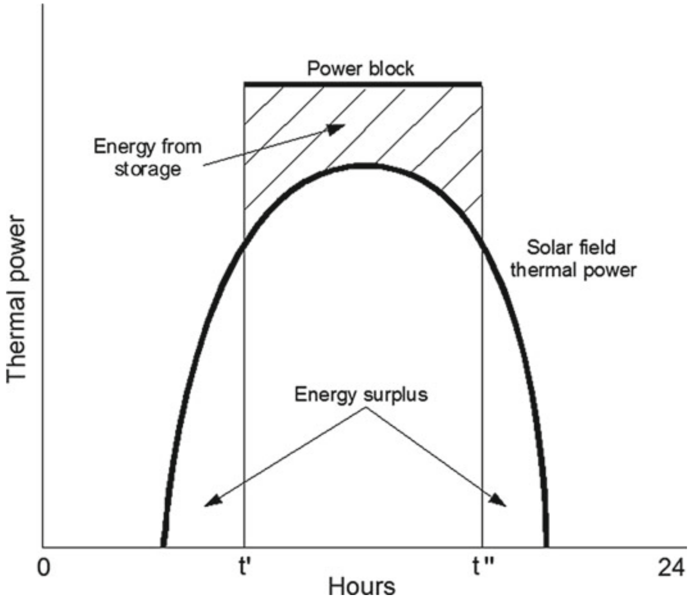


Fig. 4.9 Thermal energy deficit in the central hours of the day. *Source* Own elaboration

Therefore, the production of a CSP plant is governed by the SM. The higher the value of the solar multiple, the higher is the capacity factor. However, this implies a higher investment and availability of land (a possible limiting factor, which is much less relevant in arid zones with even land). Fortunately, the heat captured by the solar field which is above the needs of the power block can be stored at a reasonable investment cost and a low operation cost, with negligible losses. Therefore, the number of hours of operation of the power block can be extended, which distributes the weight of the investments among a much larger number of MWh. In reality, this offsets the problem of having installed a disproportionate solar field and the TES (which will feed the power block beyond the daytime hours). Thus, with 8 h of storage or more, the capacity factor may reach values above 60% [28: 84], which doubles the capacity factor without storage.[10] The result is a lower-generation cost per MWh. Some studies carried out in the past show that this cost progressively goes down with the increase in the SM and the storage hours until a minimum stretch is reached, which is very similar for slightly different plant configurations [29]. Obviously, technological changes as well as economic incentives can lower the generation cost even further. Indeed, the other variable which affects the economic performance of a plant is the advantage and requirement provided by regulation. Energy policy and its implementation can set up preferential tariffs, tenders, fiscal incentives and subsidies, limits to hybridization, etc (see Chap. 6).

---

[10] Hybridization is the alternative. However, it is subject to the evolution of the prices of the fuels being used.

4.2.2 Economic Analysis

Without losing sight of the considerations made in the previous section, the total annual cost (C_t) of electricity generation by a CSP plant in a given year can be expressed as follows

$$C_t = \left(I + I^F + I^S + I^Y\right)\frac{i(1+i)^T}{(1+i)^T - 1} + \overline{W} + \Lambda m_t + \langle \Lambda H f p\rangle^Y$$

where

I	refers to the investment for the purchase and installation of fixed fund elements of the process,[11] such as the power block, the tower (in case of a plant with a central receiver) and the buildings, and auxiliary equipments, expressed in monetary units (€, $, etc.).
I^S, I^F, and I^Y	represent the investment in the TES equipment, the solar field, and the hybridization system, respectively, expressed in monetary units.
$\overline{W}$	represents the annual payments for the services, or wages, of the human work fund involved in the control of the generation process.
m_t	is the annual O&M costs, expressed in monetary units per MW.
T	refers to the operational lifetime of the plant which, for the sake of simplicity, is assumed equal for its different equipments and systems.
I	is the interest rate applied in calculating the depreciation annuities.

As it can be observed, the investments in the solar field (trough rows, heliostats, or dish), in the TES, and in the hybridization systems (adding the equipment purchase and the setting up operations) are considered isolated from each other due to their particularities. The expenditures incurred in the elaboration and administrative processing of the project have also been added to the amount of investment. With respect to the annual wages, they probably are a comparatively small amount. Regarding O&M costs, it is assumed for simplicity reasons that they include the annual costs of the different flows needed for solar generation, such as the lubricants and spare parts. The term on the extreme right represents hybridization: the annual MWh which is generated by consuming natural gas (f^Y per MWh) at a price p^Y. Finally, the cost of purchase or hiring of the land has been ignored in the expression, and it also leaves aside the possible incentives in the form of subsidies, fiscal reductions, etc.

If C_t is divided by q, the cost per MWh$_{\text{AC}}$ is obtained (€/MWh$_{\text{AC}}$). It should be indicated that part of q, or electricity generated in a year by the plant, is produced but not sold; i.e., it is self-consumed.

The different components of the equation of the cost have a very different weight. For illustrative purposes, if a 95% of efficiency in the thermal storage, an interest rate of 9%, and a useful lifetime of the plant of 25 years are assumed, the values of the

---

[11] For the definition on the fund and flow elements in a production process, see Mir-Artigues and González-Calvet [48].

Table 4.2 Economic magnitudes (2005[a])

Variable	Unity	Parabolic trough	Solar tower
I	€/W	1.37	2.05
I^S	€/kWh	90	40
I^F	€/m^2 collector	213	150
m_t	€/kWh/year	0.12	0.146

[a] Yearly average value 2005: €1 = $1.24

Table 4.3 Economic magnitudes (2015)

Variable	Unity	Parabolic trough	Solar tower
I	€/W	0.87	1.45
I^S	€/kWh	69	28
I^F	€/m^2 collector	200	144
m_t	€/kWh/year	0.02–0.03	0.03–0.04

Source Own elaboration from Mehos et al. [44: 31–32] and IRENA [28: 8], and experts' advice provided to the authors

main variables, for the year 2005, would be those indicated in Table 4.2 (as shown in Izquierdo et al. [29: 6217]).

On the other hand, Table 4.3 shows more recent data.

In addition to the generally observed reduction, the interpretation of the numbers in both tables should take into account that they do not correspond to a specific plant. They only represent indicative values.

If the data presented are extended, a possible detailed disaggregation of the investment in a parabolic trough plant (based on Stoddard et al. [10: 22, 74: 5–5]) can be as follows:

- Around 50% is accounted by the solar field, with at least half of this percentage corresponding to the mirror support structured and the mounting. The absorption tubes as well as the HTF storage tanks also stand out.
- The power block itself does not reach 10%, although if control and firefighting system installations are added, the percentage can increase to between 10 and 15%.
- The storage system (tanks and heat exchangers) represents about 20%.
- The electricity installations represent between 5 and 10%.
- The rest of the investment corresponds to civil works, engineering, and administrative processing.

In the case of a solar tower, the numbers are similar, with the logical exception of the heliostats, which represent more than 1/3 of the total investment, and the central receiver (more than 10% of the total). Therefore, for both technologies, the cost of the solar field, the storage systems, and the power block is above 4/5 of the total investment.

Regarding O&M costs, Stoddard et al. [74: 5–5] indicate that labor (32%), repairs, and spare parts of the solar field (28%) and the rest of systems of the plant (10%) stand out.

Table 4.4 Efficiency criteria for CSP plants (2010 and 2015)

Collector type and turbine	Sun concentration, and peak and annual solar efficiency	kWh/year per m^2 of occupied land	Thermal cycle efficiency (%)	Annual solar-to-electricity conversion (%)		Capacity factor (no TES)
				2010[a]	2015[a]	
Trough, steam turbine	80, 21%, 17–18%	45–55	30–40	11–16	15–16	~25%
Tower, steam turbine	300–1000, 35%, 25%	70–90	30–40	12–16	15–17	
Tower, combined cycle			45–55	20–25	–	
Fresnel, steam turbine	25–100, 20%, 12%	50–60	30–40	8–12	8–10	
Dish	1000–3000, 30%, 24%	80–100	30–40	15–25	–	

[a] Year in which data were published

Regarding the evolution of the amount of investment, a 100 MW plant in 2008 required about 4900 $/kW of investment [58: 44]. This number was expected to increase in the short term, both for parabolic trough and for solar towers, due to the addition of TES with gradually more storage hours. However, given a capacity of the TES of 14 h, some projections indicated a reduction in costs to a minimum of $3000/kW for the decade of 2030 [14: 10-25/10-28].[12]

As a complement to the tables above, Table 4.4 shows the values of the efficiency indicators which are most common for thermo-solar plants. Those indicators have been:

- Sun concentration and the peak and annual solar efficiency.
- The electricity generated by the surface occupied by the plant and the collectors.
- The relationship between the direct irradiation captured by the collectors and the electricity generated by the plant, or solar-to-electricity efficiency, per unit of time (a year, for example).

Given its capacity to concentrate the sun rays, the dish/stirling and the solar tower stand out, although the greatest land-use requirements correspond to the Fresnel technology [7]. A solar tower generates less electricity per unit of land due to the large quantity of land required by a field of heliostats. However, these plants have a more homogenous generation profile throughout the year, since the heliostats are

---

[12] In this section, data on the LCOE (MWh) are not included. See Chap. 3 and [28].

always perfectly oriented to the sun and their annual solar efficiency is the highest. Whereas the capacity factor is very similar for all the plants, the values of thermal efficiency as well as the solar-to-electricity conversion factor are quite different. In this last case, the table shows the values for the end of the past decade and the middle of the present decade [2: 1009, 1012 and 1017].

4.3 The Values of Concentrating Solar Power Electricity Generation in a Changing Electricity System

The main impacts of CSP electricity on the current social, economic, and energy context have to be systematized. Therefore, first, the stages of the transformation of the electricity sector due to the progressive penetration of renewable electricity sources are described in a stylized manner. Then, the role of CSP generation is placed in such a context. Whereas the first issue is analyzed for the first time, the second one follows and expands the systematization proposed by Mir-Artigues and del Río [47: 113–152].

The goal of this section is, thus, to identify the main role of CSP generation in the different stages of the structural change of the electricity sector. In other words, the aim is to determine the value of CSP generation, which is understood as its contribution to the success of the energy transition, that is, to the evolution toward an electricity system with a dominant role of renewable energy sources. This contribution results from the combination of technical, economic, and social features which are ideal to encourage such change, as well as features whose effects hinder it and which should be mitigated in one way or another. Given that, at least today, four renewable energy technologies (wind power, PV, CSP, and biomass plants) compete to be the main agent of this transition, the next pages, which discuss the pros and cons of one of them (CSP), provide only a generic diagnostic. Therefore, it is not directly applicable to specific national electricity systems given their different electricity generation mix and particular socioeconomic requirements.

4.3.1 A Stylized Model of Structural Change of the Electricity Sector

A key economic objective of renewable electricity support is to create the conditions to reduce the cost of generation (€/MWh) to levels comparable with conventional energy sources in a reasonable time span. This is an economic requirement in order to advance toward the greatest possible decarbonization of the electricity sector. Reaching a sustainable electricity sector is, however, a complex process [17: 1175–1201, 62, 73]. This entails a long transition in which the generation mix gradually changes, new roles for T&D networks appear, new markets emerge, etc. All these happens at the same time electricity demand and stability and reliability of the electricity system are guaranteed.

A stylized model related to the structural change process [59] which is being experienced by the electricity sector is provided. This process has been divided into four stages, as shown in Fig. 4.10. This is a representation of the behavior of the main economic variables involved in the transition from an electricity generation mix dominated by technologies which emit GHG (use of hydrocarbons and coal as fuels) and nuclear generation rejected in many places due to the risks that it entails, to a mix in which renewable energy sources and, among them CSP, dominate. Obviously, the figure represents only a hypothetical conceptual framework. Its objective is to highlight the alleged evolution of costs and prices over time. In this sense, it should be taken into account that

- The figure does not have a timescale. The lapse of time covered by each stage includes a very different number of years depending on the country or region, whereas the whole process can be extended for decades.
- The factors determining the relative positions of the economic variables which have been considered are more relevant than the trajectories of those variables.
- The transition process entails gradual changes in the generation mix and, thus, the concomitant adjustment of T&D grids. Each country would represent a particular case because of the historical path being followed, but also due to the presence of the cheap primary sources in such country. This is not considered in this model: The proposed framework only pays attention to the consequences of those changes on costs and prices.
- The economic values are expressed in real terms.
- The configuration of the later stages to the present moment, that is, the end of the second stage onward, is merely speculative. The figure does not aim to be a prediction: The lines corresponding to the last two stages of the structural change process reflect the predominant expectation, although not unanimous, among the experts. There is a great uncertainty in the analysis.

To start with, p denotes the preferential tariff (whether a feed-in tariff, premium, or green certificate), c is the cost of renewable energy generation (whose rate of reduction has been assumed gradual), e is the retail price of electricity (taking into account that, although not all consumers pay the same amount per kWh, the tariffs move in tandem, i.e., they share a trend), and w represents the wholesale market price of electricity. Secondly, there are two prominent positions in Fig. 4.10:

- The points called *rpg*, which indicates the retail grid parity, and *wsg* which indicates wholesale price parity. Although they have been represented as points, they are really regions, since parity depends on many factors, some of them being idiosyncratic [47: 109–113]. It should be taken into account that not all renewable technologies achieve those parities at the same time. Obviously, if any accumulates a severe delay, its diffusion possibilities are negatively affected. However, they are not removed since there are many more factors at play than costs. In principle, however, the technologies which are deployed earlier have a greater chance to

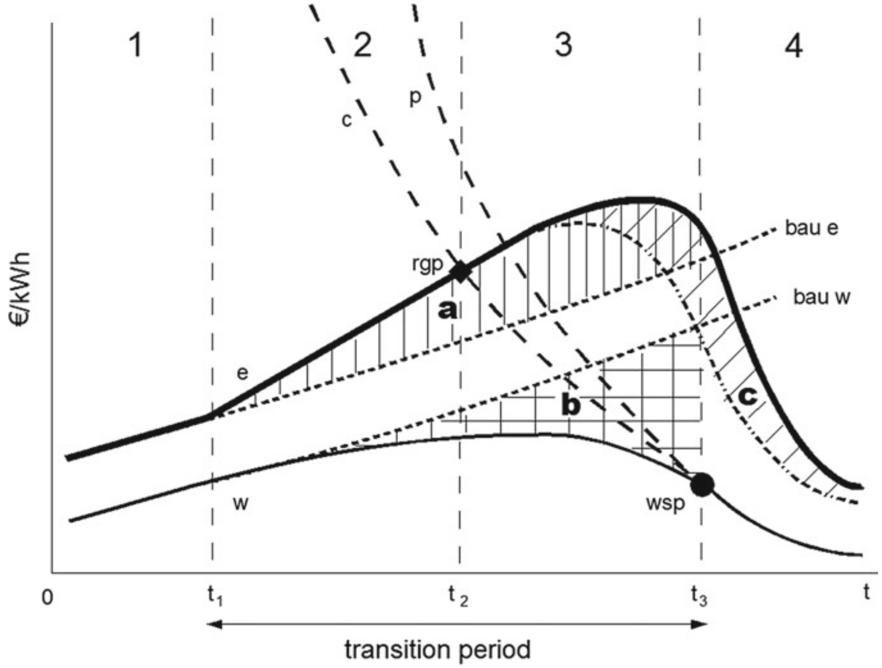


Fig. 4.10 Stylized stages of the energy transition process. *Source* Own elaboration

become dominant. It can be observed that line *p* is high above the cost line *c* up to the point *rgp*. Then, they tend to converge (which occurs in *wsp*). The reason for this behavior is that, with the gradual reduction in the costs of the renewable energy technologies, many regulations abandon the preferential prices (as well as other advantages). A premium is implemented which, when deemed necessary, is added to the wholesale electricity price. Indeed, the amount of the premium goes down (year after year, for example) given the reduction in the aforementioned costs, although there might be time spans in which the wholesale electricity prices are too low for renewable energy producers. At a certain moment, the premium will no longer be needed. Since then, the market prices already guarantee a profit.

- The shadowed zones *a*, *b*, and *c* represent, respectively, the additional increase of retail prices which is needed in order to finance the renewable promotion policy, the downward pressure of average wholesale prices due to the zero price at which renewables are offered, and the costs of providing backup to an electricity system with a strong presence of variable renewable energy sources (see below).

The upper solid line represents the hypothetical trend of the retail or final electricity price: The promotion of renewable energy sources leads to an increase above their historical trend in the case that the generation mix keeps on being only a conventional one. The circumstance that we would like to describe is that, even if a sustained increase in the price of uranium (the nuclear fuel) and hydrocarbons is assumed (including the impact of an eventual carbon tax on them), the financing needs of renewable sources, which initially have a very high generation cost, put further upward pressure on retail prices.

The consumers are the ones who bear the costs of the promotion scheme, although the regulation may distribute the costs in an unequal manner.[13] The magnitude of the increase experienced by electricity prices depends on the calculation of the remuneration and the trend in generation costs [11]. This is a problem that, with a high probability, will not affect those countries which promote renewables later on.

The solid but thinner line below indicates the particular trajectory of the wholesale electricity price with an increasing penetration of renewable electricity in the market. Since this electricity enters at a zero price in the market, the number of conventional plants which offer a higher price and, thus, are displaced increases. This impact on the merit order is greater than the amount of renewable energy that enters the market. Therefore, the trend of the wholesale electricity price gradually diverges from the trend which it would have followed without such penetration.

The displacement of conventional electricity generation plants accelerates if the costs of renewable energy technologies keep on going down. In the point noted as *wsp*, renewable energy sources with no premium start to be competitive in the wholesale electricity market.[14] At the end, the expectation is that wholesale electricity prices go down, which then ends up driving down the retail prices (FITs and FIPs fell behind), even taking into account the expenditures of backup generation (whether conventional or renewable[15]) and the financing needs of the grids.

The following subsection provides more details on the four stages of the structural change of the electricity sector shown in Fig. 4.10.

4.3.1.1 The Electricity Sector Is Still Conventional

In the initial stage, lapse $(0, t_1)$, there are only conventional electricity generation plants. These are huge hydro plants, as well as thermal plants which burn fossil fuels or nuclear plants which have large economies of scale. There is a complex T&D network which brings the electricity to the final consumers, whose role is merely passive. In many countries, after World War II, the electricity sector was dominated by a large vertically integrated public company although, in other countries, a reduced number of private companies kept operating. However, in the last quarter of the twentieth

---

[13] In case it is budget-financed, the analysis does not substantially change because the set of taxpayers and consumers coincide, given that electricity is a basic good in the sense of Sraffa [37].

[14] Furthermore, in addition to the displacement of the more expensive techniques, there might be a lower demand volume. This is due to two reasons: the modular character of renewable energy techniques, such as PV and mini-wind, which would allow the massive diffusion of prosumers (who may have storage systems [70], and efficiency and energy-saving policies, which would have an impact on such demand.

[15] Renewable energy dispatchable plants include biomass and solar thermal plants, although variable plants may participate in the intraday and balancing market, as well as in ancillary services. The electricity storage systems at scale and low cost will eventually reduce the required backup capacity.

century, liberalization processes were promoted, together with other privatization and concentration processes which led to generalized oligopolies, with different particularities depending on the country (see [18]). Simultaneously, agencies for the regulation of the electricity sector were created or encouraged.

In this stage, the discontinuous lines *bau e* and *bau w* start. They represent, respectively, the business-as-usual trends of final and wholesale electricity prices. It is assumed that both have an upward trend due to the impact of the increasing prices of hydrocarbons and the nuclear fuel, in a context in which neither renewable technologies nor the policies, which support them, are present. These trajectories reflect the gradual exhaustion of those primary energy sources,[16] although they are also related to the difficulty to exploit economies of scale in conventional electricity generation [42: 11–37]. Although some innovations, such as the ones which have improved crude oil extraction in bituminous sands or fracking, have allowed the exploitation of previously inaccessible wells, they have also delayed the concern about the scarcity of hydrocarbons (never an issue in the case of coal) but they have not stopped the concern about climate change [24]. The pressures from vested interests and/or the institutional inertia have not stopped the idea that it is necessary to advance toward a different energy model for environmental reasons.[17] The energy transition starts, aside from the prices of conventional fuels.

4.3.1.2 First Stage of the Transition Period

The change of the electricity sector starts in the period (t_1, t_2). In the beginning, the measures to promote renewable energy sources for electricity generation are shy and, thus, their presence of these sources in the system is rather residual, although they gradually increase. In historical terms, this stage started in the last third of the last century: first between the mid-1970s and the 1980s in USA as the main pioneer and, then, since the 1990s with Germany and Japan as leaders. Initially, the concern about the exhaustion of fossil fuels dominated. Then, climate change became a major concern.

Initially, some were reluctant on the need to support renewable energy technologies. In addition, the choice of the most suitable promotion scheme and its detailed design were issues solved through the essay and error method. A key decision had to be taken: whether to support investment paying preferential prices for the kWh (demand-pull option) or support the supply side by favoring the RD&D expenditures (or technology-push option). The dilemma was solved by simultaneously activating both options [54], although pioneer countries focused more on one or the other. In fact, the debate on the need to prioritize either of the two options and, also, about the specific type of demand-pull measure to implement was alive throughout the period.

---

[16] In some countries, this is aggravated by the dependency on third parties, since it may involve supply problems due to political reasons.

[17] For this reason, the argument does not change if the *bau e* and *bau w* curves are assumed to be horizontal or slightly declining.

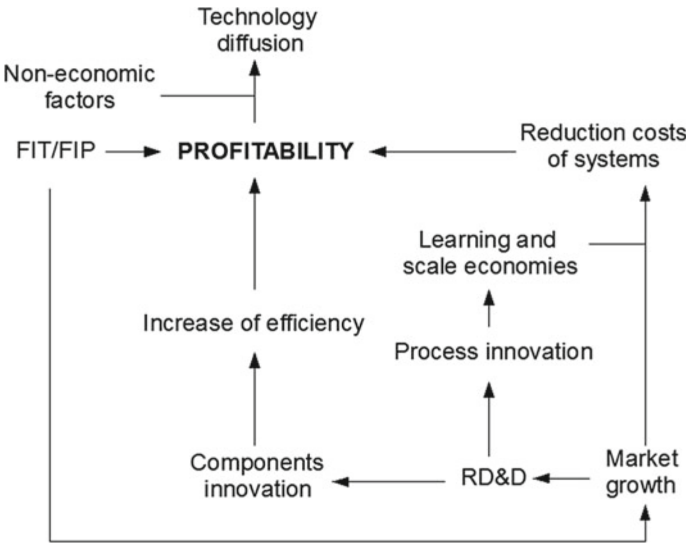


Fig. 4.11 Economic rationale for supporting renewables. *Source* Own elaboration

Both measures were arranged within a given economic rationale, whose representation is illustrated in Fig. 4.11.

The proposed scheme shows the connection between the variables which, presumably, would guarantee the growing diffusion of the renewable energy technologies by lowering the generation costs. The interpretation of the figure may start from the technical and scientific knowledge accumulated after World War II and, specially, between the 1970s and the first half of the 1980s, although its roots go back to the nineteenth century, as it is the case with wind, PV, and CSP ([47, 52]: Chap. 3 and Sect. 3.1 of this book). The knowledge accumulated in RD&D activities encourages improvements in the efficiency of components (solar collectors, cells and modules, rotors, power blocks, and so on)[18] and process (directed to reduce the manufacturing costs of the different components). Furthermore, they encourage the adaptation of innovations from other fields (or spillovers). However, renewable energy technologies are initially very far from the competitiveness frontier; that is, their generation costs are high above the wholesale electricity prices (as well as the final prices of the kWh). This huge distance discourages investments and, thus, the diffusion of the new technologies and the improvements which are incorporated in those investments, even if there might be people who are enthusiastic about renewables for reasons beyond the purely economic ones.

In order to achieve the diffusion of the new-generation technologies, their profitability expectations need to be reinforced. At this point, through FITs or FIPs

---

[18] These innovations are so-called product innovation in the literature on industry life cycles [34, 78]. For reasons of simplicity, the innovations in the design of systems and subsystems have been included in this concept.

(together with other common incentives in the regulation of the electricity sector), the recovery of the investments in renewable energy plants is guaranteed (plus a profit margin) despite their comparatively higher costs. This reinforces the demand for equipment, which encourages the opening of manufacturing plants with a greater capacity of production per unit of time, which leads to economies of scale and experience. It also facilitates the incorporation of technical advances in the laboratory and the design offices. As mentioned above, the objective is to boost the downward trend of equipment prices and, thus, the cost of renewable energy generation.

However, the causal chain described in Fig. 4.11 contains many links in which the connection can break up. It should also be taken into account that there are many factors and collateral effects. Thus, an excessively expansive conjuncture may lead to the scarcity of some inputs, leading to an increase in its price and, thus, an increase in the cost of the energy generated. This occurred with polysilicon between 2004 and 2008. An excessive support also encourages speculation. It is not only about generating with renewables, but to gain money easily and fast with the sale and purchase of administrative authorizations and connection points. Investment booms regarding renewables in several European countries encouraged these practices. If the figure is analyzed from the perspective of RD&D, the results are reached slowly and, this, together with the uncertainty that accompanies all innovation efforts, may lead to the cancelation of programs [69: 53–88]. Thus, the promising research lines may be frustrated or the tuning of new manufacturing technologies may be delayed. It should not be forgotten that a technical achievement does not involve a commercially attractive design [53: 28]. There are many unforeseen combinations of factors which may delay the adoption of technological novelties [64, 63].

In this stage, the authorities of the leading countries favor technological diversity, given the availability of primary energy sources. RD&D centers and their programs and projects tend to cover many technological alternatives, irrespective of their progressive degree of maturity or distance with respect to the desired point of market launch [83: 34–35]. Notwithstanding, the most promising options are prioritized, especially if they exploit the most accessible resource(s) in the country. CSP is among them if there is a high DNI.

In order to understand RD&D policy for renewables, the following segmentation of the innovation process is illustrative[19]:

- Basic and applied research covers a wide range of this process: from the idea that some physical and chemical properties exploited, to the preliminary definition of a specific design, especially if the results from the laboratory are encouraging. Organic photovoltaic cells with graphene are currently in this stage.
- The development of the operative capacities of the system consists of the gradual improvement of the prototypes for a satisfactory operation, a guarantee of reliability, and reasonable expectations of costs. Parabolic trough plants with steam as a thermal fluid are an example.

---

[19] Own adaptation from Daim et al. [8], Grupp [20], Weiss and Bonvillian [83], and disregarding, for the sake of simplicity, the different feedbacks that exist between the different stages.

- The stage of demonstration is decisive from a technical point of view. This is the technology launch or introduction, although not the commercial deployment, of the new technologies. The installations, whose performance under real operation conditions is subjected to an intensive checking, are eventually connected to the electricity system. In this stage, the interest for the innovation in the manufacturing process accelerates.
- Precommercial diffusion refers to the connection to the electricity distribution grid of the first commercial plants. Its routine operation regime does not hide that its generation cost is not competitive yet. Demand-pull measures are useful here. The magnitude of the support in this precommercial stage depends on the urgency with which society perceives the convenience to deploy the new technologies. Although utilities can invest in renewable plants, firms from outside the traditional electricity sector normally lead the new-generation sector. CSP technology would have been placed in this stage until very recent times.
- Fully commercial. The ordinary regime for the exploitation of the plants, i.e., according to the conditions of the wholesale electricity market, is already profitable. There might be secondary improvements in this stage. The installations will be retired due to obsolescence or functional reasons. The diffusion leads to the replacement of existing plants by the new improved ones.

The low maturity of renewable energy technologies requires extending the public support beyond the basic and applied research stage, as we have tried to represent in the upper part of Fig. 4.12. The high risk of failure has been represented with a curve that does not follow the standard trajectory (thin line) but an upper one (thick line). The risk of failure in the stages of development and demonstration is so high that it discourages the massive arrival of private funds. In fact, until the end of the innovation cycle, the risk of failure is not reduced significantly. There are even serious doubts regarding its economic viability in the demonstration stage. Therefore, commercial diffusion requires demand-pull policies.[20] This is known since the 1940s in the realm of RD&D for defense and nuclear energy for civil uses.

The lower part of Fig. 4.12 shows that the provision of public funds is high in all the stages of the innovation process ([43]: Chaps. 6 and 7). This high and persistent provision of public funds for electricity generation technologies is justified in order to guarantee the security of supply and to mitigate climate change. Nuclear generation was prioritized according to the first argument, and the second argument was added later on.

The analysis of the features of demand-pull policies and instruments has to be added to the issue of the particularities of RD&D for renewable electricity. See Table 4.5. This would complete the view of the first stage of the process of the electricity transition.

The specific choice of an instrument by one country or region is related to ideological aspects, scenario analysis, the imitation of the experience of others, etc.

---

[20] The accumulated cost curve has a secondary role. Whatever is the public–private mix of support to a given RD&D project, its cost accumulates fast after the development stage.

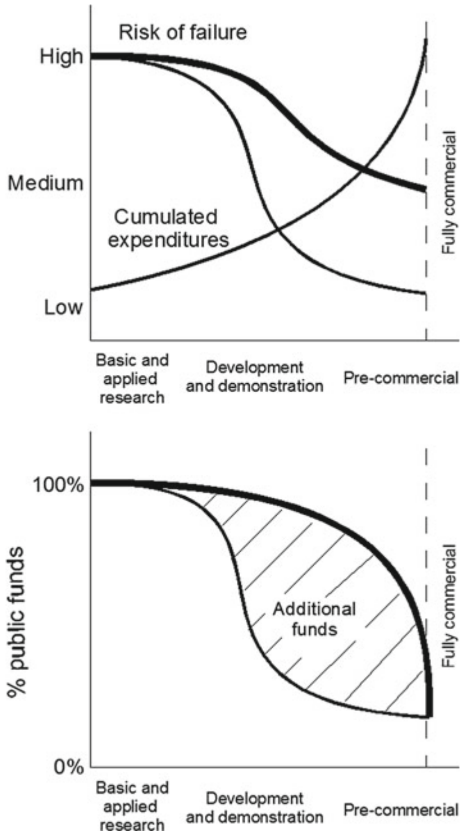


Fig. 4.12 RD&D stages and support for renewable energy technologies. *Source* Own elaboration

Table 4.5 Demand-pull policies and tools

Support mechanism	Main tool	Some features
Production-based (per kWh generated)	Feed-in tariff	Unforeseeable systemic rate
		Constant (for a given time)
		Decreasing at different rates
	Premium	Fixed
		Sliding
	Tradable green certificates	Different market conditions and production goals
Capacity-based (per kW installed)	Several reference plants and criteria for setting up the support amount according to a given variable (normally investment amount and/or operation costs)	

Source Own elaboration

Additionally, legal changes are also needed in order to facilitate the access of renewable energy plants to the grids and the access of its output to the wholesale market. Consumers are the ones finally paying for the policy, which is not a concern as long as the installed capacity is small.

The greatest challenge of demand-pull measures is to appropriately adjust the remuneration level to the reductions in the cost of equipments. This would avoid speculative booms, thus taking measures later which involve a sudden stop of the expectations of the sector. However, this is not an easy task. Not all the regulators are able to achieve a precise adjustment between both variables. Deviations may lead to ex-post cuts in the promised remuneration, which are interpreted as retroactive by those being affected by them. This may lead to lawsuits in the national courts and international organizations.

The impact of demand-pull policies can be easily modeled. The net cost of the promotion policy (V_T) is related to the capacity which is being accumulated over time, the dynamics of the tariff which is initially paid to investors in renewable energy plants, the annual updating of the tariff while the plant is active, and the evolution of the wholesale electricity price. With the aim to obtain a simple expression of such amount of costs, let us consider the following notation and simplifying assumptions:

- There is only a single renewable energy source, whose efficiency is constant.
- It is assumed that the amount of renewable electricity which is added every year is constant ($q_0 = q_t = \overline{q}$).
- The wholesale electricity price (w_t) goes down at a constant rate ρ (see below) so that $w_t = w_0(1 + \rho)^t$, con $-\infty < \rho < \infty$.
- δ represents the annual rate of reduction in the preferential tariff. This reduction allows its adaptation to the reduction of generation costs (to simplify, it is assumed constant), whereas ϕ is the annual increase, for plants in operation, of the remuneration with which they were initially authorized. O&M grows over time.

Following the analysis carried out in Mir-Artigues and del Río [46: 434], for $t = T$, the promotion costs are equal to the accumulated amount of payments minus the observed reduction in the wholesale price. More specifically,

$$V_T = p_0\overline{q}\frac{(1+\phi)^{T+1}}{\phi+\delta} - w_0(1-\rho)^T$$

The behavior of this expression depends on the changes in the variables $\overline{q}$, ϕ, ρ, and δ. However, it can be demonstrated that the capacity which is added every year is the most relevant factor. In this case, if there is a boom, the resulting financial burden can be a slab for the electricity sector for years and, by extension, for society at large, unless cost-containment measures are taken, although they are never welcomed.

Although at the start of this stage the skepticism dominates and the option for renewables seems a laudable and expensive proactive effort, the fact is that some renewable energy sources, such as wind, PV, or CSP generation, have achieved a considerable degree of competitiveness. Even though the expectations of an increase in the price of traditional fuels have not been achieved, the improvements in the manufacturing processes of the equipments and the learning in their operation methods have been well above those imagined.

At present, it can be stated that many countries have deployed a volume of renewable energy which puts them at the end of this stage. Therefore, the description of the following two stages goes into unknown territory and the last one is a mere conjecture.

4.3.1.3 Second Stage of the Transition Period

The interval (t_2, t_3) in Fig. 4.10 represents the end of the structural change of the electricity sector. In this stage, a sharp reduction in the costs of renewable electricity is experienced and, thus, its presence in the electricity mix ends up being massive. This stage has two opposing trends:

- A maximum of the retail electricity price which is followed by its stagnation (maybe a reduction in some countries). The impact of the pioneering renewable energy plants, whose generation costs were high, reaches its maximum.[21] What to do, then, with the obsolete renewable plants whose lasting financial obligations distort the financing of the electricity system (the reason that the area *a* is extended beyond point *rgp*)? It is likely that controversial cost-containment measures will be implemented to reduce support costs. A better (but difficult to implement measure) is to replace these obsolete plants, which are not fully depreciated yet, with improved ones. Of course, this only affects the pioneering countries and, fortunately, the weight of the obsolete installed capacity is progressively lower.
- The growing presence of renewable electricity which enters the wholesale market at zero prices (since it has been remunerated with regulated prices) widely affects the merit order[22]: The supply curve shifts to the right, which further reinforces the pressure to close the generation plants with a higher cost. However, this effect changes depending on the hourly provision of renewable electricity, especially if it comes from variable renewable sources such as wind and PV. Furthermore, if dispatchable renewable energy sources have a small weight in the generation mix, and there is still not an important storage infrastructure, the variability of renewable electricity generation requires having a backup capacity which is able to face rampings and unexpected events. Maintaining a reserve of backup generation is expensive, and its retribution, which will probably fall on the consumers, is a thorny regulatory issue.

In this stage, the integration of traditional and new-generation sources is an issue of enormous complexity, which every country or region has to solve in a particular

---

[21] The gap between the wholesale and retail prices goes beyond T&D expenditures and other general costs of the electricity system.

[22] A critical explanation of the merit order effect can be found in Mir-Artigues and del Río [47: 143–144].

manner according to its starting mix, the available primary resources, and the weight of variable renewable sources. However, this singularity does not prevent us from drawing the contours of the issue. Let us consider the following notation:

D_p	electricity demand peak
$\overline{D}$	average electricity demand
C	capacity needs of the electric system
μ	margin above demand peak in the conventional fuel generation system, usually 10%.

The required capacity is given by

$$C = D_p(1+\mu), \quad \text{or} \quad C = 3/2\overline{D}(1+\mu)$$

since, in a conventional generation system, it is usually assumed that $\overline{D} = 2/3\ D_p$. It should be added that the average load capacity factor is defined as $\overline{D}$ /C. Therefore, if, for example, $D_p = 100$ GW (or capacity required to generate the flow of electricity which is needed in order to cover peak demand), then $\overline{D} = 67$ GW and $C = 110$ GW. On the other hand, the average load capacity factor is 67/110, that is, 60%.

If it is assumed that this electricity system only has variable renewable sources (for instance, wind and PV), with its capacity factors (L) being $w_L = 0.3$ and $s_L = 0.15$, respectively, and with the renewable capacity (C_R) half wind and half PV, then the renewable average capacity factor ($\overline{L}$) would be 0.5·0.3 + 0.5·0.15 = 0.22. If it is assumed that $C_\mathrm{R} = 50$ GW, then the renewable capacity which, on average, provides electricity to the system is 50 GW · 0.22 = 11 GW. This figure means that 11/67 GW, or a 16.4%, is the electricity which, on average, comes from the renewable energy sources being considered.

According to the previous reflections, the required capacity of the system with the presence of variable renewable sources should be

$$C_C + C_R \cdot \overline{L} = 3/2\overline{D}(1+\mu)$$

where C_C is the manageable conventional capacity ($C > C_\mathrm{C}$). In this way, the presence of electricity from renewable sources necessarily displaces the electricity from conventional plants. However, things are not so simple. Variable renewable energy sources have two important limitations:

- The coincidence (or not) between their generation peaks and the peaks in the daily (which, for example, in the case of PV is very good in warm and Mediterranean climates at noon, but very bad at sunset in winter in temperate and cold climates).
- The possibility that, in extreme cases, they are not available (in daytime hours, the absence of wind is quite common).

In order to solve such contingencies, several options exist:

- To increase the value of μ through conventional thermal plants which are able to face fast rampings, as it is the case with gas-fired plants.

- To build new (international) grids for transmission of the electricity, where they are non-existing.
- To increase the variable renewable provision by expanding the installed capacity over the widest possible geographical area (which maintains, or even reduces, its average capacity factor) in order to reduce the possibility of non-availability.
- To encourage dispatchable renewable plants, such as closed-cycle hydro, biomass, and CSP plants. They provide the ancillary services which are required by the electricity system in order to maintain its stability, while simultaneously reducing the need for conventional backup capacity.
- To take measures regarding interruptibility and demand response (see below).

As observed in Fig. 4.10, this stage ends when the renewable plants are competitive under the conditions set by the electricity market. This is the ultimate goal of renewable energy promotion schemes: to engage in an interaction dynamics between the average cost of a given j renewable technology $\overline{c}^j$ and its average preferential tariff $\overline{p}^j$ so that, after T years, $\overline{p}^j = 0$ that is, $\overline{c}^j \leq \overline{w}$ with $\overline{w}$ being the average wholesale electricity market price. Notwithstanding, it should be taken into account that those policies affect the later.[23] In other words, the aim is that the evolution of $\overline{c}^j$, $\overline{p}^j$, and $\overline{w}$ finally allows reaching the point *wsp* without serious distortions. This objective is not easy to achieve and includes a couple of key formal relationships between those variables. The next paragraphs discuss these relationships, leaving aside the factors which govern them and the vicissitudes over time.

To start with, let us consider the following notation and assumptions:

- The preferential tariff has a double dynamic: On the one hand, the tariffs of the already authorized projects increase and the initial tariffs for the new plants go down over time [47: 285–290]. If δ refers to the rhythm of reduction, whereas γ is the rate of updating of the average tariff,[24] the evolution of $\overline{p}^j$ per kWh of renewable electricity expressed in continuous time for t years is given by

$$\overline{p}^j_T = \overline{p}^j_0 \frac{\mathrm{e}^{\gamma t}}{\mathrm{e}^{\delta t}} = \overline{p}^j_0 \mathrm{e}^{(\gamma - \delta)t} \quad 0 < \gamma < 1,\ \delta > 0$$

  This dynamic highlights both the willingness of the regulator to remunerate investments in renewables in a reasonable way, and to have the costs of the promotion policy under control.
- The term α denotes the rate of reduction of the average cost of the j-technology due to technical innovations, which improve the performance of the equipments and/or lower the manufacturing cost, to which learning and economies of scale also contribute. This all stems from RD&D efforts. The expression in continuous time corresponding to the cost dynamics is:

---

[23] The relationship $\overline{c}^j \leq \overline{w}$ only indicates that renewable energy plants may be profitable without any type of support. FITs or FIPs, and other support measures, are no longer required, as it has been represented in Fig. 4.10. The complexity that the variability of w entails has been ignored.

[24] There are plants with different ages, each with a specific remuneration regulation. Given the double dynamics, the average tariff for a given renewable energy will evolve according to the evolution of the initial tariffs and their updating rates.

$$\overline{c}_t^j = \overline{c}_0^j \mathrm{e}^{-\alpha t}$$

In order to strengthen renewable energy policies, the profitability of investments has to be as stable as possible over time. Let us assume, then, a constant value $r_t = r^*$. Or, in other words, let us assume that:

$$\frac{\overline{p}_t^j - \overline{c}_t^j}{\overline{c}_t^j} = r^*$$

which has to stand for the whole interval t ($t = 0, 1, 2, \ldots, T$) years. For a given technology, if $\alpha > \delta$, then the profitability of the projects increases, since the reduction in the costs offsets the reductions in the tariffs. Then, in case a reduction of δ is not foreseen, or that this reduction lags behind, investments can be very lucrative, which feeds bubbles. The opposite is the case if $\alpha < \delta$. Then, given that a horizon of $t = T$ years has been considered, the profitability of the investments in renewable will be constant throughout the period if the following condition is fulfilled:

$$\frac{\overline{p}_0^j \mathrm{e}^{(\gamma-\delta)t} - \overline{c}_0^j \mathrm{e}^{-\alpha t}}{\overline{c}_0^j \mathrm{e}^{-\alpha t}} = r^*$$

If this equation is solved for α and it is taken into account that $\overline{p}_0^j = \overline{c}_0^j(1 + r^*)$, then the final expression is derived, $\alpha = \delta - \gamma$. This means that the profitability (r^*) will stay constant as long as, for each technology, the rate of reduction in the cost and the difference between the regulated reduction in the price and the rate of updating of the tariff are equal.

On the other hand, given that the initial average wholesale electricity price $\overline{w}_0$ is too small for the investments in renewable energy plants to be profitable, a surcharge $\left(\lambda_0^j\right)$ is stablished, that is, $p_0^j = \lambda_0^j \overline{w}_0$, $\lambda_0^j > 1$. This surcharge is specific to each of the j-technologies. The advantage will disappear $\left(\lambda_T^j = 1\right)$ when the point *wsp* is reached, in $t = T$ years. It is reasonable to assume that, despite its volatility in the very short term and its changes of trend, the average wholesale market price experiences a reduction at the rate of ρ, due to the merit order effect. Thus, given that $\overline{w}_t = \overline{w}_0 \mathrm{e}^{-\rho t}$, in $t = T$ it is verified that $\overline{w}_t = p_T^j$.[25] Therefore, the point $t = T$ can be calculated, starting from the equality $p_T^j = \lambda_T^j \overline{w}_t$ and taking into account, in addition, that $p_t^j = p_0^j \mathrm{e}^{-\delta t}$. The result is the following expression:

$$t = \frac{\ln \lambda_0^j}{\delta - \rho}$$

---

[25] The different technologies do not reach point *wsp*. Those arriving there first will have a high probability to become dominant.

For example, for $p_0^j = 80$, $\overline{w} = 10$, $\rho = 1\%$, and $\delta = 10\%$, the value of λ^j is 8 and, therefore, $T = 23.1$ years.[26] This is the time lapse in which the trajectories of the preferential tariff and the wholesale electricity market price meet, given the initial distance which separated them. Obviously, it has been assumed that the evolution of the tariffs reflects the evolution of the renewable generation cost.

Three last remarks are worth making before closing this section. First, the dominance of renewable energy technologies will not avoid the presence of quasi-rents, or windfall profits,[27] in the wholesale electricity market. The electricity market quasi-rents are caused by the need to cover electricity demand with technologies whose generation costs are different. This is explained by the efficiency inherent to the different technologies, but also by the impact of exogenous factors (i.e., by a high price of fuels). Since the market price is set by the last plant which is needed to meet the demand at every moment (a price which only covers its variable costs), the rest of installations will benefit from differential rents. These rents will be higher the lower are those generation costs. Although those windfall profits will allow the accumulation of the resources required for the depreciation of the generation plants, quasi-rents will last commonly longer than necessary for capital recovery. Appropriate fiscal measures can be implemented in order to correct these rents [47: 119–121, 80].

The massive presence of renewable energy in the market, whose fuel costs are usually null (except in hybrid CSP plants and biomass plants), will not avoid the existence of quasi-rents, given that the levels of efficiency will be different (better locations and embedded technological advances). If the level of demand requires the activation of plants with comparatively high unitary costs, the rest of plants will keep on benefiting from differential rents. Moreover, it should be pointed out that, in the long term, the market price is set by the LCOE of the cheapest base load technology [38]. In appropriate places, CSP plants with TES are a strong candidate to play this role.

Secondly, once the point *wsp* gets close, many countries opt to organize renewable capacity auctions with the aim to reveal the lowest prices which investors are willing to accept. Regarding RD&D expenditures, there is no reason to suspect that they will be reduced in this phase. Apart from improvements in the manufacturing processes,

---

[26] In discrete time, $p_t^j = p_0^j(1-\delta)^t, 0 < \delta < 1$, and $\overline{w}_t = \overline{w}_0(1-\rho)^t$. After mathematical operations, we arrive at $t = \frac{\ln \lambda_0^j}{\ln(1-\rho)-\ln(1-\delta)}$. With the previous data, $T = 21.8$ years.

[27] Quasi-rents are a kind of differential rents currently associated with industrial activities: They happen when different technologies with different efficiencies are needed to satisfy the demand of a given product (i.e., quasi-rents are defined by the unit of output). In such a context, price is fixed by the less efficient plant and, thus, the other plants obtain increasing benefits with increasing efficiency levels. However, quasi-rents are temporary because, as time goes by, technological change modifies the efficiency order. For this reason, quasi-rents can also be understood as sustained windfall profits. It should be pointed out that there are many types of windfall profits. They normally occur due to unforeseen circumstances, such as an unexpected demand increase. For a detailed explanation on rents and quasi-rents, see Abraham-Frois and Berrebi [1: 113–118], Kurz and Salvadori [37: 277–320], and Salter [68: Chaps. 3 and 4].

there always be important technical aspects which can be improved, such as heat storage in CSP plants or the performance of photovoltaic cells.

Finally, demand-side generation can be generalized in this phase, which reduces the global electricity demand which is satisfied by traditional electricity and/or gas companies and, thus, their revenue expectations. Furthermore, the diffusion of self-generation leads to the concern of regulators and utilities about the remuneration of their investments in grids. In some cases, governments will be pressed to discourage on-site generation, although in other cases, some utilities may evolve to become energy service providers for the prosumers.

4.3.1.4 A Decentralized and Basically Renewable Electricity Sector

Achieving wholesale price parity confirms the success of renewables, but it is not the end of the story. Although the transitory period came to an end, deep changes in the technical and institutional configuration of the electricity sector are likely to happen. In Fig. 4.5, the fourth and definitive stage (t_3, t) has the absolute dominance of renewable electricity sources as its main feature. In this stage, the expectation is a deep reduction and later stabilization of electricity prices (in real terms). This evolution stems from the end of the preferential financing of the renewable plants and from the fact that the generation costs of the new installations are clearly competitive. Since there is dispatchable renewable capacity, all the electricity demand is progressively being covered only with renewables. The conventional backup capacity (zone c) is, then, reduced.

The key concept to be developed at this point is the distributed energy system (DES), in other words, an electricity system characterized by a scattered distribution of generation points (numerous small and medium-size plants, or distributed generation), to which distributed storage, electric vehicles, and devices which allow demand response at the industrial, commercial, and residential levels can be added. This is a complex technological framework which is connected to distribution grids under the supervision of refined and powerful information and communication technology (ICT) systems. These expectations are, however, totally uncertain. Therefore, the next paragraphs are mere conjectures, although the vision is shared by many experts.

In this period, the distribution grid becomes the key asset of the electric system. The large generation plants, which were a main element of the electricity system since the twentieth century, hand over the leading role to the smart distribution grids. The myriad of devices which make up the DES are connected to them. Although the transmission grid may still exist, the distribution grid can become a sort of federation of micro-grids, with even peer-to-peer platforms [57, 66, 82].[28] These micro-grids exchange energy with the rest of the electricity network. Two types of micro-grids may exist: those which gather generation and distribution in a given place under the control of a single owner, such as a university campus, a gated community,

---

[28] There might be cases of grid departure if the regulation allows it [5]. This possibility is currently unfeasible [33].

and a commercial or an industrial area, and those micro-grids which extend over a neighborhood or a whole city, or even beyond, pursuing the affiliation of more and more people and their generation and storage plants. The distribution grid, therefore, hosts autonomous sections and needs to be capable of managing energy flows in all directions, under the control of ICT systems in order to ensure its stability and reliability. Obviously, there will be some large conventional or renewable energy generation plants, all of them dispatchable (as CSP and biomass, perhaps coal with CCS and other technical possibilities which are unknown today), as well as the transmission grid in order to feed electricity to industrial areas and transport systems [49].

The ICT devices would facilitate that consumers have a greater control over their electricity consumption, responding to price signals. However, there are not likely to be many individuals and SMEs who are interested on the load management systems. There will even be fewer actors who might become potential suppliers of ancillary or capacity services to the electricity system. New firms which will carry out these functions will likely be created, and dominant firms in the ICT sector with branches dedicated to the intermediation between consumers and distribution and/or commercialization firms may enter this business. Those firms may install devices for the tracking and control of electricity consumption, which are able to send them a large quantity of information online which can be sold to the large generators and grid operators, as well as to regulatory agencies. In this sense, the electricity sector of the future could see a growing information asymmetry between utilities/ICT firms and regulators.

In this stage, it can be expected that saving and improving energy efficiency measures will be spread. In some countries or regions, it may mean that the global demand is stagnant or grows at a very small rate. This expectation also depends, as it is obvious, on economic and demographic growth.

The traditional distinction among industrial, commercial, and residential consumers, each with their own demand profile and passive behavior, could be blurred. The plausible abundance of prosumers may make it recommendable to establish charges for the use of the grids, according to the principle of cost causality [50]: The tariffs try to reflect the contribution of each user, whatever its size, to the costs of the grid (and its different components). This is a criterion which removes the problem of cross-subsidies. In order to do so, [60] propose that

- A reference network model (RNM) will have to be developed in order to ensure that the extension and reinforcement of the grids are planned in an appropriate manner. Without a detailed forecast, the grid could grow in a whimsical manner and thus the distribution costs could increase. This model allows the identification of the drivers of the distribution costs (new investments, amortizations, and O&M expenditures).
- The global cost (with the minimum profitability rate incorporated) is shared between the users depending on the time of use (per hour or fraction), assuming that this reflects their contribution to the total cost.

It is assumed, then, that the investments in grids are carried out in order to have a better knowledge about what is happening in them and to facilitate the fitting of the new users (generators and/or consumers). However, the change to a more decentralized electricity system does not imply that this will be more competitive. Although many DESs are owned by individuals, the larger generation plants, the grids, and the information flows will be in a few hands. There might even be alliances and mergers between utilities and ICT firms. Indeed, the traditional utilities, which have not played a main role in the development of renewable energy technologies or ICT systems, will hardly drive the transformation of the electricity system. It is perhaps more plausible to assume that those firms will focus on the management of the electricity grid under the supervision of the regulatory agencies (which will need to guarantee a level playing field for its access). Historical and institutional factors will determine the particularities of the electricity sector in this stage.

4.3.2 Values of CSP Electricity

The outline on the transition of the electricity sector represents a mere approximation. In practice, there are many details, some of which are specific to the country or region considered. In addition, the emerging elements mature over the years, although this process can accelerate at a given moment. The obsolete pieces slowly disappear. However, in spite of all the possible nuances, no one doubts that, when seen in a historical perspective, the configuration of the electricity system is changing. What we will see in 2050 will be very different to what we have seen a century before.

The aim of these pages is not to make predictions. The stylized model of the transition of the electricity system has been designed with a single purpose: to refine the analysis of the value of CSP generation, that is, to discuss its different effects on the transition of the electricity system and, by extension, on the economy and society. Thus, with this purpose in mind, we use the conceptual framework on the value of photovoltaic electricity provided by Mir-Artigues and del Río [47: 113–124] and apply it to the two hypothetical stages of the transition of the electricity system. This is a conceptual improvement since it is considered as a fact that the value of solar electricity will change with the transformation of the electricity sector. Although the attention falls on CSP generation, the comparison with PV is unavoidable.

To start with, let us consider Table 4.6, which lists the different components of the social value of CSP electricity (SV_{CSP}), together with the burden (−), benefits (+), or irrelevant effects (0) that they entail for society, the economic system, and the electricity sector. This is merely a theoretical exercise, although liable to empirical application since the evaluation takes into account the specific technological features of CSP generation and its degree of diffusion. All in all, the interpretation of the table has to consider that solar thermal electricity does not have a meaningful share in the

Table 4.6 Values of CSP generation and the energy transition model

Components of the value/effects				Stages of energy transition	
				First	Second
Social value (SV_{CSP})	Environmental value			+	+
	Welfare improvement value			0	+
	Economic value (EcV)	Cost of generation and early deployment		–	0
		Less hydrocarbon imports		+	+
		Market integration value (MIV)	Merit order effect	+	0
			Balancing services	0	+
			Grid-related costs	–	–

power mix of any country, with a few possible exceptions.[29] As it was mentioned in the beginning of this book, the best locations for CSP generation are between 20° and 35° north latitude and south latitude, that is, the subtropical climate zones which are delimitated by the Tropic of Cancer and the Tropic of Capricorn, and where the larger deserts of the planet are located. This region, however, also includes countries with very different levels of economic development: from USA and the rich oil states of the Arabian peninsula to Mauritania. This has important implications with respect to CSP diffusion since knowledge and financial resources are unevenly distributed.

In the case of the first stage of the transition, the local and global scale effects of thermo-solar generation are very small or negligible whereas, in the second phase, their impact will depend on the extent of its diffusion in some countries.

The first term of Table 4.6 is the environmental value (EnV). The positive sign for both periods reflects the contribution of CSP generation to CO_2 emission reductions (see Chap. 2), both regarding electricity generation and producing of steam for industrial uses. The importance of the environmental value does increase not only when the installed capacity increases in the world, but also when more and more electricity from renewable energy sources is used in order to manufacture components and equipment for the plants.

Obviously, the inexistence of a clear penalty for the negative externalities caused by the emissions of greenhouse gases or the incapacity of the carbon market to set

---

[29] For example, in 2016, solar thermal generation in Spain (a country which currently has a relatively high share of CSP) was only $\geq$5% during 16.6% of the hours in that year, with only a few hours above 10% (the maximum was 10.15%). Given the high share of hours with very low (or even inexistent) generation, the annual average was only 1.96% (source: own elaboration based on TSO data from https://www.esios.ree.es/es/generacion-y-consumo). However, in the future, in countries with arid or desert regions the proportion of CSP electricity could be important.

a sufficiently high carbon price undermines the expectations of CSP generation as well as the other renewable energy sources. In this case, promotion policies have to be considered as second-best to the first-best carbon policies, which were deemed politically unfeasible.

CSP generation can have an important positive effect on the welfare of the residents of the region where the plant is located. Indeed, thermo-solar production can provide large quantities of desalinated water and, thus, contribute to the improvement of the surrounding agriculture and farming activities or to the urban supply of drinkable water. However, in contrast to photovoltaic generation, solar thermal electricity is not a modular technology, its operation is complex, and its maintenance is demanding. Thus, its role as a source of energy for the many rural or suburban communities in poor countries located in the tropics (whether to pump irrigation water or to generate electricity) has been very limited [61: 105–106]. A different issue is that CSP plants, which provide electricity and freshwater to its surroundings, entail an improvement of the living conditions of the residents which encourage migration toward those places.

The possibility of desalination justifies scoring a positive sign to the welfare improvement value of CSP. However, in the first phase of the transition process there is not any plant which produces desalinated water. If, as it seems likely, this use is diffused in the next years, the welfare value will turn from negligible to positive. It should be pointed out that this is only a possibility: The water for irrigation may be dedicated to crops for exports whose activities are carried out with a high degree of mechanization, or the supply may prioritize touristic areas and the richest districts in neighboring cities. If this is so, then the poorer population will not experience an improvement in its living conditions. Therefore, any specific diagnosis about the welfare impact of CSP with desalination will need to include the direct and indirect socioeconomic benefits of the drinkable water being produced.

There is no doubt that the main analytical concept of these pages is the economic value (EcV) of CSP, that is, its economic impact in terms of material and financial resources required to become a mature renewable technology and, as a result, its effects on the electricity markets. Its first component focuses on the Levelized-Cost-of-Electricity (LCOE).

The concept of LCOE is well known. It refers to the estimation of the generation cost of a plant (€/kWh or €/MWh), whether renewable or not, considering all the factors which affect its performance throughout its operative lifetime. However, the calculation of the LCOE is a delicate issue given the numerous elements involved, some of which are uncertain. This is the case with future fuel prices. Fortunately, CSP generation uses a free fuel (direct solar irradiation). Therefore, the CSP electricity LCOE may be defined in the following manner (adapted from [4: 70, 9: 3134]):

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{t=T} \frac{C_t^*}{(1+i)^t}}{\sum_{t=0}^{t=T} \frac{q_{AC_t}}{(1+i)^t}}$$

As it can be observed, the LCOE is a ratio between the present value of the sum of the net costs of the plant (C_t^*) throughout its lifetime and the discounted flow of the energy generated. The costs include the initial installation expenditures, O&M costs, rental fees, charges and taxes, financial costs, and hybridization fuels. In case subsidies or any other incentives are incorporated in these variables, they should be deduced. In this definition, it is assumed that the electricity generated has the same value in all the hours of the year. Moreover, from the social perspective, the comparison of the LCOE of renewable energy and conventional technologies should consider the externalities [27: 15–16]. Finally, the costs of transporting the electricity to the consumption centers are not a part of the LCOE. This factor is considered in another section (see below).

The LCOE is calculated for specific plants. Therefore, even for the same technology, the LCOE of two plants will differ. On the one hand, the differences are smaller for conventional thermal plants than for renewable plants as the latter are very influenced by the climatic conditions. On the other hand, the LCOE significantly changes depending on the technical and economic assumptions used in its calculation. Therefore, we should pay attention to those assumptions, the origin of the data used, and the specific context in which they are interpreted.

It is also important to mention that the LCOE is an abstraction. It cannot be directly observable. It was a concept created in order to compare the generation costs of the different technologies from the point of view of investors, taking advantage of the fact that its output (electricity) is a physically homogenous good. Therefore, the LCOE can be interpreted as the minimum price that the owner of a plant should receive per kWh in order to cover the different costs of generation and still receive a normal profitability level [4: 70, 51: 104].

In Table 4.6, the value of the LCOE factor appears with a negative sign for the first part of the energy transition, whereas in the second part its impact is deemed null. The reason is quite simple: CSP generation is comparatively very expensive in the beginning, and thus, it needs strong support in the form of FITs or FIPs, whereas with technological improvements and learning, it is expected that its cost goes down and converges to the costs of the most competitive renewable and conventional technologies. When CSP plants do not receive any support (i.e., when they operate at market prices), the economic burden associated with early deployment will be null. It was negative when their deployment involved an extra cost for the electricity system. The trend of the LCOE for the coming years (see Chap. 3) points to a progressive reduction, until support is not needed. Of course, when this happens, it is likely that there will be plants in operation which have been deployed years before, which will continue to receive a preferential remuneration for the period envisaged in the regulation. Perhaps, measures to modernize these obsolete plants may be implemented.

The following component of the EcV is the lower fossil fuel and uranium imports which are allowed by an increasing deployment of CSP plants. The impact due to savings in imports is always positive, although its magnitude grows with CSP installed capacity. Taking into account its geographical conditions, CSP generation may be a key in order for countries with a strong solar irradiation to reach electricity self-sufficiency (to which the other solar sources, i.e., photovoltaic generation, will also contribute).

The entry of growing CSP volumes in the wholesale electricity market has different effects which are encompassed under the term market integration value (MIV). This component refers to the benefits and costs of thermo-solar electricity integration in the current managing of electricity market (assuming that this institution exists, as it is the case in countries with a liberalized electricity sector). The MIV includes three effects: merit order effect (MOE), balancing effect (BE) or service, and grid-related costs (GrC).[30]

Since the analysis of MIV is a complex issue, the following assumptions are adopted in the following pages:

- The country or region has very good direct solar irradiation.
- The limitations in forecasting the Direct Normal Irradiance have been completely solved. Different prediction methods have been studied, and as a result, DNI forecasting has hugely improved in these later years [36, 55, 71, 79].[31]
- There is a transmission grid which connects the production places to the consumption areas which are probably located far away.

In order to analyze the issue of the integration of variable sources, it should be clear from the start that capacity is not a proxy for flexibility. All electricity systems have some level of variability and uncertainty. Indeed, load changes over time (season, day of the week, and hour), sometimes in an unpredictable manner. Conventional resources can also fail without prior notice. However, variable renewable sources can vary in a way previously unknown for the SO, which have also difficulties to perfectly forecast them. As a result, there can be frequency deviations, load drops, energy curtailments, and price volatility, among other distress signals. These problems can be prevented if there is enough availability of ramping and fast response, transmission capacity (bottlenecks were removed), access to peaking plants (reserve capacity), load management, and so on. All of them are coupled with flexible system operations, that is, decisions that can be made closer to real time.

The value factor is an indicator which shows the interest that the electricity from a given source has for the electricity sector. Given the strict conditions under which the electricity system operates (equilibrium between generation and consumption, stable voltage, etc.), a maximum concern of SO is to have reliable sources, i.e., those which are capable of providing the needed electricity at a specific moment. From this point of view, there is not a perfect technology, although the cyclically intermittent and variable ones cause the greatest headaches. This is the case, for example, of solar photovoltaic generation. The additional costs that it may entail for the electricity system justify the statement that its LCOE is not a sufficient indicator of its value. The value factor, then, tries to quantify the cost of integration; i.e., it indicates the

---

[30] See [47] for a detailed definition of balancing deviations. See Hirth [23], IEA [26: 28–31, 34 and 67–82], and Mehos et al. [44: 6–9] for a complete analysis on the impact of variable generation on the management of the electricity system.

[31] The detailed prediction of the DNI requires collecting data for months. Its average annual values fluctuate up to ±15%. Having real time on ground and satellite data is also important.

difficulties in managing variable energy sources in the electricity system (see, e.g., Hirth [21, 22], IEA [26: 22–24], MIT [51: 104–106]). The value factor is the ratio of the average price per kWh received in the wholesale market by renewable generators divided by the hourly average market price during a certain time period (a year). In order to calculate the former, the revenues obtained by all the renewable plants in each hour are added and divided by the annual quantity of renewable electricity being sold. Therefore, this ratio shows the proportionality between the price received by the renewable generator and the market price, all over the yearly hours.

If we consider the case of PV generation, its value factor is greater than 1 when its degree of penetration is very small (<5%), given that the producers are in the best position to cover the peak of electricity demand in the middle of hot days (due to the high consumption of air-conditioning devices). However, when more and more solar PV electricity enters the system, problems in the management of surpluses in the central hours of the day emerge. There are also problems due to the lack of PV generation in the cold sunsets of temperate latitudes, when there is not any solar light and electricity consumption grows fast [3: 18–19, 47: 133–143].

The diagnosis regarding the integration of solar thermal electricity in the market is very different: The hybridization of CSP plants makes them a dispatchable source, which is a feature that is reinforced with TES [14: 10-35/10-36, 16, 44]. The hypothetical evolution of the value factor of CSP electricity is shown in Fig. 4.8. The thick discontinuous line reflects the value factor of CSP, whereas the thinner line refers to PV.

Figure 4.13 distinguishes between the first and the second stages of the electricity transition. The contribution of both solar technologies to the management of demand peaks in hot middays justifies that its initial value factor, that is, when the installed capacity is modest, is the same and above 1. As PV capacity increases, the management of the electricity system becomes more complicated. PV electricity generation is concentrated, especially in the hours with the highest irradiation. Its value factor goes down fast. In contrast, since the heat can only be stored for a limited number of hours, it can be assumed that the value factor of CSP could go down although such reduction is not so sharp. If regulation would allow total hybridization, the value factor of CSP in this first transition stage would not fall below 1.

The aim since the first CSP plants has been to saturate the capacity of the power block the maximum number of hours during the day. Thus, the size of the solar field, given the DNI, is adjusted in order to store the possible surpluses of heat and, from this, the period of only-solar operation can be extended. Therefore, in the second phase of the electricity transition, CSP plants are designed in a way that the volumes of TES allow operating in solar mode without interruption 24 h a day. Thus, it can be expected that the value factor of CSP generation increases to reach the level of dispatchable technologies (value factor equals 1). This is shown by the figure. Solar PV generation may also move in that direction, although the maturity of the electricity storage technology lags behind thermal storage. In the competition between both solar sources, one (PV) has an advantage in terms of location (almost the whole planet, since it can also operate with diffuse irradiation), and the other (CSP) has an advantage in terms of easiness to store energy, which allows it to be a

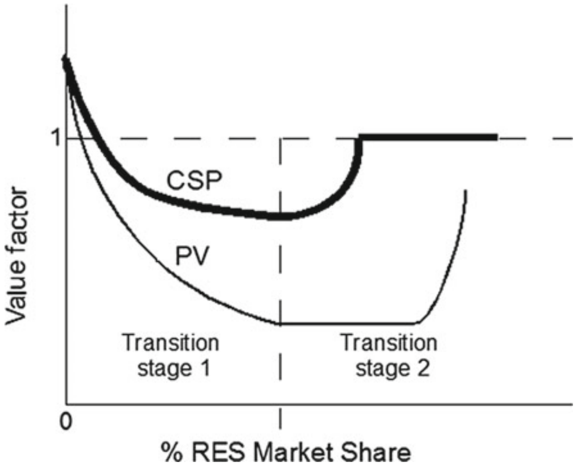


Fig. 4.13 Value factor of CSP electricity. *Source* Own elaboration

dispatchable generator. In reality, both complement each other: The dispatchability of CSP makes it feasible to have high levels of penetration of variable renewable, especially solar PV (see Denholm et al. [13: 38–40] and MIT [51: 198–199] for the case of USA). The combination of solar PV generation and CSP with TES allows solving demand peaks at middays in the summer through PV generation, whereas in the colder months and with fewer hours of sun, CSP allows overcoming the ramping when it is getting dark. This is shown in Fig. 4.14 where generation extends for 24 h, with a central day interval in which all the thermal contributions come from the solar field. The surpluses stored are used for electricity generation at night, which is never interrupted. Hybridization is not needed, except perhaps as a security measure in order to sustain the HTF temperature and in the event of breakdowns. Nevertheless, there are two time intervals at the start and the end of the daylight hours when the thermal flow of the solar field (which is below the one which is necessary in order to satisfy the rated power of the turbine) is combined with the one coming from the TES.

In this context, the variability featuring wind generation, which includes the interruption of its production (in the absence of wind or in the presence of strong winds), also increases the value of the dispatchable CSP electricity. However, the specific form of such complementarity between the electricity generation sources depends on the particular mix of each system. This is an issue which should be analyzed case by case with complex simulation models.

In case the generation capacity through the accumulated heat reaches the next day, CSP plants will displace conventional sources. This is a fact that can be generalized in the second phase of the electricity transition. If CSP generation does not slow down, the displacement of plants due to their comparatively higher costs could be permanent and definitive. In this case, the contribution of CSP to the merit order effect is out of doubt.

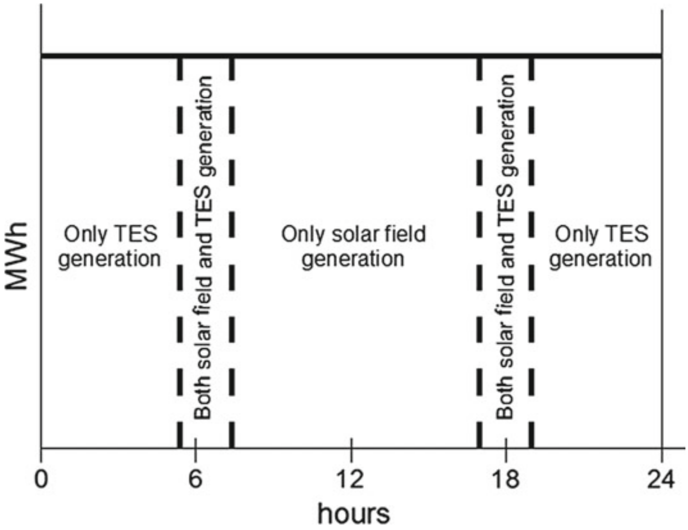


Fig. 4.14 CSP + TES 24/24 generation. *Source* Own elaboration

However, the merit order effect may end up being detrimental to CSP generation in the long term (a sort of cannibalization effect). The sustained reduction in the wholesale market prices would damage existing plants and would bring doubts about the profitability of new investments. The reduction in equipment prices (due to technical improvements and economies of scale) and, hence, electricity generation prices, would facilitate CSP diffusion, but would worsen the revenue expectations of planned plants as well. Therefore, the fitting between the successive reductions of the average prices in the wholesale electricity market and the improvements in the efficiency of the successive generations of renewable plants (until the possibilities of the technological paradigm are exhausted) should be addressed. In the best locations for thermo-solar generation, both trends should not put at risk the profitability of new plants, given electricity demand and its oscillations.

In general, and seen in perspective, the condition of entry into the market of the consecutive generations of renewable plants of a given *j*-technology can be written in a simplified manner as follows

$$w_0 \frac{q^j}{\Lambda} T \mathrm{e}^{-\rho t} = \frac{I_0^j}{\Lambda} \frac{r(1+r)^T}{(1+r)^T - 1} \mathrm{e}^{-\xi t}, \quad t = (1, 2, 3, \ldots, T)$$

The downward trend of wholesale prices, $w_t = w_0 \mathrm{e}^{-\rho t}$, leads to a downward trend of the revenues, assuming that the performance of new plants, that is, its annual production (q^j) per kW installed (Λ), is constant during the T years of its useful life. Since, for simplicity reasons, maintenance costs have been ignored, those revenues per installed kW have to allow the depreciation and profitability of the initial investment per kW (I_0^j/Λ), whose amount also goes down (at a rate of ξ). The new plants which comply with this condition will be able to access the market despite the reduction of wholesale prices.[32] This means that CSP, even in the best regions, needs to make a constant effort in order for the successive generations of plants to achieve higher levels of competitiveness. Obviously, the degree of maturity should not fall behind other renewables, especially PV.

Regarding balancing services, a plant without storage and/or hybridization has low probabilities to participate in those services.[33] If it has storage, then it can offer ancillary services, such as contingency/flexibility reserves, stabilizing frequency, and so on. This provision requires taking into account the ramping capacity and faster (less than hour) scheduling of solar thermal plants [72: 1].

The MIV analysis of CSP cannot conclude without addressing the issue of the impact of the cost of the transmission line of the electricity generated. The GrC might be the Achilles heel of CSP generation: It is expected that new investments in transmission lines will be needed to deliver the electricity produced by CSP plants. In fact, the best locations for CSP are unfortunately very far (hundreds of kilometers) from consumption areas, that is large cities and industrial centers. The exceptions are the countries in the Middle East, Maghreb, Sahel, Botswana, and Namibia and all those countries whose territory is mainly a desert, as well as some large urban areas located in far arid regions, such as Las Vegas, Iquique, or Yinchuan. In all these cases, the possible CSP plants can be deployed close to consumption areas. However, in the tropical countries, the population and economic activities prefer to be located in areas with moderate temperatures and safe access to water. The deserts are considered as very remote regions without substantial human activity (perhaps with the exception of mining activities, which employ only a few thousands of people). They are appropriate locations to install a thermo-solar plant, although a long transmission grid which reaches highly populated areas will need to be built. This is the case of Australia, Chile, China, South Africa, USA, etc.

The high voltage lines entail a very high investment, due to the cost of terminals as well as the fact that the wires need to be extended for hundreds of kilometers (especially if they are under water, where the savings in towers are more than offset by the strength which the wire requires). However, HVDC transmission lines over long distances are cheaper than the HVAC lines of the same distance, although the cost of the HVDC conversion equipment at the terminal stations is much higher, as shown by Fig. 4.15.

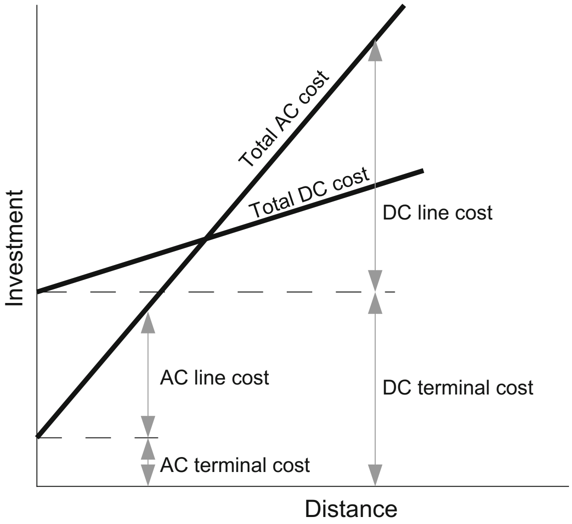
It is difficult to provide representative numbers of the cost in both cases, since each line represents a particular case. However, for the same path, the cost per kilometer of wire (whether on the air with supporting towers or under water) for an HVDC line is usually 1/3 of the cost of an HVAC line. The conversion equipment, on the

---

[32] As it is obvious, although it has been assumed for reasons of simplicity that only the investment per installed kW goes down, the increase in the efficiency of plants (more kWh per kW) is another factor that should be taken into account.

[33] The improvements in DNI predictions have encouraged the participation of CSP plants in the day-ahead electricity markets. Another measure to prevent high penalty payments for not achieving the predicted generation is to make CSP part of the portfolio of a market agent.

Fig. 4.15 Power transmission cost over long distances. *Source* Own elaboration



contrary, usually costs between 3 and 4 times more in the case of HVDC. The losses are also different: Regarding an aerial line, the losses are between 6 and 8% in the case of HVAC and half of those values for an HVDC. The losses for a line under water are very different: For example, for a submarine cable of 135 kV AC the loss is 18%, but for 400 kV DC it is 0.85%, both of 300-km length [30: 33–41]. Since the investment in transmission lines is on the order of billions of €, the distance between the generation and the consumption points the type of space to be crossed and the weight of losses are factors which need to be taken into account when choosing one or the other line. All in all, the final costs of the MWh of CSP can be affected by the cost of transmission or, rather, by the way in which its construction is financed and how such cost is distributed among the users of the line and the different consumers. This is a complex issue (see MIT [49: 88–96] and Rivier et al. [65: 293–309]).

References

1. Abraham-Frois G, Berrebi E (1980) Rentes, rareté, surprofits. Paris, Economica
2. Baharoon DA et al (2015) Historical development of concentrating solar power technologies to generate clean electricity efficiently—A review. Renew Sustain Energy Rev 41:996–1027
3. Baker E et al (2013) The economics of solar electricity. Energy Institute at Haas working paper series, p 240. Berkeley (Ca). Available at http://ei.haas.berkeley.edu. Accessed December 2013
4. Borenstein S (2012) The private and public economics of renewable electricity generation. J Econ Perspect 26(1):67–92
5. Bronski P et al (2015) The economics of load defection: How grid-connected solar-plus-battery systems will compete with traditional electric service, why it matters, and possible paths forward. Rocky Mountain Institute and Homer Energy, USA. Document available at www.rmi.org. Accessed July 2016

6. Caldés N et al (2009) Economic impact of solar thermal electricity deployment in Spain. Energy Policy 37(5):1628–36
7. Cocco D, Cau G (2015) Energy and economic analysis of concentrating solar power plants based on parabolic trough and linear Fresnel collectors. Proc Inst Mech Eng Part A: J Power Energy 22(6):677–688
8. Daim TU et al (eds) (2015) Policies and programs for sustainable energy innovations. Renewable energy and energy efficiency. Springer, Heidelberg
9. Darling SB et al (2011) Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 4:3133–3139
10. De la Tour A et al (2010) Economic analysis of the CSP industry. Paris, CERNA, Mines ParisTech and Agence Française de Développement. Available at http://www.cerna.mines-paristech.fr/Donnees/data07/704-CSP_report.pdf. Accessed Nov 2012
11. Del Río P, Mir-Artigues P (2014) A cautionary tale. Spain's solar PV investment bubble. Winnipeg (Can), International Institute for Sustainable Development/GSI. Available at http://www.iisd.org
12. Deloitte (2011) Impacto macroeconómico del sector solar termoeléctrico en España. Madrid, Protermosolar
13. Denholm P et al (2016) On the path to SunShot: emerging issues and challenges in integrating high levels of solar into the electrical generation and transmission system. NREL/TP-6A20-65800. Golden (Co) National Renewable Energy Laboratory. Available at http://www.nrel.gov. Accessed Feb 2017
14. Drury E et al (2012) Chapter 10. Solar energy technologies. In: Hand MM et al (eds) Renewable electricity futures study. Volume 2: Renewable electricity generation and storage technologies, pp. 10-1–10-60. Report NREL/TP-6A20-52409. Golden (CO) National Renewable Energy Laboratory (NREL). Available at http://www.nrel.gov/analysis/re_futures. Accessed July 2014
15. ESTELA (2018) Overview of the european solar thermal electricity industry directory. ESTELA
16. Gauché P et al (2017) System value and progress of CSP. Sol Energy 152:106–139
17. GEA (2012) Global energy assessment. Toward a Sustainable Future. Cambridge University Press and IIASA, Cambridge and Laxenburg
18. Grand E, Veyrenc T (2011) L'Europe de l'électricité et du gaz. Acteurs, marchés, régulations. Paris, Economica
19. Greenpeace et al (2009) Concentrating solar power global outlook 09. Greenpeace, Hamburg
20. Grupp H (1998) Foundations of the economics of innovation. Theory, measurement and practice. Edward Elgar, Cheltenham (UK)
21. Hirth L (2013) The market value of variable renewables. The effect of solar and wind power variability on their relative price. Energy Econ 38:218–236
22. Hirth L (2014) The market value of solar power: is photovoltaics cost-competitive? Paper presented at the 2013 solar integration workshop in London. Available at http://www.neon-energie.de. Accessed May 2015
23. Hirth L (2018) What caused the drop in european electricity prices? A factor decomposition analysis. Energy J 39(1):143–157
24. Houghton J (2015) Global warming. The complete briefing, 5th ed. Cambridge University Press, Cambridge
25. IEA (2010) Technology roadmap. Concentrating solar power. OECD/IEA, Paris. Available at http://www.iea.org. Accessed Jan 2011
26. IEA (2014) The power of transformation. Wind, sun and the economics of flexible power systems. OECD/IEA, Paris. Available at http://www.iea.org. Accessed Sep 2015
27. IRENA (2015) Renewable power generation costs in 2014. International Renewable Energy Agency. Available at http://www.irena.org/publications. Accessed March 2015
28. IRENA (2018) Renewable power generation costs in 2017. International Renewable Energy Agency, Abu Dhabi (UAE). Available at http://www.irena.org/publications. Accessed April 2018

29. Izquierdo S et al (2010) Analysis of CSP plants for the definition of energy policies: the influence on electricity cost of solar multiples, capacity factors and energy storage. Energy Policy 38:6215–6221
30. Jayasinghe K (2017) Power loss evaluation of submarine cables in 500 MW offshore wind farm. Department of Earth Sciences, Uppsala University
31. Jorgenson J et al (2013) Estimating the performance and economic value of multiple concentrating solar power technologies in a production cost model. NREL/TP-6A20-58645. Golden (Co), National Renewable Energy Laboratory. Available at http://www.nrel.gov. Accessed May 2016
32. Jorgenson J et al (2014) Estimating the value of utility-scale solar technologies in california under a 40% Renewable Portfolio Standrad. NREL/TP-6A20-61685. National Renewable Energy Laboratory, Golden (Co). Available at http://www.nrel.gov. Accessed May 2016
33. Khalilpour R, Vassallo A (2015) Leaving the grid: an ambition or a real choice? Energy Policy 82:207–221
34. Klepper S (1996) Entry, exit, growth, and innovation over the product life cycle. Am Econ Rev 86(3):562–583
35. Komendantova N, Patt A (2014) Employment under vertical and horizontal transfer of concentrated solar power technology to North African countries. Renew Sustain Energy Rev 40:1192–1201
36. Kraas B et al (2013) Economic merits of a state-of-the-art concentrating solar power forecasting system for participation in the Spanish electricity market. Sol Energy 93:244–255
37. Kurz HD, Salvadori N (1995) Theory of production. Cambridge, Cambridge University Press, A long-period analysis
38. Lamont AD (2008) Assessing the long-term system value of intermittent electric generation technologies. Energy Economics 30:1208–1231
39. Lilliestam J (2018) Whither CSP? Taking stock of a decade of concentrated solar power expansion and development. Deliverable 4.2, MUSTEC project. Zürich, ETH Zürich
40. Lilliestam J et al (2017) Empirically observed learning rates for concentrating solar power and their responses to regime change. Nat Energy 2:17094
41. Lilliestam J et al (2018) Policies to keep and expand the option of concentrating solar power for dispatchable renewable electricity. Energy Policy 116:193–197
42. Lovins AB et al (2002) Small is profitable. The hidden economic benefits of making electrical resources the right size. Rocky Mountain Institute, Boulder (Co). Available at https://www.rmi.org. Accessed May 2008
43. Mazzucato M (2013) The entrepreneurial state. Debunking public vs. private sector myths. Anthern Press, London
44. Mehos M et al (2016) On the path to SunShot: advancing concentrating solar power technology, performance, and dispatchability. NREL/TP-5500-65688. National Renewable Energy Laboratory, Golden (Co). Available at http://www.nrel.gov. Accessed Apr 2017
45. Mehos M et al (2015) An assessment of the net value of CSP systems integrated with thermal energy storage. Energy Procedia 69:2060–2071
46. Mir-Artigues P, del Río P (2014) Conbining tariffs, investment subsidies and soft loans in a renewable deployment policy. Energy Policy 69:430–442
47. Mir-Artigues P, del Río P (2016) The economics and policy of solar photovoltaics generation. Springer, Switzerland
48. Mir-Artigues P, González Calvet J (2007) Funds, flows and time. An alternatives approach to the microeconomic analysis of productive activities. Springer, Berlin
49. MIT (2011) The future of the electric grid. An interdisciplinary MIT study. Massachusetts Institute of Technology, Cambridge. Available at http://web.mit.edu/mitei. Accessed Feb 2013
50. MIT (2015a) The MIT study: utility of the future. White paper. The MIT Energy Initiative/IIT Comillas, Cambridge. Available at http://energy.mit.edu. Accessed May 2016
51. MIT (2015b) The future of solar energy. An interdisciplinary MIT study. Massachusetts Institute of Technology, Cambridge. Available at http://mitei.mit.edu. Accessed May 2015
52. Musgrove P (2010) Wind power. Cambridge University Press, Cambridge

53. Nemet (2007) Policy and innovation in low-carbon energy technologies. Dissertation for the degree of PhD. University of California, Berkeley. Available at https://mywebspace.wisc.edu/nemet/web/Thesis.html. Accessed Jan 2010
54. Nemet GF, Baker E (2009) Demand subsidies versus RD&D: comparing the un-certain impacts of policy on a pre-commercial low-carbon energy technology. Energy J 30(4):49–80
55. Nonnenmacher L et al (2016) Day-ahead resource forecasting for concentrated solar power integration. Renew Energy 86:866–876
56. Palenzuela P et al (2015) Concentrating solar power and desalination plants. Engineering and economics of coupling multi-effect distillation and solar plants. Springer, Berlin
57. Parag Y, Sovacool BK (2016) Electricity market design for the prosumer era. Nat Energy 32, art. 16032
58. Pariente-David S et al (2009) L'initiative de la Banque mondial en faveur d'une montée en puissance des centrales solaires à concentration (CSP). Utilisation du Fons des Technologies Propres en faveur d'une approche coopérative pou faire face aux défis du Changement climatique et aux défis énergétiques des pays du Moyen-Orient et d'Afrique du Nord (MENA). Réalités Industrielles, pp 42–49, Nov 2009
59. Pasinetti L (1993) Structural economic dynamics: a theory of economic consequences of human learning. Cambridge University Press, Cambridge
60. Pérez-Arriaga IJ, Bharatkumar A (2014) A framework for redesigning distribution network use-of-system charges under high penetration of distributed energy resources: new principles for new problems. CEEPR WP 2014-006. MIT, CEEPR
61. Perlin J (1999) Form space to earth. The story of solar electricity. Aatec Publications, Ann Arbor
62. Pollit MG, Anaya KL (2016) Can current electricity markets cope with high shares of renewables? A comparison approaches in Germany, the UK and the State of New York. Energy J 37(2):69–88
63. Popp D et al (2009) Energy, the environment, and technological change. (NBER working paper series 14832). NBER, Cambridge. Available at http://www.nber.org/papers/w14832. Accessed Mar 2011
64. Popp D (2010) Innovation and climate policy. (NBER working paper series 15673). NBER, Cambridge. Available at http://www.nber.org/papers/w15673. Accessed July 2012
65. Rivier et al (2015) Chapter 6. Electricity transmission. In: Pérez-Arriaga IJ (ed) Regulation of the power sector. Springer, London, pp 251–339
66. Rodríguez-Molina J et al (2014) Business models in the smart grid: challenges, opportunities and proposals for prosumer profitability. Energies 7:6142–6171
67. Rodríguez-Serrano I et al (2017) Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA). Case study of a solar thermal electricity project in Mexico. J Clean Prod 149:1127–1143
68. Salter WEG (1966) Productivity and technical change, 2nd ed. Cambridge, Cambridge University Press
69. Scherer FM (1999) New perspectives on economic growth and technological innovation. Brookings Institution Press, Washington DC
70. Schill W-P et al (2017) Prosumage of solar electricity: pros, cons, and the system perspective. Econ Energy Environ Policy 6(1):7–31
71. Schroedter-Homscheidt M et al (2013) Aerosols for concentrating solar electricity production forecasts. Requirement quantification and ECMWF/MACC aerosol forecast assessment. Bull Am Meteorol Soc. Available at https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-11-00259.1. Accessed Jan 2018
72. Sioshansi R, Denholm P (2010) The value of concentrating solar power and thermal energy storage. TP-6A2-45833. Golden (Colorado), NREL. Available at http://www.nrel.gov. Accessed June 2012
73. Sovacool BK et al (2016) Fact and fiction in global energy policy. Fifteen Contentious Questions. Johns Hopkins University Press, Baltimore

74. Stoddard L et al (2006) Economic, energy, and environmental benefits of concentrating solar power in California. NREL/SR-550-39291. National Renewable Energy Laboratory, Golden. Available at http://www.nrel.gov. Accessed May 2012
75. Trieb F et al (2005) Concentrating solar power for the mediterranean region. Final report, German Aerospace Center-Institute of Technical Thermodynamics/Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Stuttgart. Available at www.dlr.de. Accessed Apr 2010
76. Trieb F et al (2009) Global potential of concentrating solar power. SolarPaces Conference, Berlin. Available at http://www.desertec.org. Accessed Apr 2010
77. Trieb F et al (2015) North Africa case study. German Aerospace Centre (DLR), Stuttgart
78. Utterback JM (1994) Mastering the dynamics of innovation: how companies can seize opportunities in the face of technological change. Harvard Business School Press, Boston
79. Vasallo MJ et al (2017) Economic MPC applied to generation scheduling in CSP plants. IFAC-PapersOnLine 50(1):115–120. Available at https://www.sciencedirect.com. Accessed Jan 2018
80. Verbruggen A (2008) Windfalls and other profits. Energy Policy 36:3249–3251
81. Wang J et al (2017) Status and future strategies for concentrating solar power in China. Ener Sci Eng 5:100–109
82. Weiller CM, Pollitt MG (2013) Platform markets and energy services. EPRG Working Paper 1334, Cambridge Working Paper in Economics 1361. University of Cambridge, Cambridge. Document available at www.eprg.group.cam.ac.uk. Accessed Dec 2016
83. Weiss C, Bonvillian WB (2012) Structuring an energy technology revolution. The MIT Press, Cambridge