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ORIGINAL ARTICLE

Concentrating solar power in a sustainable future electricity mix

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Abstract The capacity of a concentrating solar thermal power (CSP) plant can be considered flexible and firm, just like that of a conventional steam cycle power station. Periods without sunshine can be bridged by thermal energy storage or fuel, enabling a CSP plant to deliver power on demand at any time. To this technical quality is added the economic quality of electricity costs that will be stable for a lifetime because they are mainly composed of capital costs, spare parts and personnel. CSP is competitive with power from fuel oil and moving to break even in costs with natural gas by around 2020 and steam coal by around 2025. Carbon dioxide emissions of 10–40 tons/GWh, land use of 250–550 m^2/GWh and water consumption of 250 m^3/GWh (using dry cooling) compare favorably with other energy sources. Environmental benefits, the technical imperative of firm and at the same time flexible power supply, and the economic targets of affordability and cost stability are the main reasons for a significant role for CSP in a sustainable future electricity mix. Two case studies show the different roles CSP can play north and south of the Mediterranean Sea, in one case importing CSP to Germany for flexible power and in the second case using CSP in Jordan to provide firm and at the same time renewable power capacity for the quickly growing electricity demand.

Keywords Flexible power · Renewable energy storage · Concentrating solar power

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Introduction

Utility-scale concentrating solar thermal power (CSP) plants were first installed in California between 1986 and 1991 and have been reliably delivering electricity to the Californian grid since then, in the meantime for over 25 years. However, during times with low fuel prices, no new plants were installed, and only the dramatic global fuel cost escalation after the year 2000 allowed for a restart of this technology in Nevada in 2007 and in Spain in 2009.

Today, introducing CSP technology on the market is still difficult terrain. The utility-scale size of such power plants with 10 to 250 MW capacity and the large collector areas needed to collect enough solar energy for such a large size lead to much higher unit investments than those required for other renewable energy technologies such as photovoltaic (PV) or wind power, which can be implemented on a much smaller scale.

A consequence of this is that in the meantime about 300 GW of wind power and 100 GW of PV power capacities have been made available worldwide, but only 3 GW of CSP. Facilities for a further 2.5 GWs are under construction and for 8.5 GWs are in the planning stage, numbers that are still dwarfed by the 40 GW wind and the 30 GW PV capacity made available in 2011 (ESTELA 2012; GWEC 2012; EPIA 2012). Figure 1 shows that an installed capacity of 1.5 GW was achieved by CSP in 2011, by PV in 2000 and by wind power in 1990. As a consequence, the cost of PV and wind power has been reduced considerably in the past decades by learning and economies of scale, while the cost of CSP is still at a relatively high level at the beginning of its learning curve.

In the following, we provide information about the technical, economic and environmental quality of CSP and show two examples where this quality can be applied to achieve a sustainable future energy mix. In the first part of the article, we describe the fundamental characteristics of concentrating solar power technology with respect to its operational function in electricity grids, cost and environmental impact. In the second part, we present the results of two case studies on CSP integration in the national electricity mix. The first case study shows the potential role of CSP in Jordan as a Middle Eastern country with a fast-growing electricity demand and limited domestic fossil fuel resources, and the second case study shows the potential role of solar electricity imports from North Africa to Germany, complementing the German electricity mix with flexible, renewable power on demand.

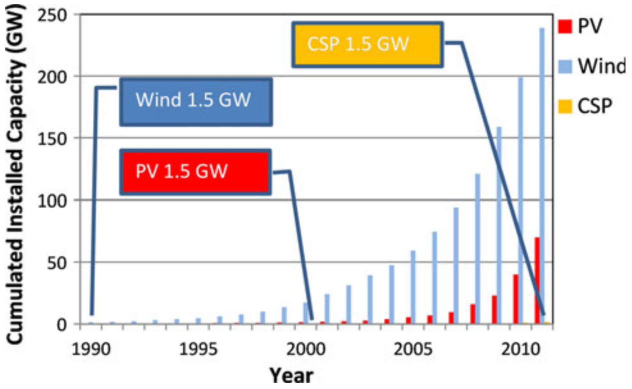


Fig. 1 Cumulated installed capacity of wind power, PV and CSP as a function of time according to ESTELA 2012; GWEC 2012 and EPIA 2012

Technical attributes of concentrating solar power

Availability, firm capacity and load flexibility are important technical attributes of power supply for stable and reliable electricity grid operation. In the past, these features were achieved by consuming ideally stored primary energy sources such as fuel oil, natural gas or coal and by burning them on demand in order to deliver electricity at any capacity needed and whenever required. Using freely flowing energy from renewable sources, which is not as easily stored as fossil fuels, will change this picture in the near term future. While the share of variable, fluctuating renewable sources is going to increase, flexible fossil and renewable energy sources will gain increasing importance and value (Chandler 2011).

The flexibility of power technologies refers to the minimum capacity at which a plant can be operated before it has to be shut down completely, the range of power capacity that can be freely set by the plant operator without limitations and the possible maximum speed of capacity changes that can be achieved (Table 1). Once shut down, the time required for restart is also relevant as it limits the availability of the plant. Especially thermal power plants take a long time to return to the grid if they are not kept on stand-by status, which however implies the consumption of fuel or other stored energy without generating electricity.

Flexible power will be an important element of a transformation of the electricity sector toward higher shares of renewable energy. It will be required to compensate fluctuations of supply from sources such as wind and photovoltaic systems that strongly depend on the changing availability of the natural resource. While Europe has considerable hydro-pump storage capacities and a relatively

Table 1 Technical parameters describing the flexibility of different power technologies related to the nominal capacity PN and the time needed for cold start after several days shutdown and for warm start after several hours shutdown (Nitsch et al. 2012)

Type of generation unit	Minimum capacity [% P_N]	Flexible range [% P_N]	Typical speed of capacity changes [% P_N/min]	Cold start [h]	Warm start [h]	Firm capacity [% P_N]
Lignite steam cycle	50	50–100	3	6–8	2	92
Coal steam cycle	30	30–100	4	4–5	2	86
Combined cycle	20	20–100	5	3–4	1	86
Natural gas Brayton cycle	20	20–100	10	0	0	42
Natural gas steam cycle	20–30	30–100	6	4–5	0.5–1	86
Nuclear steam cycle	60	60–100	4	8–12	2	93
Pump storage hydropower	25	25–100	100	0	–	90
River runoff hydropower	25	25–100	–	0	–	40
Biomass steam cycle	30–70	30–100	3–4	N.a.	N.a.	88
Wind power	0	–	–	–	–	0–12
Photovoltaic system	0	–	–	–	–	0
Geothermal organic Rankine cycle	N.a.	N.a.	N.a.	N.a.	N.a.	90
Concentrating solar steam cycle (CSP)	20–30	20–100	4–6	4–5	0.5–1	90

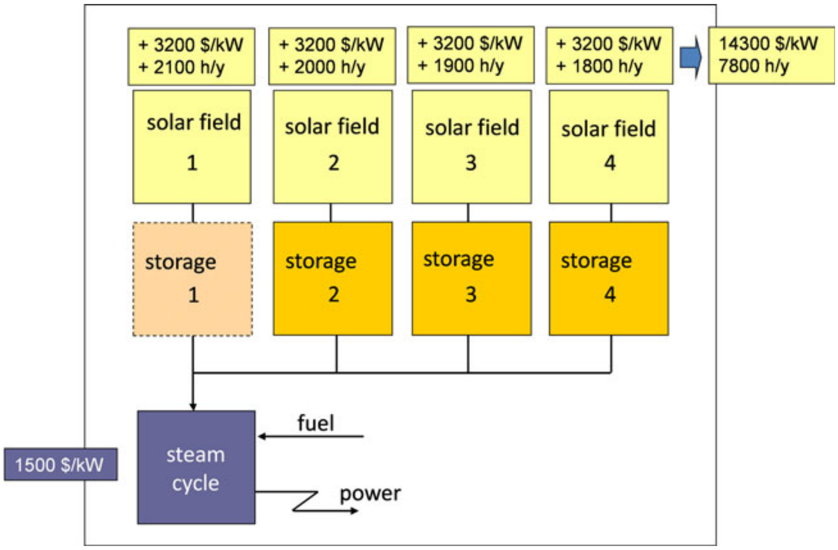


Fig. 2 Typical configuration of a hybrid CSP plant: the larger the solar field and storage, the higher the equivalent solar full load hours and the related investment of the plant. By adding fuel, the capacity can be guaranteed, and sunshine fluctuations can be compensated. Storage 1 is only needed in case solar energy is to be shifted toward the nighttime peak load; otherwise, the first solar field will directly feed the turbine

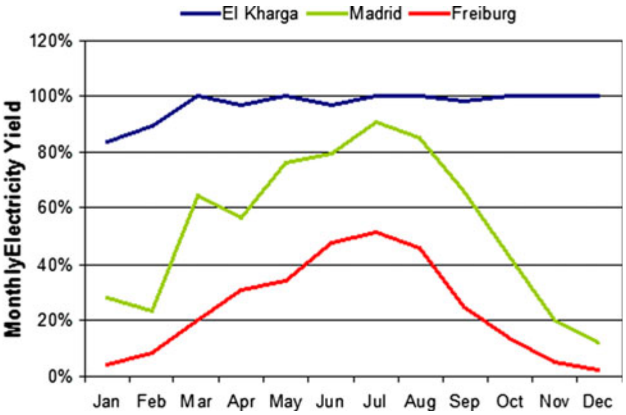


Fig. 3 Monthly solar electricity yield of a hypothetical CSP plant with a full-scale baseload design (Solar Multiple 4). The plant would provide around 8,000 equivalent fullload operating h/year in El Kharga, Egypt, 5,150 h/year in Madrid, Spain, and only 2,260 h/year in Freiburg, Germany (May 2005). The reasons for the clearly better performance in Egypt are more sunny days and a higher position of the sun in the sky (lower latitude), both leading to very high availability of solar power during the whole year

high net transfer capacity within its electricity grid to share energy flows among several countries, the Middle East and North Africa lack any options to buffer or compensate strong fluctuations of supply except fossil fuels and CSP plants with thermal energy storage and fossil fuel backup.

Another important attribute of power supply is firm capacity. As an example, baseload power plants such as nuclear or lignite plants are not necessarily very flexible, but most of their nominal installed capacity can be considered as fully available and firm. PV and wind power do not have the quality of firm capacity, because a simple cloud or calm can reduce the available capacity to a few percent or zero (Table 1). Wind and PV systems are flexible because their capacity can be reduced, but only when they are running. In contrast, CSP plants can produce flexible power on demand and can rely on their thermal energy storage capacity and eventual backup fuel to provide firm capacity whenever required.

Flexible power capacity on demand

A typical configuration of a CSP plant is shown in Fig. 2. While the size of the power block—e.g., an air-cooled steam cycle power station—is defined by the maximum power capacity required, the size of the solar field and the thermal energy storage system is defined by the annual equivalent full load operating hours scheduled for the plant. In other words, the capacity required defines the size of the turbine, while the energy required over the year defines the size of the solar field and storage, as shown in comprehensive reviews by Gil et al. (2010) and Medrano et al. (2010). The site of the plant will define its output (Fig. 3).

For economic reasons, the capacity of the thermal energy storage will not exceed the amount of heat required for more than 1 day of full load operation of the turbine. Therefore, even if the solar field and storage are designed for a certain number of solar operating hours per year, there may be periods without sunshine that must be bridged to provide power on demand. This can be achieved by using any available fuel as backup for steam generation, such as natural gas, coal or biomass, for example. If site conditions are as good as they are in most MENA countries, and the layout of the plant has been optimized for a specific demand, the need for co-firing usually will not exceed 30 % of the total annual electricity delivered by the plant, no matter whether the CSP plant is used for peaking, mid-merit or baseload supply. The main advantage of CSP over other renewable power technologies such as wind and PV systems is that the energy storage and backup capacity are already included in the plant design. Because CSP is complementary to wind and PV, Sionshansi and Denholm (2010) have found that the maximum achievable renewable energy share will be higher in case CSP can be added to the renewable energy mix, because otherwise fossil fuel would have to be used for balancing.

Primary, secondary and tertiary reserve capacity

Like any other turbine for power generation, the steam turbine of a CSP plant can act as a spinning wheel that will stabilize grid operation for several seconds during unforeseen outages that may occur somewhere in the grid. If the turbine is operated in a mode that leaves room for elevating the capacity further, a secondary reserve can also be provided. Unlike coal or gas plants, CSP plants can be operated in stand-by mode and kept “warm” without any fuel consumption, as long as the thermal energy storage is regularly filled by solar energy. This makes them a first-class option for renewable reserve capacity in future electricity grids, especially in regions where hydropower is scarce.

Reactive power

There is increasing concern about the availability of reactive power in future electricity grids that to a great extent would be fed by renewable energy. As the power generator of a CSP plant is the same as the one in a conventional steam cycle power station, the provision of reactive power is a normal service function that any CSP plant can deliver for stable grid operation.

Cost and value of concentrating solar power

Renewable and conventional power plants should be compared on the same basis of quality of supply, taking into account the ability to deliver electricity on demand, the stability of electricity costs and environmental impacts. Fossil fuels are ideally stored forms of energy with a high value providing power on demand, while electricity from PV or wind power is fluctuating and can only be stored with great technical effort and cost. Price stability is a natural intrinsic quality of all renewable sources of energy, as their cost is mainly composed of capital cost and personnel, while fossil fuel prices are rather volatile.

In the past decades, cost reduction rates of PV and wind power were around 20 %, and those for CSP were around 10–15 % each time the global installed capacity doubled (Neij 2008). Lower learning rates of CSP can be explained by its conventional power block component, which represents a significant part of the investment based on already well-developed technology and bearing only limited potential for further cost reduction.

This seems to support the opinion that PV and wind power are more competitive renewable energy options. However, pump storage and conventional backup plants must be included in any PV and wind power solutions in order to provide electricity on demand and to achieve a supply quality comparable to CSP.

Pump storage and conventional power plants are fully developed and also have only limited potential for further cost reduction. While pump storage has an efficiency of 70–90 %, thermal energy storage used by CSP shows efficiencies better than 95 %. While CSP already contains a conventional power plant that can rely on fossil or bio-fuel for backup in case there is a longer period without sunshine, the external backup capacity for wind and PV will continuously change between full load and minimum load in order to fill the remaining energy gaps, with related detrimental effects on cycle efficiency, durability and specific fuel consumption. Transmission losses among the supply, pump storage and conventional backup also play an important role in wind and PV systems, but are not relevant for CSP.

Therefore, learning rates and total system costs will be affected significantly if storage, backup and effects on the overall system efficiency are taken into consideration. Unfortunately, comparisons among PV, wind power and CSP often do not consider the total infrastructure and grid costs needed to achieve power on demand. In this respect, more investigation must be done, and a standard for such comparisons must still be established (Moser et al. 2013).

Figure 4 shows the expected cost of CSP versus fossil fuel-powered electricity generation under the assumption that a learning rate of 12 % can be applied to CSP expanding on a global scale from 1 GW in 2010 to about 950 GW in 2050 according to Trieb et al. (2012), Greenpeace (2009) and Philibert (2010). For a comparison with power from fossil fuels, we have assumed investment cost, efficiencies and annuities according to the numbers given in the caption, and we have taken the historical fuel cost development from Fig. 5 as reference to calculate a linear cost trend for gas, oil and coal for the coming decades. Finally, we have calculated the related electricity cost and its—also linear—trend into the future.

The comparison shows that CSP is already competitive with electricity from fuel oil and could break even with natural gas around 2020 and with coal about 5 years later. Again, when comparing these options, one must consider that the technical quality of CSP is almost equivalent to that of fossil fuels, while its economic quality with respect to cost stability is considerably higher. Feed-in tariffs for CSP are fixed for 20–30 years and will be lower for plants added at a later stage. For better comparison with fuels, the

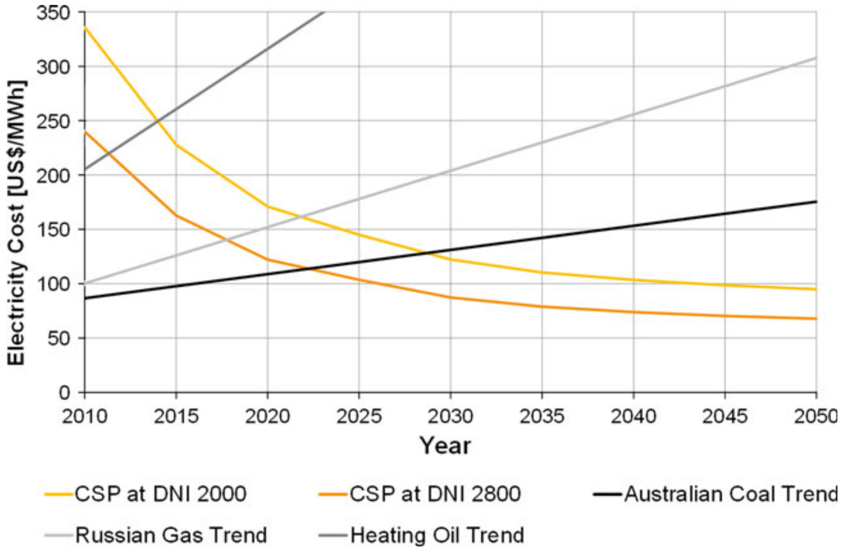


Fig. 4 Projected CSP electricity cost in US$/MWh$_{el}$ (solar only operation, dry cooling) for an assumed global capacity expansion from 1 GW in 2010 to 950 GW in 2050 for two different direct normal solar irradiance (DNI) levels of 2,000 and 2,800 kWh/m^2/year according to Trieb et al. (2012) in comparison to electricity costs from oil, coal and gas assuming a linear cost escalation trend as described in the text. Investment $1,500/kW for coal and oil, $750/kW for gas; total annuity 15 % of the investment per year including capital, insurance, operation and maintenance costs; average annual cycle efficiency 40 % for coal and oil, 50 % for gas; all plants assumed to have 4,000 equivalent full-load operating hours per year. Fuel prices from Fig. 4 were used for trend estimates. All numbers in constant $US in the year 2010

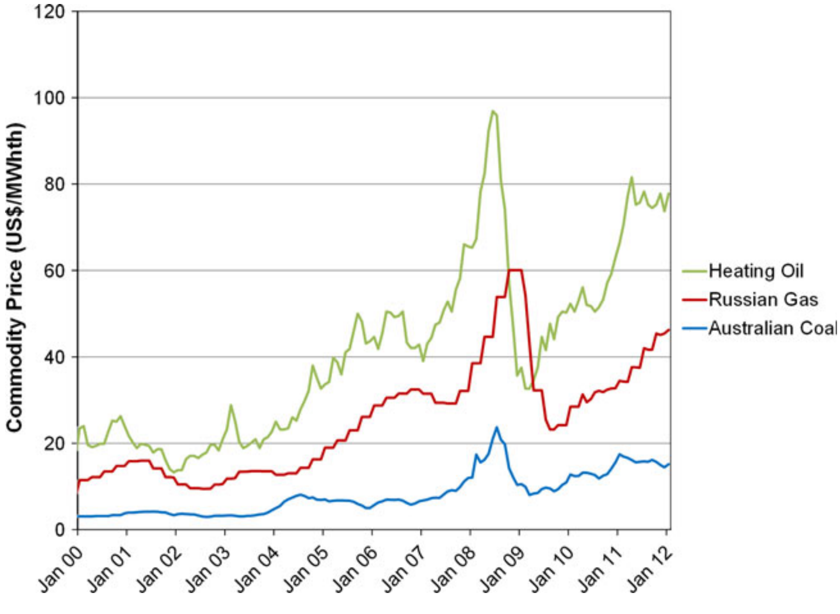


Fig. 5 Monthly mean commodity prices in the EU-MENA region in US$/MWh$_{th}$ for heating oil, natural gas and thermal coal between January 2000 and January 2012 from Indexmundi (2012) show a high volatility and reveal an increase of 400–450 % in the past decade (conversion from original data was calculated with heating values of 8.14 MWh$_{th}$/ton for steam coal, 9.6 MWh$_{th}$/1,000 m^3 for natural gas and 0.0392 MWh$_{th}$/gallon for heating oil, respectively)

cost of CSP shown here only relates to the solar part. Co-firing with fossil fuel would deliver additional power at a marginal cost approximating that of conventional plants.

Today, there is still no incentive for electricity producers to guarantee stable electricity prices for a long period. This type of quality is not requested yet, because fuels have been cheap in the past. However, this picture has changed dramatically, surprising all national economies worldwide with up to 450 % fuel cost escalation within the past 10 years. The consequences of not requesting price stability as an intrinsic quality of energy supply structures, and instead insisting on short-term least cost solutions, has in some cases proven to be rather painful and expensive: negative national budget balances, repressed economic development, economic and environmental damages, armed conflicts, pollution and climate change are only a few examples that prove that apparently cheap solutions can have a high cost.

Future escalation of electricity costs can be effectively fought by expanding renewable energy, because the capital and personnel costs of renewable power plants are fairly stable, while their marginal cost—the cost of primary energy consumed—is close to zero. Power supply security can be guaranteed by equally developing variable and flexible forms of renewable energy and by giving priority to fossil fuel only for balancing power. A well-balanced mix of flexible and variable, renewable and fossil forms of energy will be the basis for a high-quality future electricity supply. In order to achieve this objective, the present least-cost policy must be transformed into more comprehensive high-quality (sustainability) targets.

Environmental impacts of concentrating solar power

According to EASAC (2011), the potential environmental impacts of CSP include the following:

1. Atmospheric pollution from fuel combustion (in hybrid operation) and during production and construction of equipment (lifecycle emissions)
2. Impacts on flora and fauna
3. Water consumption
4. Land use and visual impact
5. Consumption of energy and materials
6. Noise of cooling towers when applying air or evaporation cooling
7. Smell and potential pollution of soil and water and fire hazard for systems using synthetic oil heat transfer fluid, which is considered a hazardous material.

However, also environmental benefits are obtained, for instance, from significantly reduced carbon dioxide emissions compared to fossil fuel-fired power generation, while providing electricity with the same quality in terms of firm power capacity on demand, flexibility, spinning reserve and reactive power. When comparing CSP to other renewable energy sources, only wind power and hydropower (and biogas from manure, not shown here) show lower lifecycle emissions of greenhouse gases (Fig. 6). However, the quality of power from those sources is not necessarily the same as that of power from CSP: hydropower usually has a significant impact on the environment if stored in large reservoirs or—like wind power or river-runoff hydropower—cannot be delivered on demand or used for balancing.

Emissions of other pollutants such as sulfur oxide, nitrates, etc., are also reduced significantly compared to the use of fossil fuels, and—on a lifecycle basis including production of the plants—are in the same order of magnitude as those emitted by other renewable sources of energy. A multi-criteria decision analysis (MCDA) from the NEEDS project by Ricci et al. (2009) ranks CSP among the best renewable options with respect to environmental impacts and the related external socioeconomic costs.

The use of water for evaporation cooling of the power cycle can be avoided using dry cooling instead. This will limit water consumption to mirror cleaning and basic plant services and reduce total water consumption from about 3,500 m^3/GWh to only 250 m^3/GWh according to Burkhardt et al. (2011).

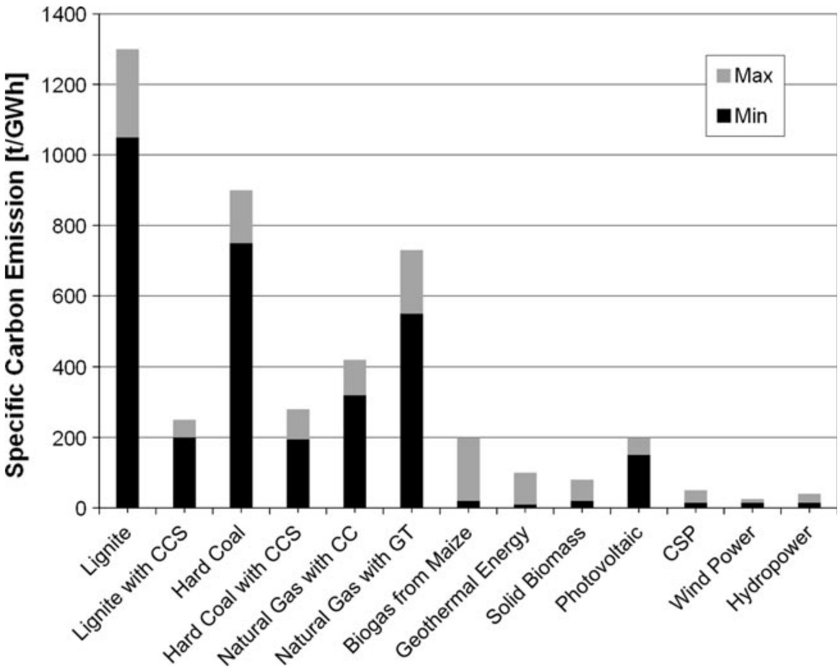


Fig. 6 Range of lifecycle greenhouse gas emissions (CO_2 equivalents in tons per GWh) for different electricity-generating technologies according to BMU (2011) and our own estimates, *CCS* Carbon capture and sequestration, *CC* combined cycle, *GT* gas turbine

Another important impact on the environment is the amount of land area required. A comparison of lifecycle land use of power generation from fossil fuels and from renewable sources can be found in Fthenakis and Hyung (2009). It shows that solar power technologies such as PV and CSP have the least impact on land transformation compared to other renewable sources and even compare favorably to electricity from coal and natural gas if the total land demand is considered not only for the power plants, but also for the required mining, transport infrastructure and eventual carbon capture and sequestration (Table 2).

Considering rooftop PV systems or wind parks, for example, in comparison to surface coal mining, oil spills or nuclear accidents that result in very long periods of recovery of the affected land areas, also the quality of land transformation can be significantly different, making a direct comparison of land transformation by different technologies in terms of area rather difficult.

A first estimate of the technology footprint of different renewable energy technologies in different regions can be derived from comparing the land-area-related electricity yield, shown in Fig. 7. The electricity yield from solar technologies includes large PV and concentrating PV installations as well as CSP plants.

While 1 km^2 of desert land can produce up to 250 GWh of electricity per year if CSP technology is implemented, energy crops from agricultural areas in Europe would only provide around 1 GWh/year even on the best available sites. In other words, in order to produce the same amount of electricity as 1 km^2 of desert in Egypt, for example, could produce by CSP, about 250 km^2 of arable land would be needed in Europe by energy crops. Such a consideration is of course relevant when developing strategies for sustainable energy supply.

Figure 7 also shows that easily storable forms of renewable energy such as hydropower and biomass are rather scarce in the MENA region, while relatively abundant in Europe. This explains why scenarios such as the MED-CSP study by Trieb et al. (2005) consider a large portion of the future electricity supply of the MENA region to be delivered by CSP. Adding up to 8 % load to their power system every year, the MENA countries will be forced to add an equivalent firm power capacity as well. The renewable energy option for firm power capacity in MENA with the largest potential is CSP, while hydropower, biomass and geothermal energy are much more limited and restricted to specific regions.

Again, this does not mean that wind, PV, biomass and hydropower are not interesting energy options for the MENA region, on the contrary. But it shows that a well-balanced mix of all available options that takes into consideration the different qualities and regional availabilities of resources will be of major importance in achieving a sustainable supply.

When comparing options with the same quality of supply defined by a firm power capacity available on demand and by a stable cost for the plant's total economic lifetime, concentrating solar power is one of the leading technologies, because it combines both qualities in one system. To this technical and economical quality is added the high environmental quality of CSP.

Table 2 Land transformation in m^2/GWh for specific power plant examples according to Fthenakis and Hyung (2009) and our own estimates

Photovoltaic	160–750*
Concentrating solar power	250–550**
Wind power	1,000–3,200
River runoff hydropower	3–5
Hydropower reservoirs	2,300–25,000
Natural gas	300–400
Natural gas + carbon capture	400–650***
Nuclear power	100–150****
Coal underground mining	60–550
Coal surface mining	150–1,500
Coal + carbon capture	100–2,500***

* Near zero for rooftop PV

** Original data for parabolic trough and regular sites; up to 50 % lower values than those shown here could be achieved by linear Fresnel systems at very good sites

*** This results from 30 % lower efficiency and higher land use for CO_2-sequestration and transport

**** The values shown here do not include major nuclear accidents and long-term contamination of land

External cost of power generation

The cost of producing electricity from a certain source usually does not include the following items, which can be considered as the external costs of power generation:

- Carbon emissions
- Pollution
- Electricity storage and backup capacity to balance load and demand
- Electricity transmission capacity to balance the grid
- Price volatility
- Decommissioning cost
- Insurance cost

Figure 8 shows some examples of a preliminary analysis of the literature and some of our own estimates for the above-mentioned different categories of external costs.

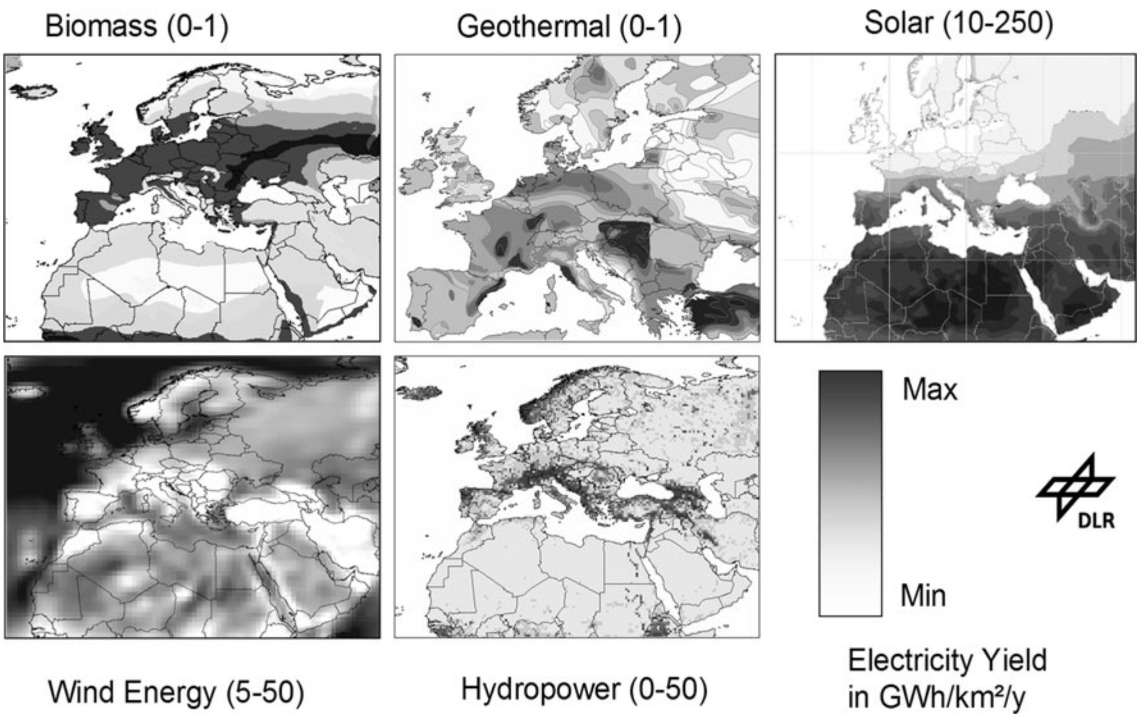
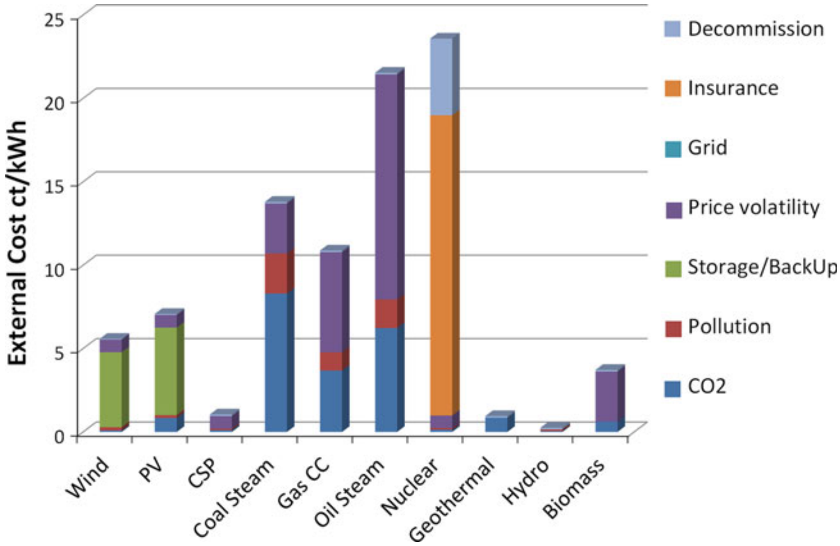


Fig. 7 Spatial distribution of the electricity yield per square kilometer land area from different renewable energy sources in GWh/km^2/year. Dark areas show maximum yield; bright areas show minimum yield. The range of electricity yield from each source is given in brackets. Source: Trieb and Müller-Steinhagen (2007)

Fig. 8 Exemplary external cost estimates for different power technologies. For nuclear insurance cost only the minimum value is displayed (NAO 2008; Günther et al. 2011; Wissel et al. 2008; Ricci et al. 2009; Krewitt and Schlomann 2006)



Decommissioning

Decommissioning is usually part of the direct cost calculation and is the difference of decommissioning costs and the rest value of the plant when decommissioned, e.g., the value of materials for recycling. In the case of nuclear power, decommissioning cost is often neglected or submitted to public or institutional financing by tax payers. For example, according to the National Audit Office of the UK, the decommissioning cost of the existing British nuclear plants is as high as 10,000–12,000 $/kW (NAO 2008). This would add around 4–5 ct/kWh of external cost for the decommissioning of this type of plants, basically doubling the price of nuclear power.

Insurance

Insurance is usually part of the fixed running cost of all types of power plants except for nuclear power plants, which are usually not insured, as the damage caused by nuclear accidents such as Chernobyl or Fukushima would lead to insurance rates that would make nuclear power economically unfeasible. Therefore, insurance for nuclear power can also be considered a significant external cost in the order of around 18 ct/kWh up to over 80 $/kWh, as calculated in a study of the top 100 German insurance companies (Günther et al. 2011).

Grid

Grid expansion is necessary once fluctuating sources such as wind and PV produce power capacity that is larger than demand and the available storage capacity, allowing surpluses to be exported to more distant regions to be used there. The cost cannot be generalized as it is dependent on the total power supply structure and the solar and wind supply share. Nuclear power and lignite plants can induce grid costs because of their limited flexibility (Table 1).

Backup

Backup must be provided when wind and PV plants cannot deliver power on demand. Wissel et al. (2008) estimate a backup cost of 2–3 ct/kWh for wind and PV power in Germany.

Pump storage

Pump storage required to attenuate the fluctuations of wind and PV would add an external cost of 2–3 ct/kWh assuming an additional investment cost of 1,700 $/kW and a storage efficiency of around 85 % (own calculations).

Price volatility

Price volatility induces external costs in the future that can only be avoided by buying the total fuel for the complete lifecycle of the power plants on the first day and treating it as part of the initial investment with its respective capital cost (interest rates). Assuming an interest rate of 7.5 %, the additional cost of fuel, if part of the initial investment, would today be around 3 ct/kWh for coal, 6 ct/kWh for gas and 13.5 ct/kWh for fuel oil. This would guarantee price stability for the lifetime, but turn power from fossil fuels into a rather expensive source of energy. The cost of renewable power is mainly based on the capital cost and cost of personnel, thus being intrinsically stable except for the part of fossil fuel backup required. In the cases of wind power, PV and CSP, we have assumed that 10 % of energy production must be provided by backup natural gas. Depending on the demand situation and having in mind possible competition with food, the price of biomass is also affected by considerable volatility and thus can induce a related external cost.

The external cost of pollution and carbon dioxide emissions from power generation on the basis of lifecycle analysis has already been assessed by Ricci et al. (2009) and Krewitt and Schlomann (2006). The external cost of pollution ranges between 1 ct/kWh for natural gas and 2.5 ct/kWh for coal plants. The cost of carbon emissions varies from 3.5 ct/kWh for gas to 7.5 ct/kWh for coal plants.

The examples of external costs given here are limited to the assumptions and cases given and cannot be easily generalized. However they show that fossil fuels, nuclear power as well as fluctuating renewables tend to induce significant external costs, while flexible renewable energy sources do not, thus compensating part of their usually higher direct cost by lower external costs. Electricity cost optimization for a national economy should always have that in mind.

Case studies for CSP applications

Case 1: CSP imports in the future German electricity mix

The availability of flexible power capacity will achieve major importance in the future electricity mix, especially if this mix is supposed to be dominated by renewable sources. Germany, like many European countries, has abundant potentials for variable renewable energy sources such as river runoff, wind and photovoltaic power, but only limited potential for easily storable sources such as biomass, hydropower from large dams and geothermal power (Nitsch et al. 2012).

Under German climatic conditions, there is no economically attractive potential for the installation of CSP plants. Therefore, flexible power from CSP will have to be imported from the south. The time series in winter and summer in Fig. 9 show two typical situations that may occur in a future electricity mix that would be based to a large extent—in this case by about 90 %—on renewable sources.

In summer, there will be little power from wind parks but high input from PV, while the other power sources will be used for the baseload and balancing power and will have to fill the gap between fluctuating renewable supply and otherwise fluctuating demand. Scenario 1, which will be based mainly on fluctuating sources such as wind and PV

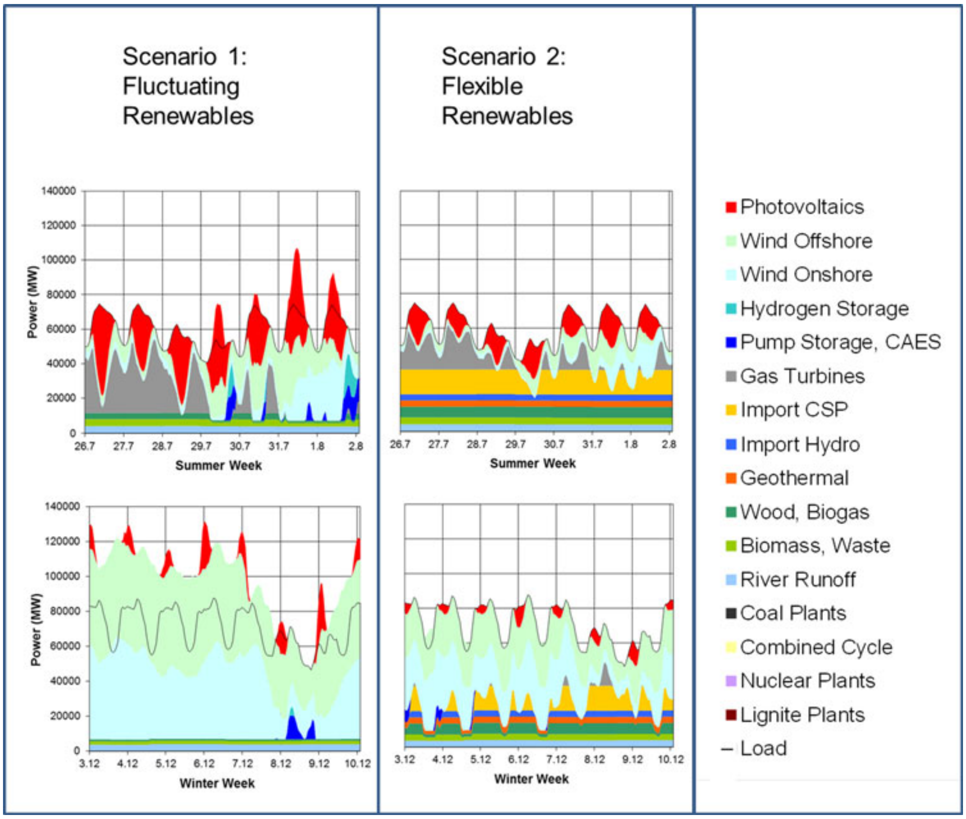


Fig. 9 Flexible renewable and fossil sources complementing fluctuating renewable sources in a possible future electricity mix in Germany with a 90 % renewable share in two scenarios for the year 2050. The figure shows a selected 1-week sequence in summer (*top*) and winter (*bottom*) from an annual hourly time series analysis of the German power plant structure. Significant surplus power and thus the need for electricity storage and grid expansion in scenario 1 are effectively avoided in scenario 2 with solar electricity imports from North Africa (Trieb 2013)

will produce noticeable surplus peaks during daytime, while scenario 2 with solar power imports from North Africa will not produce considerable surplus.

In winter, wind power from onshore and offshore wind parks will deliver major shares of energy to the grid, requiring sufficient network transfer capacity from north to south and sufficient electricity storage capacity to buffer related fluctuations. On the other hand, there will be very little input from PV in this season. During peak wind supply and low demand, all other power plants will be operated at their minimum capacity or stand-by in order to be able to come into operation as fast as possible when the supply from wind power is reduced. Scenario 1 will produce surplus in the order of magnitude of the peak load, while scenario 2 will not produce noticeable surpluses (Trieb 2013).

The role of CSP imports in such a mix is to provide flexible, cost-efficient and sustainable electricity on demand. This high-quality electricity would be transported from North Africa and the Middle East to Europe via high voltage direct current (HVDC) power lines that would be explicitly built and financed for that purpose. The lines would provide renewable electricity on demand just as required at the feed-in points in Europe at a cost that would be stable for at least 40 years of operation. The cost of solar electricity imports from North Africa to Germany has been quantified by Trieb et al. (2012) to be in the range of 0.07–0.11 €/kWh after being introduced for the first time in 2020.

Another source of energy with comparable quality of supply will be electricity imported from Norway, which will mainly consist of wind power stored in large hydropower pump storage facilities and hydropower from dams released on demand for the German supply. The proportion of either one or the other solution in the future electricity mix will be determined by public acceptance, political frame conditions, environmental impacts, costs and technical restrictions (Trieb and Müller-Steinhagen 2007).

Case 2: CSP in the Jordanian electricity mix

Jordan, as well as many other countries in the MENA region, has experienced a significant increase in both peak load and annual electricity consumption within the last decade due to strong growth of the economy and population. The peak load of Jordan’s interconnected system has more than doubled from 1,206 MW in the year 2000 to 2,650 MW in 2010, which is equivalent to an average growth rate of 8 % per year. The electricity generated per year increased within the same time-frame from 7,375 GWh to 14,683 GWh. Jordan has reacted to the increased electricity demand by adding almost 2000 MW of new combined-cycle gas turbine (CCGT) power plants (ERC 2010).

In Jordan, baseload and mid-merit power are generated by the newly added CCGT power plants using natural gas imported from Egypt. The annual gas imports from Egypt have been in the range of 3 billion m^3 whereby 80 % of the annual electricity demand could be generated. However, at the end of 2011, Jordan and Egypt signed a new contract for gas imports that specified a price of around 18 US\$/MWh$_{th}$. This represents a triplication of the gas price of the former contract between both countries. The price will be reviewed every 2 years and will be adapted step by step to European price levels—which at present are more than twice as high as the Nuqudy price (2011).

During hours of peak and upper mid-merit demand, old and inefficient gas and steam turbines powered by expensive light fuel oil (LFO), diesel or heavy fuel oil (HFO) are utilized for power generation. Crude oil and LFO are imported from Saudi Arabia, UAE, Kuwait and Iraq for a price just slightly below world market prices as reported by Fox Business (2011). Thus, costs for peak and upper mid-merit power generation are significantly higher than the average electricity cost and especially the cost of baseload power from natural gas.

A strategy of introducing large amounts of renewable energy into the Jordanian power supply structures must take into account that no significant electricity storage options are available in the region. Large-scale pump storage, compressed air energy storage and hydrogen production from water are not feasible or at least are rather limited in their potential in Jordan and the MENA region, as their natural prerequisites are not abundantly available. The only easily storable energy options in the region are fossil fuels and solar heat within a CSP plant. Flexible and at the same time renewable energy sources such as hydropower, biomass or geothermal energy are also rather scarce, while only the potential for CSP is extremely large (Trieb et al. 2005).

The possibility to compensate large-scale fluctuations of wind and PV power by exchanging power with neighbors through the international electricity grid is also very limited in the MENA region, because the net transfer capacity between most MENA countries does not exceed 500 MW.

In order to cope with growing demand, a country like Jordan has to add a firm power capacity of up to 2,000 MW every 5 years for the next 2–3 decades. The compulsive need for firm capacity only leaves the option of conventional or CSP sources for power plants to be installed, while in both cases wind and PV can be used as complementary fuel savers.

Such a transition has been described by Fichter et al. (2013). Figure 10 shows an analysis of the Jordanian power park. The mixed integer linear optimization program REMix-CEM (Renewable Energy Mix-Capacity Expansion Model) optimizes the unit commitment of the existing power plants in hourly time steps for a 1-year cycle taking into account all relevant restrictions on the system level (e.g., peak, spinning and tertiary reserve requirements or fuel availability) as well as on the unit level (e.g., start-up time, part load efficiency, ambient temperature influence, minimum load rate or maximum ramp rates). Besides the already existing power plants, several investment opportunities for new conventional and renewable power plants are taken into account and added to the existing portfolio if the utilization and the associated capital and operation costs contribute to lower total system costs.

Figure 10 (top) shows the situation in the year 2012 with almost 100 % fossil fuel fired power generation. A strategy to introduce large amounts of CSP in a national electricity mix is to substitute the most expensive elements of the national power supply structure first, which typically are fuel oil fired peaking plants. While the cost learning curve of CSP proceeds (Fig. 4), mid-merit and baseload supply will subsequently also become competitive. As shown in Fig. 10 (center), by 2017 the full cost including capital and operation of first CSP peaking plants would already be lower than the marginal cost of diesel- and LFO-based power plants, thus substituting the electricity output from existing and also from competing new power plants of this type.

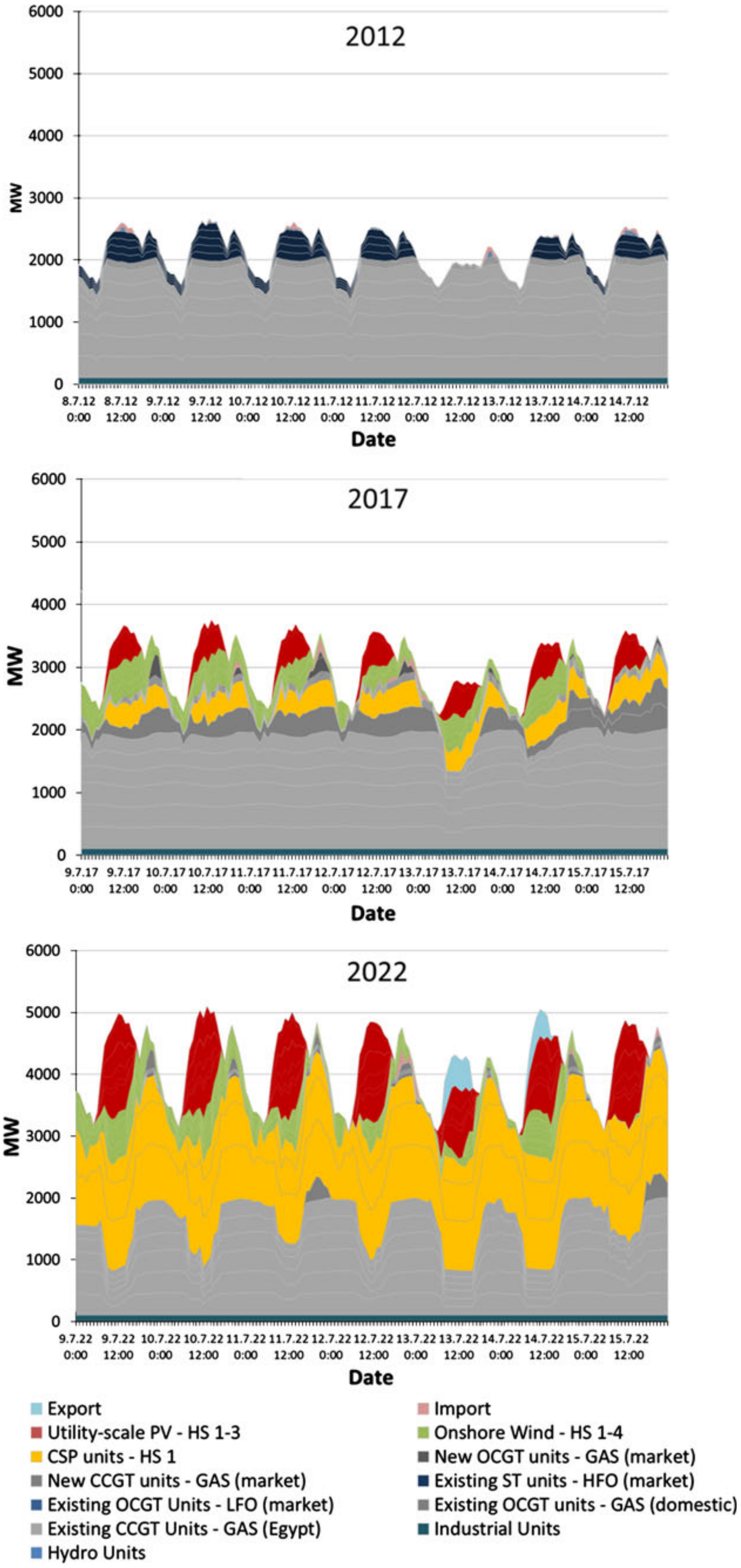
Due to further fuel cost escalation and further reduction of the capital cost of CSP by learning and economies of scale, in the long term large amounts of the baseload and medium load segment in Jordan could be provided competitively by CSP, and the remaining use of fossil fuels could increasingly concentrate on the firm and flexible power capacity (Fig. 10, bottom).

A very interesting integrated option for Jordan is the future interaction of PV and CSP, with CSP being introduced for peaking and later for baseload and flexible power, and PV being applied to deliver low-cost power during daytime peaking hours (Fig. 10, center and bottom). The introduction of wind power will also be of advantage, e.g., saving rather expensive natural gas within the baseload segment. A well-balanced mix of renewable sources together with intelligent use of ideally stored fossil fuels can lead to a reliable and economic supply structure, and can stop the never ending spiral of energy cost escalation as well as the related explosion of energy subsidies in many countries like Jordan.

Conclusions

The role of concentrating solar power technology in the future electricity mix is to provide reliable, flexible and at the same time renewable energy for grid balancing, price stabilization and limiting the environmental impacts of power generation.

Fig. 10 Power generation in Jordan in a selected summer week for the years 2012, 2017 and 2022 according to the results of the Jordan case study (Fichter et al. 2013). RE technologies are integrated step by step, whereby Jordan's dependence on fossil fuel imports is significantly reduced, security of the electricity supply is maintained by sufficient firm capacity, and total power generation costs are minimized



A CSP plant can provide firm power capacity on demand, and it can be designed for baseload, mid-merit or peak load supply. Due to the massive introduction of variable renewable energy technologies such as PV and wind power, these load categories will however disappear in the medium-term future and will be replaced by new, more dynamic transients that will occur in the electricity grid. These transients will have to be balanced out by power plants that are capable of providing firm, continuous power, but are at the same time very flexible with respect to their power capacity. Especially the MENA region, with its fast-growing electricity demand, will require the addition of firm power capacity on a large scale.

This technical quality of power supply can be provided by fossil fuels, large hydropower dams, biomass, geothermal energy and, last but not least, CSP stations. Fossil fuels, which are ideally stored forms of energy, are in principle perfect for balancing power, but are causing both economic and environmental instability worldwide. The availability of hydropower and biomass is limited even in Europe, and much more so in arid regions such as the Middle East and North Africa. On the other hand, a large potential for CSP exists in the arid regions worldwide, which is several orders of magnitude larger than human energy demand will ever be (Trieb et al. 2009).

In terms of economic quality, renewable energy sources have the large advantage of providing power at stable prices, because their cost is mainly composed of capital costs, personnel costs, and operation and maintenance, which usually do not contribute to significant cost escalations. CSP is already competitive with power from fuel oil. Due to learning and economies of scale, the cost of future CSP plants can still be reduced significantly to break even with natural gas around 2020 and with steam coal around 2025. Once installed, the cost of a CSP plant will be stable[1] for its total lifetime.

The economic quality and cost stability of renewable electricity sources cannot be provided by any other energy carrier. The cost of fossil fuels is highly volatile and has a clear trend upwards, while the true cost of nuclear power is revealed during events such as the Chernobyl and Fukushima disasters and after the decommissioning of such plants.

Environmental concerns such as climate change and pollution have triggered the development and market introduction of all forms of renewable energy except hydropower. The environmental quality of renewable energy compared to fossil or nuclear fuels is beyond dispute. However, there are significant differences among the renewable options with respect to greenhouse gas emissions, local pollution and land transformation that will have an impact on project realization and cost. As an example, lifecycle carbon emissions of CSP of 20–40 t/GWh are significantly lower than those from biomass or photovoltaic power, and land transformation by CSP of 250–550 m^2/GWh can be several orders of magnitude lower than that caused by hydropower or energy crops.

There is no doubt that CSP is one of the most complex elements of a future sustainable energy supply system: its single-unit investment—especially for baseload design—can be extremely high, feasible unit sizes of CSP plants of 10–250 MW capacity are not really small, most of the existing potential sites for CSP are located in relatively remote regions, and a CSP plant obviously requires considerable land that has to be secured before any project development can take place. The construction of a CSP plant (2–3 years) usually takes longer than that of a PV plant or an onshore wind park, which can be erected in less than 1 year.

The major economic drawback—which in the long run could however turn into an advantage—when comparing CSP to other fossil and renewable electricity options seems to be that costs that are typically externalized by other technologies, such as electricity storage, backup capacity and grid stabilization, and environmental and societal costs, are almost totally covered directly within the CSP system instead of being externalized. It is true that the investment cost of CSP is usually higher than that of wind parks and PV panels, but the quality of CSP supply is also higher and thus justifies a higher cost. The same is true for a comparison with fossil fuels.

Decision makers aiming toward sustainable supply structures must change from the common “least-cost thinking” to “comprehensive economic quality thinking.” They must change from apparently cheap solutions with high external costs to high-quality integrated solutions in order to build diversified supply structures that really are secure, affordable and compatible with the environment and socioeconomic development, or, in one word, sustainable.

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[1] This is only valid in terms of constant (real) monetary value.

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