Description of electricity generation technologies

This chapter describes the eight electricity generation technologies considered in this publication by illustrating the basic principles behind each form of electricity generation, the conventional sub-types for each technology, as well as their common application and specific technological characteristics. Lastly, it will outline certain characteristics of power plants for each technology, which were assumed to be found most commonly[32] in the MENA region as primary reference to obtain the attribute values.

Solar power technologies

There are two main groups of technologies that are being used to generate electricity based on solar radiation: Photovoltaic (PV) cells directly convert solar radiation into electricity; Concentrating Solar Power (CSP) plants capture energy from solar radiation to produce heat that is then converted into electricity via a conventional thermal cycle. These two technologies are described in detail below.

Photovoltaics

PV cells directly convert solar radiation into electricity by exploiting the photovoltaic effect[33] using semiconductor materials. This process is silent and requires no moving parts (IFC, 2015, p.24). In contrast to CSP technologies, PV cells can use direct and diffused solar radiation[34] making operation possible even on cloudy days, albeit with reduced efficiency (IRENA, 2012b, p. 4; IEA, 2014a, p. 13). Individual PV cells are combined in series or in parallel to produce higher voltage. Together, they form a PV module or panel. In general, a PV system consists of a

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32   However, it is beyond the scope of this publication to select or propose a detailed sub-technology configuration for each electricity generation technology for several reasons: first, attribute values are often only available for each technology family with only few distinctions for sub-configurations. Secondly, it is the focus of this publication to compare the different technology families without going into details for exact technological configurations. Thirdly, it is also often not very clear which technology configurations will be chosen in the future and it can be assumed that a mixture of sub-technologies will be implemented.

33   If solar radiation falls onto two semi-conducting materials that are in close contact, it provides the electrons with energy to move in one direction across the cross-junction between the two materials. This process generates voltage and direct current as one side of the p-n junction is negatively charged compared to the other (IEA-ETSAP & IRENA, 2013b, p. 5). The photovoltaic effect is explained in detail in Kaltschmitt & Rau (2007, p. 229-238).

34   The total solar radiation received on an area unit is measured with the "Global Horizontal Irradiance" (GHI) that is the sum of the "Direct Normal Irradiation" (DNI) and the "Diffuse Horizontal Irradiation" (DHI) (IFC, 2015, p. 43).

number of PV modules that are connected, forming the PV field. Additionally, the "Balance of Systems" (BOS) includes auxiliary components, such as the racking and mounting structure, cabling, power, and monitoring controls, and - as PV systems produce direct current (DC) - an inverter that converts DC into alternating current (AC), if the system will be connected to the grid (for a schematic overview of a PV system see Figure 31).
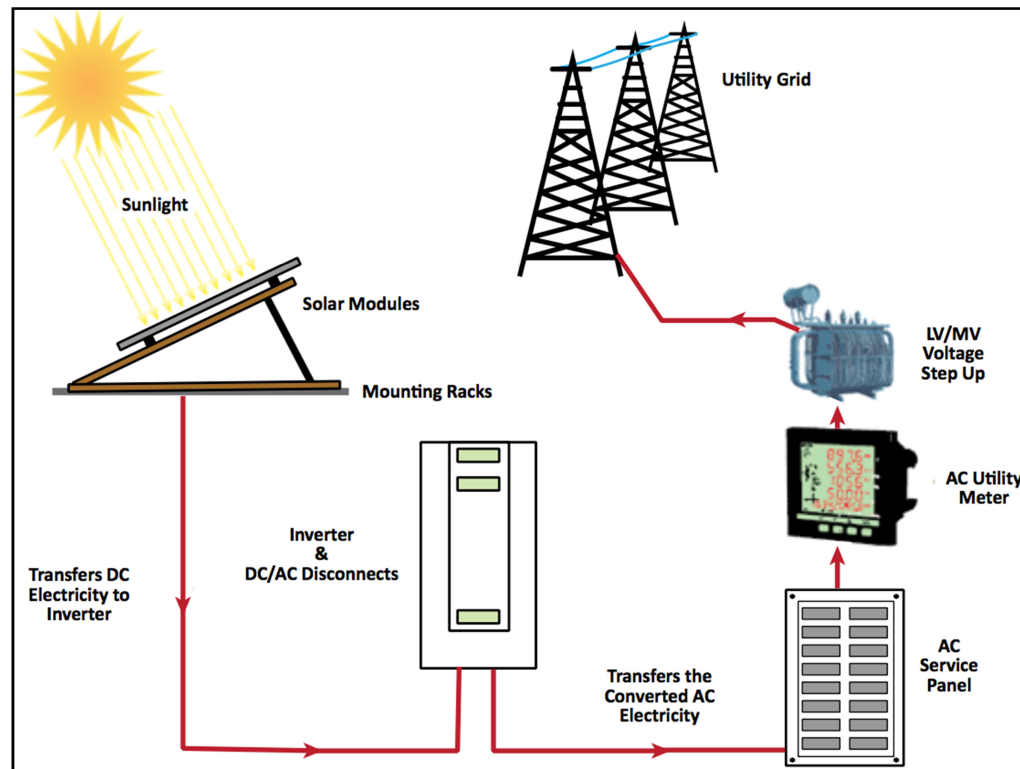

Figure 31: Schematic overview of a PV power plant.

Source: IFC, 2015, p. 24.

Installations of PV systems can either be fixed or track the sun on one or two axis (IEA-ETSAP & IRENA, 2013b, p. 7; IEA, 2014a, p. 11). As they vary greatly, PV technologies are grouped into three categories based on their difference in basic materials used and their commercial maturity.

\   **First-generation PV systems**: First generation PV systems are based on crystalline silicon (c-Si) wafers, which are either monocrystalline silicon (mono-Si) (also called single crystalline, sc-Si) wafers or polycrystalline silicon (also called multicrystalline, mc-Si) wafers. They are manufactured by growing ingots of silicon and cutting wafers of silicon from the block. Cells based on multicrystalline silicon are cheaper to manufacture, but also have lower efficiency (see Figure 32) (IPCC, 2012, p. 351; IEA-ETSAP & IRENA,

2013b, p. 7). PV systems based on c-Si are fully commercial and mature, dominate the current market with about 90% share (IEA, 2014a, p. 9) and will likely continue to continue to do so until 2023 (Rech & Elsner, 2016, p. 19). Despite recent drastic price reductions, it is expected that cost reductions are still possible, e.g., through economies of scale and technological advances in the manufacturing process due to R&D activities (IRENA, 2012b, p. 5; Rech & Elsner, 2016, p. 25).

\ **Second-generation PV systems**: These PV systems are based on a different manufacturing process: instead of growing and cutting an ingot of silicon into wafers, the method involves depositing a thin film of photosensitive material on a low-cost substrate (Frankl et al., 2005, p. 6). The manufacturing process of thin-film based modules is highly automated with no need to assemble modules from individual cells and consumes less materials as well as energy compared to c-Si-based modules (IEA, 2014a, p. 11; Solarserver, 2016). Three[35] main families of thin-film technologies can be distinguished: amorphous (a-Si) and micromorph silicon (a-Si/μc-Si), cadmium telluride (CdTe), copper indium selenide (CIS), and copper indium (gallium) diselenide (CIGS). Thin-film technologies are in general cheaper than crystalline wafers, but also have lower efficiency (for a comparison of PV module efficiencies see Figure 31). Second-generation PV systems are in an early market deployment stage (IRENA, 2012b, p. 4).

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[35] The heterojunction with intrinsic thin-film layer (HIT) technology represents a mixture between wafer-based silicon and thin-film technology. It consists out of a mono-thin-crystalline silicon wafer that is surrounded by a thin amorphous silicon layer and has even higher efficiency than normal crystalline modules, but also higher costs (IFC, 2015, p. 27).
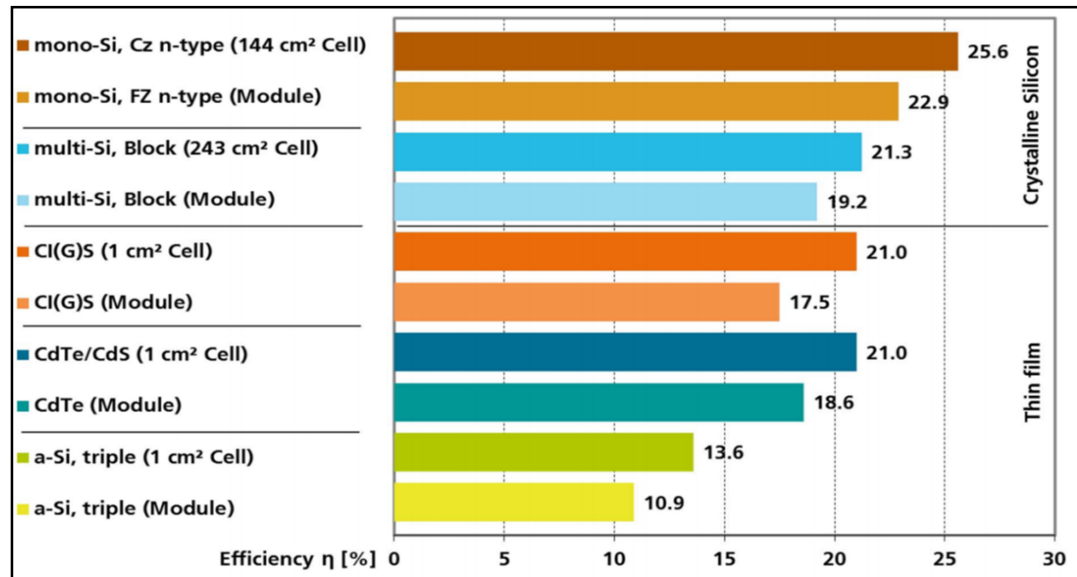
Figure 32: Efficiencies of crystalline silicon and thin-film based PV cells and modules.

Source: Fraunhofer ISE, 2016, p. 24.

Third-generation PV systems: Third-generation PV systems are emerging and novel technologies that are in a pre-commercial stage. They promise higher efficiencies, but still need more R&D (see Figure 42) (Fraunhofer ISE and NREL, 2016, p. 14). As can be seen in Figure 42, divers third-generation PV technologies are projected to reach an efficiency up to 50 % until the year 2035, which well exceeds the currently highest rate of mono-Si crystalline silicon wafers. Third generation technologies include Concentrating PV (CPV), dye-sensitized solar cells (DSSC), and organic solar cells. CPV is the most advanced technology within this group. CPV concentrates direct solar radiation - as do CSP technologies - via lenses or mirrors onto highly efficient multi-junction solar cells, allowing concentration factors ranging from 2 up to 1,000. To maximize this effect, CPV needs tracking systems (single or double axis) resulting in higher costs that may be offset by higher efficiency. Due to their dependence on direct solar radiation, CPV systems make the most sense within in the "sun-belt" region of the world (see below) (IRENA, 2012b, p. 6-7; IEA-ETSAP & IRENA, 2013b, p. 13-15).
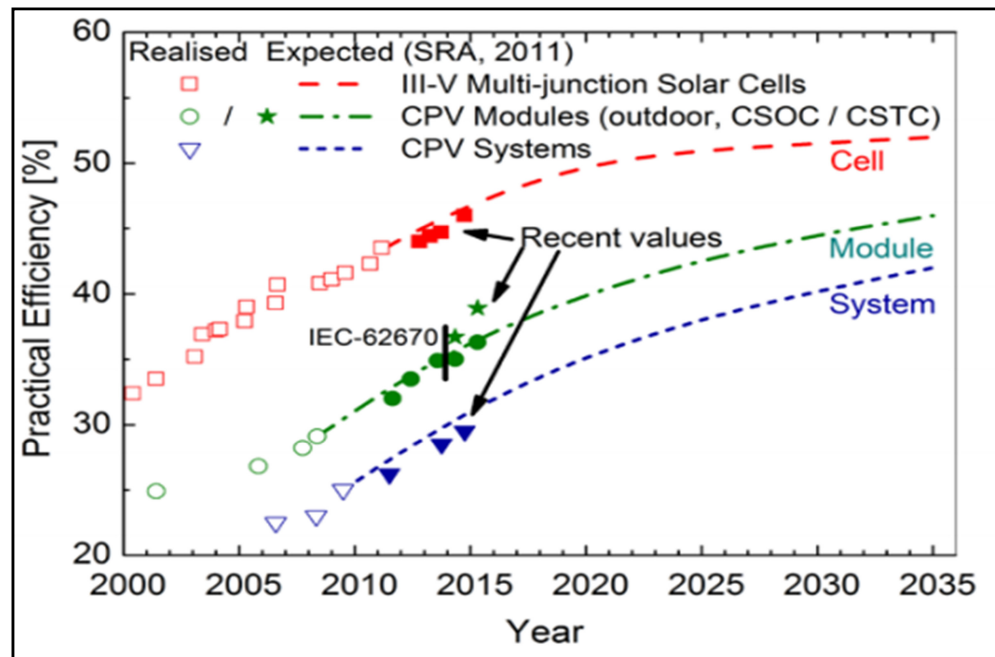
Figure 33: Efficiency of third-generation III-V multi-junction solar cells and CPV modules.
Source: Fraunhofer ISE & NREL, 2016, p. 14.

One reason for the wide deployment of PV systems is their modular design and, hence, their large application span that includes roof-mounted residential PV systems, which usually do not exceed 20 kW; roof-mounted large-scale systems on buildings (about 1 MW), e.g., on hospitals, schools, and shopping centers; and utility-scale PV systems (> 1 MW to more than 500 MW), both on- and off-grid (IRENA, 2012b, p. 22; Breeze, 2014, p. 283). Historically, decentralized systems have dominated the PV market. However, driven by the drastic price decline and regulatory incentives, the growth of utility-scale applications has accelerated in recent years. Consequently, centralized PV systems nowadays have equal market shares compared to decentralized systems and, if current trends continue, will dominate the future market (IRENA, 2012b, p. 13; SPE, 2015, p. 16). Environmental concerns for PV systems are relatively low as there is no fuel combustion process involved during their operation. However, large-scale storage devices are still relatively uncommon as they are not cost-competitive, yet, making PV systems a fluctuating source of electricity with limited capacity factors (IEA-ETSAP & IRENA, 2013b, p. 16). However, the capacity factor of a PV system depends highly on the solar insolation. PV systems in regions with relatively low insolation achieve a capacity factor of 11.6%, while PV systems in regions with good solar resources can achieve a capacity factor of up to 24.3% (IEA, 2014a, p. 12). Like CSP mirrors, PV

systems need water for cleaning the modules (1.5 l/m^2 of PV module) (IFC, 2015, p. 63).

The cost structure of small-scale and utility-scale PV systems differs significantly: while the balance of systems and installation can add up to about 50 to 60% of the total costs for residential applications, it can be as low as 10 to 20% for utility-scale systems (IRENA, 2012b, p. 19; Fraas, 2014, p. 77). This is why the costs of modules are more important for utility-scale applications and, hence, that the market share of cheaper, but less efficient thin-film-based PV modules is relatively higher compared to c-Si modules for utility-scale applications (IRENA, 2012b, p. 23). Indeed, the two biggest utility-scale PV systems in the MENA region, Ramat Hovav in Israel (37.5 MW) and Shams Ma'an[36] in Jordan (52.2 MW), both use thin-film based PV modules (Firstsolar, 2015).

For these reasons, a utility-scale PV ground-mounted power plant based on second generation thin-film modules using a single-axis tracking device is assumed as the reference PV power plant in this publication.

Concentrating Solar Power (CSP)

The principle functionality of a CSP plant can be described as follows: a collector system, mostly different kinds of mirrors depending on the CSP technology, is used to concentrate solar radiation onto a receiver. The solar radiation is then converted into thermal energy inside the receiver and transferred to a heat transfer medium. In the next step, the thermal energy is transformed into mechanical energy through a steam turbine. Lastly, the mechanical energy is converted into electricity by the means of a generator (Weinrebe & Ortmanns, 2007, p. 172). Because high temperatures are needed to operate thermal power engines effectively, the solar radiation must be concentrated. CSP plants basically replace the heat source of conventional power plants, e.g., coal, gas, or oil, with an alternative heat source. Hence, two parts of any CSP plant can be distinguished: a solar part and a conventional power block (for the conventional part of a thermal power plant see chapter 1.5 coal-fired power plants) (Viebahn et al., 2011, p. 4421; IPCC, 2012, p. 355).

In contrast to PV, CSP plants can utilize only the direct component of the sunlight, i.e., Direct Normal Irradiance, DNI, also simply called "direct sunlight." On sunny days, this direct sunlight can be as high as 90% of the total sunlight (see Footnote 34), but it can, however, also be negligible during cloudy days (IEA-ETSAP & IRENA,

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[36] The plant is currently under construction.

2013a, p. 5). As a consequence, CSP plants are typically utilized in the global "sun belt" between 20 and the 40 degrees south and north latitudes with an annual DNI higher than 2000 kWh/m^2/y, which are often cloud-free, arid, or semi-arid regions, e.g., the MENA-region, but also South Africa, the southwestern United States, Australia, and parts of China (Trieb et al., 2009, p. 2; Viebahn et al., 2011, p. 4421; IPCC, 2012, p. 355; IRENA, 2012a, p. 7; IEA-ETSAP & IRENA, 2013a, p. 5).
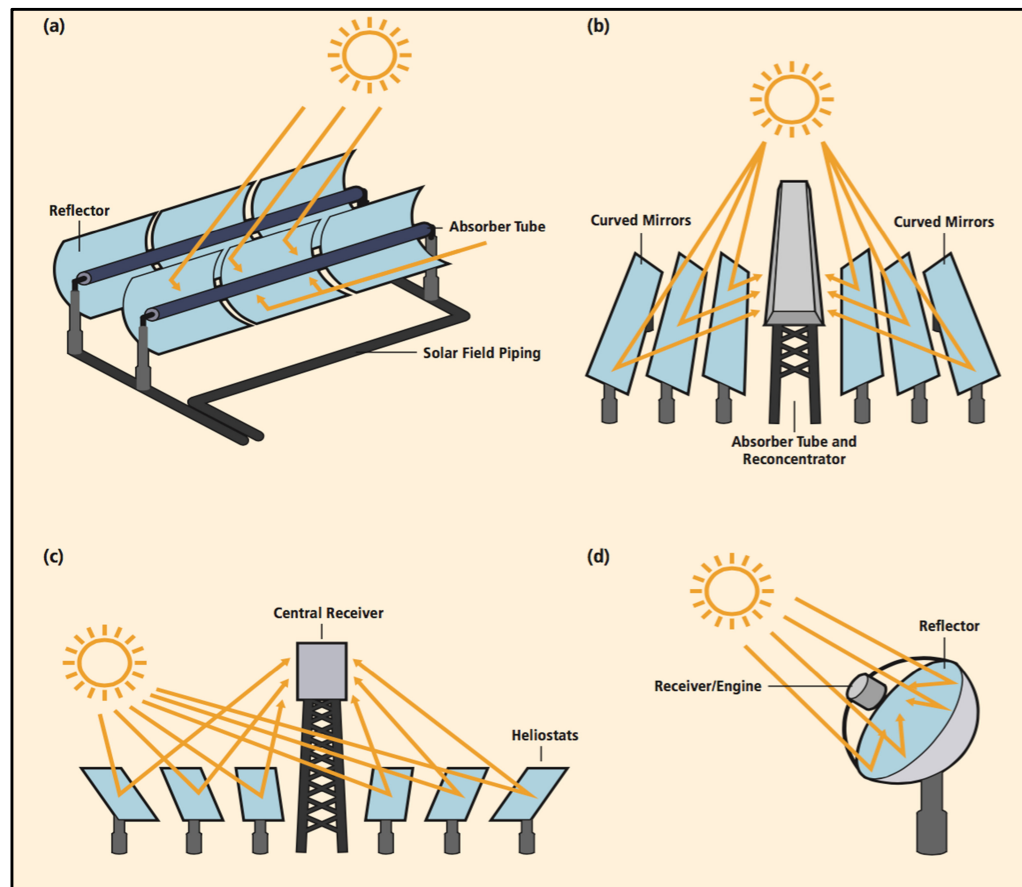

Figure 34: Schematic overview of the four CSP technologies: (a) parabolic trough, (b) linear Fresnel, (c) power tower, and (d) dish systems.

Sources: IPCC, 2012, p. 356.

There exist four CSP technologies, which are distinguished by the way they concentrate the solar radiation: the "line-focusing systems" that concentrate the solar radiation on a line, including parabolic trough and linear Fresnel collector systems, and "point-focusing system" that concentrate solar radiation on a single point, including dish systems and central receiver systems, i.e., solar tower plants (IRENA, 2012a, p. 4; IPCC, 2012, p.355). The specific features of each of the four CSP technologies (see Figure 34) are described below.

\ **Parabolic Trough Collector technology**: Parabolic Trough Collectors (PTC) are the oldest CSP technology, first build in Cairo in 1912; the first modern PTC CSP plants were built in California in the 1980s (Breeze, 2014, p. 264). PTCs concentrate the solar radiation onto a central receiver tube at the focal line of the collector, where the PTC is a parabolic-shaped mirror. A PTC solar field consists of parallel rows of mirrors, which can be up to 100 to 150 meters long, while each of the troughs is typically 5 to 6 meters wide. Usually, these arrays of mirrors are aligned in a north-south direction and combined with a single-axis tracking mechanism, which allows the arrays to track the sun as the sun moves from east to west (IRENA, 2012a, p. 4). A PTC system can concentrate the solar radiation by the order of 60 to 100 times, which heat the heat-transfer fluid (HTF) flowing in the absorber tubes, such as synthetic oil, up to 550 °C. However, the generated temperature in the absorber tubes must be kept under 400 °C as the synthetic oil decomposes with higher temperatures, which restricts the possible exploitation of solar energy. Alternative HTFs, e.g., molten salt or steam, currently used in demonstration projects, can operate at higher temperatures, which in turn would allow the CSP plant to operate with higher efficiencies (IPCC, 2012, p. 355; IRENA, 2012a, p. 5; Breeze, 2015, p. 264). Nowadays, total efficiency, i.e., the ratio of electricity generated to the solar input, is about 14-16% (IEA-ETSAP & IRENA, 2013a, p. 3).

\ **Linear Fresnel Collector systems**: In contrast to PTC systems, Linear Fresnel Collector (LFC) systems consist of long flat mirrors, which represent an attempt to reduce costs and also allow for easier, faster, and cheaper construction (Schinke et al., 2015, p. 124). The mirrors, which are again equipped with a single-axis tracking system, concentrate the solar radiation on either side of a stationary, fixed receiver that is installed several meters above the mirror field (IEA-ETSAP & IRENA, 2013a, p. 9). However, the optical efficiency of LFC compared to PTC systems is lower due to geometric properties of the LFC, which means that they perform weaker under low DNI conditions. Consequently, total efficiency is lower (about 13%) compared to PTC systems (IRENA, 2012a, p. 5 & 10).

\ **Central Receivers:** Central Receivers (CR) or Solar Tower systems use a field of flat mirrors, called heliostats, which track the sun individually over two-axes and concentrate the solar radiation onto a single, central receiver mounted on a tower where each heliostat tracks the sun individually. CR systems can reach much higher temperatures than line-focusing systems, improving the efficiency of the thermodynamic cycle. Hence, CR systems can

reach an efficiency of up to 20% (IPCC, 2012, p. 355; IRENA, 2012a, p. 10). CR systems can use water-steam (Direct Steam Generation, DSG), synthetic oil, or molten salt as the primary HTF whereas considerable higher temperatures can be generated using molten salt (i.e., up to 565 to 650 °C). While the DSG systems do not need a HTF, the use of thermal storage is more difficult.

\ **Dish-engine systems:** Dish systems use a parabolic dish-shaped concentrator that focuses the solar radiation onto a receiver at the focal point of the dish. They can reach high temperatures and normally use a Stirling engine[37] in combination with a generator unit. Even though dish systems have the highest net efficiency compared to all other CSP technologies ranging from 12-25%, their inability to store thermal energy is a major drawback (IRENA, 2012a, p 10; Schinke et al., 2015, p. 125). Furthermore, dish systems are not used on a utility scale, but rather for small-scale, stand-alone applications. Therefore, this technology is not further considered in this study.

The key advantage of the CSP technology is its ability to store thermal energy and, therefore, raise the capacity factor and generate electricity on demand or in the evening when peak demand occurs. For example, the capacity factor of a CSP power plant without storage is typically between 25 and 30%, whereas thermal energy storage of 6 hours increases the capacity factor up to 40% and thermal energy storage of 15 hours up to 70% (IEA-ETSAP & IRENA, 2013a, p. 3). Hence, thermal energy storage is considered to be one major attribute of CSP technologies, which increases the value of the technology to electricity system stability, i.e., by providing dispatchability, and it also is a key advantage compared to other technologies based on renewable resources, like PV or wind power plants. However, thermal energy storage also comes with a price: the solar field must be oversized in order to work the turbines during the day while simultaneously charging the storage system, which increases installation costs (IPCC, 2012, p. 357). As with all power plants using a steam cycle, CSP plants require water for efficient cooling of the condense exhaust steam from the turbines. However, air also can be used to cool the exhaust steam, i.e., through "dry cooling," but this reduces the overall efficiency of the power plant and increases investment costs and, consequently, the LCOE. In addition, CSP plants need water for mirror cleaning purposes (Pitz-Paal & Elsner, 2015, p. 9).

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[37] A Stirling engine uses the flow of gases at differing temperatures in a closed cycle to convert the expansion and compression of the gas into mechanical energy.

For the purpose of this study, a parabolic trough CSP plant is assumed as it represents the most widespread and common CSP technology. Furthermore, it is assumed that the plant will be dry cooled and have a storage capacity of ca. 6 hours.

Wind power

Wind turbines - also called Wind Energy Conversion (WEC) systems - harness the kinetic energy of wind and convert it into mechanical energy and then electricity (IPCC, 2012, p. 550; IEA-ETSAP & IRENA, 2016, p. 8). Often, a number of wind turbines are grouped together and, along with roads, buildings, and the grid connection point, they form a wind farm that can have a capacity of more than 100 MW. Wind farms can be realized on- or off-shore (Kosmadakis et al., 2013, p. 13; Reuter & Elsner, 2016, p. 10).
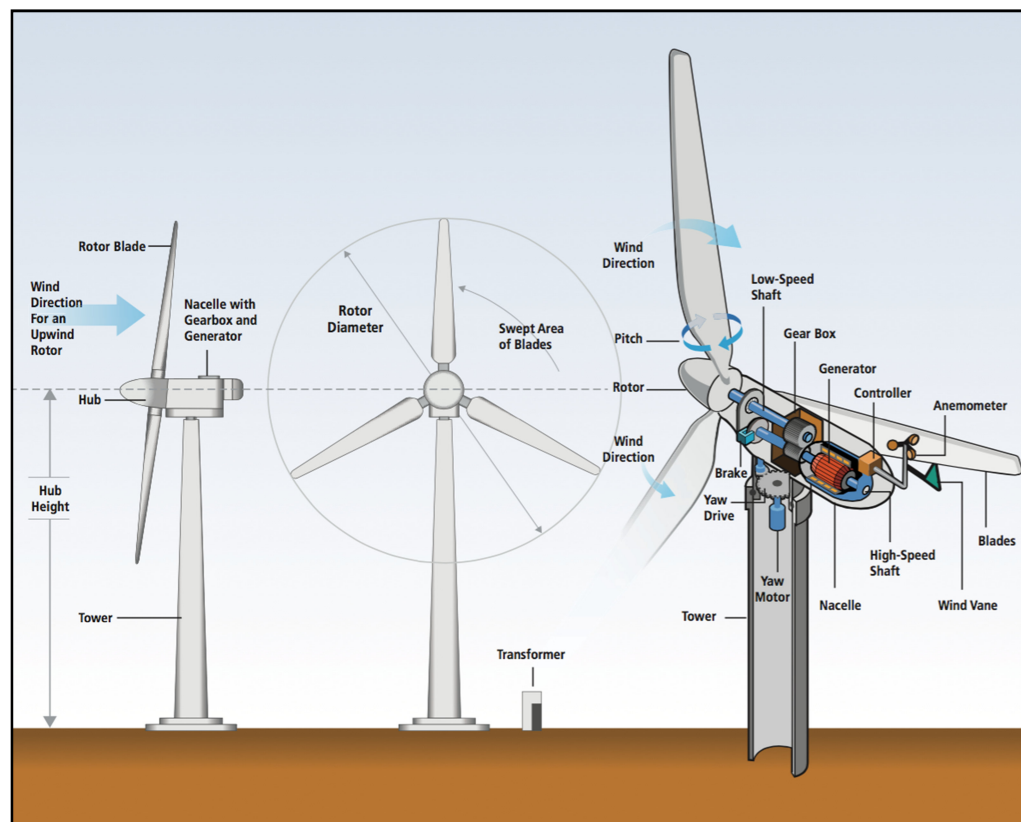

Figure 35: Schematic overview of a wind turbine.

Source: IPCC, 2012, p. 552.

A typical wind turbine consists of the following components: the blades, which are typically manufactured from fiberglass-reinforced polyester or epoxy resin, though new materials are emerging; the nacelle, which is a protective housing that includes all the main components of the turbine; the rotor hub, which transfers the rotational

energy to the rotor shaft; the gearbox, which converts the low-speed, high-torque rotation of the rotor to high-speed rotation with low-torque for input to the generator; the generator, which converts the mechanical energy from the rotor to electrical energy providing AC; the controller, which monitors the turbine and collects information so that the turbine constantly faces the wind; the tower, which can be made out of steel or concrete; and the transformers, which transform the electricity from the generator to meet the requirements of the grid (IEA, 2013, p. 7) (see Figure 35).

The amount of electricity that can be generated is proportional to the wind speed as the amount of kinetic energy increases with the cube of wind speed. That means that if wind speed doubles electricity output increases eight-fold. Additionally, the maximum output of a wind turbine is proportional to the swept area of the blades and the capacity of the turbine (IEA-ETSAP & IRENA, 2016, p. 8). These factors strongly influenced the design of modern wind turbines where the goal was to increase the height of the tower, the length of the blades, and the capacity of the turbine (IEA, 2013, p. 12; IEA-ETSAP & IRENA, 2016, p. 8).

Wind power systems can roughly be distinguished by the orientation of their wind turbine, which can be horizontal or vertical,; by their installation type, meaning whether or not they are realized on- or off-shore,; and by their grid-connection type (connected or standalone) where small-sized systems are usually standalone systems in remote areas (IEA-ETSAP & IRENA, 2016, p. 8). Horizontal-oriented turbines, which clearly dominate the utility-scale market, while vertical oriented turbines have a negligible share, and are fully commercial and mature, can further be distinguished by a number of technical aspects, such as the rotor type or placement (which can be up-wind or down-wind), the number of blades, the hub connection to the rotor, the gearbox design, and the wind turbine capacity (IRENA, 2012b, p. 3). Off-shore wind farms are more expensive than on-shore installations, but the come with the benefit of higher average wind speed at sea, thus higher potential efficiency.

Typically, overall generation efficiency of a modern wind power plant is between 42 and 45% (Reuter & Elsner, 2016, p. 9). The capacity factor highly depends on the average wind speed at a given location. Hence, wind power plants in very windy locations with average wind speeds of about 10 m/s can achieve capacity factors of over 56%. However, these locations are mostly off-shore locations. For on-shore locations with lower wind speeds (6.2 m/s) capacity factors of 34% can be achieved (IEA, 2013, p. 12; Reuter & Elsner, 2016, p. 11).

Wind power systems emit almost no emissions during their operation. However, there are environmental concerns associated with wind power systems with regards to fauna as well as with local impacts on amenity. Additionally, energy storage is difficult making wind power systems also a fluctuating source of electricity (Reuter & Elsner, 2016, p. 13).

A typical utility-scale, on-shore wind turbine nowadays has three blades that are horizontally oriented and sweeps a diameter of about 80 to 100 meters. The capacity of the turbine ranges from 0.5 MW to 3 MW with an average of 2 MW in 2014.[38] Usually, between 15 and 150 turbines form the wind farm that is connected to the grid (IRENA, 2012b, p. 5; Broehl et al., 2015, p. 6). Hence, this configuration was adopted as the reference wind power plant in this publication.

Hydro-electric power

Hydro-electric power plants (HPPs) use the potential energy that is embedded in a mass of water as a result of its elevation and converts it into electricity. Thereby, the flowing water turns a turbine that provides the mechanical energy to drive a generator (Breeze, 2015, p. 255). The simple concept of a conventional HPP is also reflected in its basic elements that are: the dam that holds back the water; the intake, penstock, and surge chamber, which is basically a cavity or pipeline that leads towards the turbine; the turbine, which is turned by the water and connected to the generator with a shaft, whereas small projects often utilize only one turbine and large-scale projects utilize a number of turbines; the generator that produces alternate current (AC); the transformer that converts the AC to higher voltages; as well as transmission lines and the outflow of water (IRENA, 2012b, p. 7). HPPs constitute a fully commercial, mature, and reliable technology, which are implemented all over the world; HPPs built in the 19th century are still operational today (IPCC, 2012, p. 452; IEA-ETSAP & IRENA, 2015, p. 5).

HPPs can be distinguished based on different characteristics, such as their size[39] (pico-hydro: up to 5 kW; micro-hydro: 5 kW to 100 kW; mini-hydro 100 kW to 1 MW; small-hydro 1 MW to 20 MW; medium-hydro 20 MW to 100 MW; large-hydro > 100 MW), their "head", meaning the height of their water fall, or their

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[38]   Off-shore wind turbines have on average larger capacities ranging from 3 MW to 4MW (IEA, 2013, p. 13).

[39]   There is no general definition of what constitutes a small or large-scale HPP and definitions also vary from country to country. However, even though HPPs with an installed capacity of 1 MW to 20 MW are called "small-scale" HPPs, they nevertheless classify as utility-scale power plants according to the definition used in this study.

function/facility type reflecting also the diversity and flexibility of this technology (IRENA, 2012b, p. 11). Concerning the size of an HPP, this publication follows a classification based on the facility type that is also used by IEA and IRENA (IEA, 2012a, p. 11; IRENA, 2012b, p. 8; IEA-ETSAP & IRENA, 2015, p. 5). Consequently, three major categories[40] can be distinguished: Run-of-River HPPs, reservoir or storage HPPs, and pumped storage HPPs, which are described in more detail below.

\   **Run-of-River HPPs:** In Run-of-River (RoR) HPPs (see Figure 36) the electricity generation is driven by the available flow of the river. These kinds of HPPs usually have no or only little short-term storage capacities[41] that allow for some adaption to the demand profile. Hence, the electricity generation depends on the timing and size of the natural river flow, which can be subject to daily, monthly, or seasonal variations.

A drawback of RoR HPPs without or only small storage is that in times of huge inflows, the HPP might reach its capacity limit and, thus, water is "spilled" that could otherwise be used for electricity generation (IEA, 2012a, p. 12; IRENA, 2012b, p. 9). In principle, the generation of base-load is possible with RoR HPPs providing that there exists a very constant river flow (IRENA, 2012b, p. 8). RoR HPPs are often found downstream from a reservoir HPP as the reservoir HPP allows for regulation of the water flows. The construction costs of RoR HPPs are in general lower than those for reservoir HPPs since they do not require a dam and environmental impacts are also lower as the natural flow of the river is less affected (IPCC, 2012, p. 451). However, RoR HPPs require the construction of a canal, called the "headrace," which directs some part of the river to a steep pipe, the "penstock," which is connected to the hydraulic turbine (Breeze, 2014, p. 160).

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[40]   This classification is based on on-shore HPPs. Off-shore HPPs also exist, but are not considered within this publication (https://www.hydropower.org/types-of-hydropower). Additionally, there exists the "in-stream technology" that basically works as RoR HPPs, usually with small-scale application. However, this technology is relatively young and less developed (IPCC, 2012, p. 452).

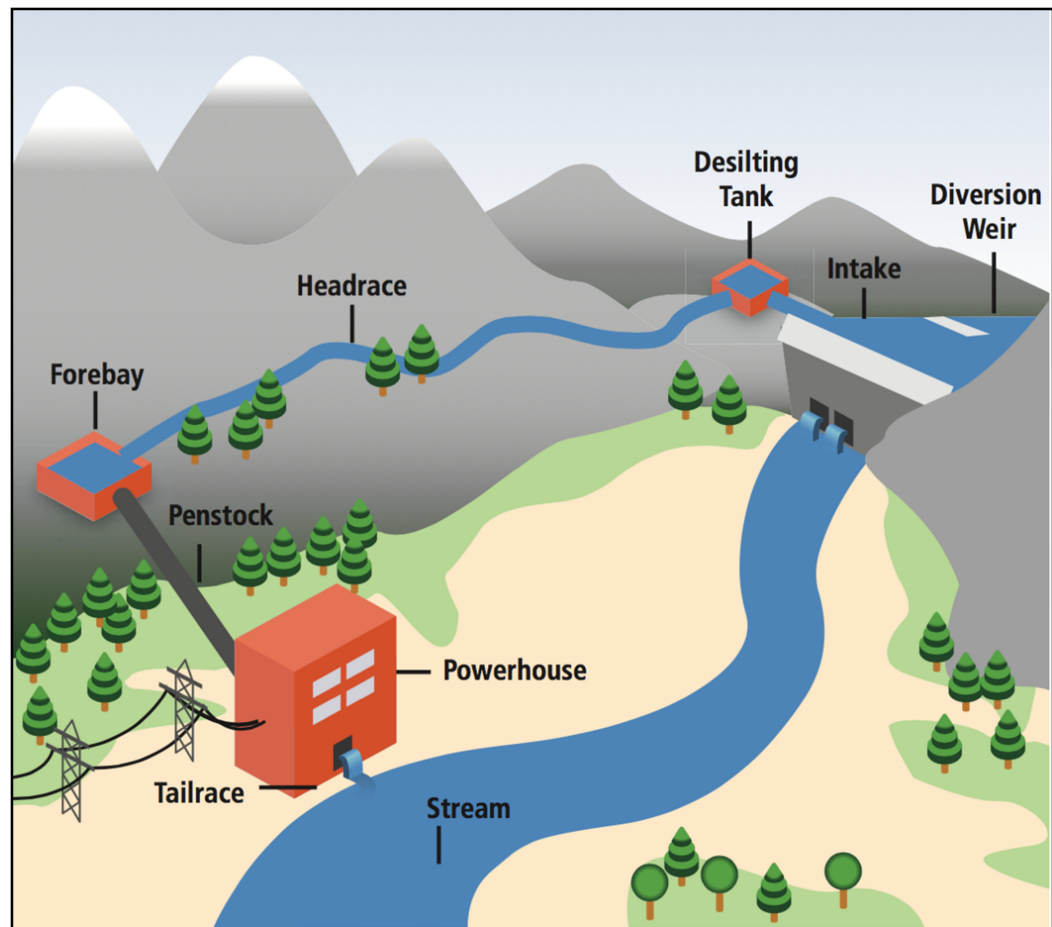[41]   Within RoR HPPs the storage is called "pondage" (IRENA, 2012b, p. 8).

Figure 36: Schematic overview of a RoR HPPs.

Source: IPCC, 2012, p. 451.

\\   **Storage or reservoir HPPs:** Storage or reservoir HPPs (see Figure 37) tackle the problem of often variable water inflows and, hence, varying electricity outputs through their reservoirs, using artificial lakes, which effectively work as an energy storage system. In the reservoirs energy can be stored over days, weeks, months, or even years to meet systems peaks (providing peak-load). Additionally, storage HPPs can also provide base-load, i.e., if turbine capacity is small compared to the generation potential and if the reservoir size allows for it (IEA, 2012a, p. 12). However, storage HPPs normally require the construction of a dam, which is a huge engineering task, whereas the dam construction can make up two-thirds of the total project costs with significant environmental impacts and is often determined by the topographic opportunities offered (Breeze, 2014, p. 161). Normally, storage HPPs serve multiple purposes in addition to electricity

generation, such as flood protection, fresh water supply, and water for irrigation. In fact, the IEA states that most large dams are not build primarily for electricity generation. Furthermore, the design of this hydropower application is dependent on the environment and the social needs of the region where it is to be installed (IEA, 2012a, p. 35).
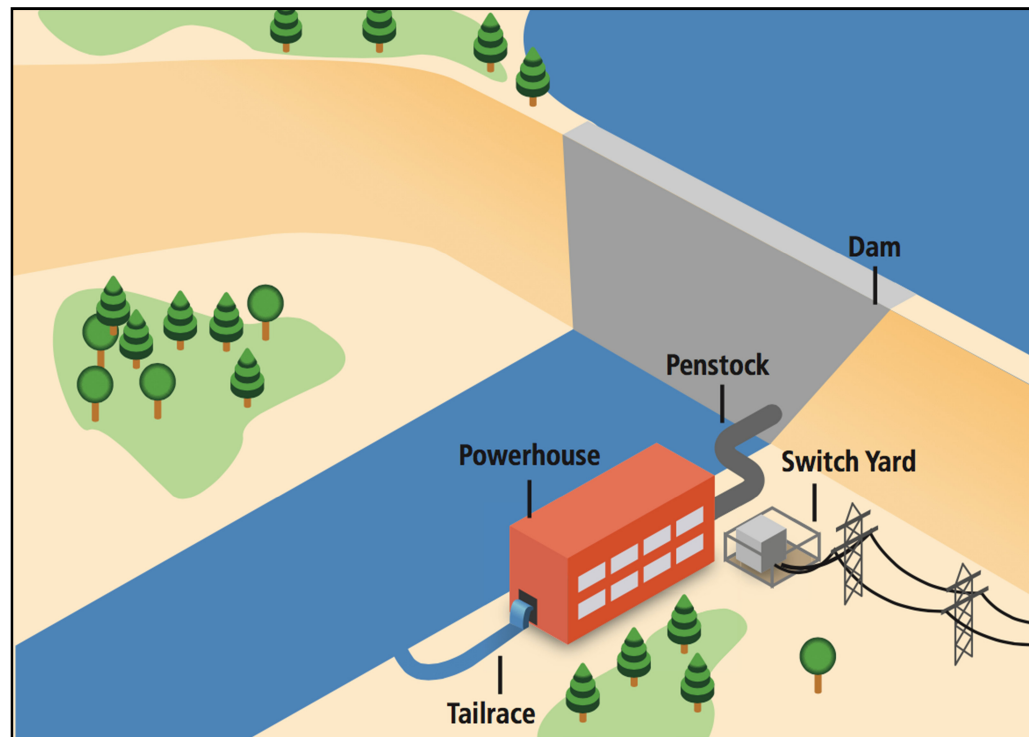

Figure 37: Schematic overview of a reservoir HPP.

Source: IPCC, 2012, p. 451.

\ **Pumped-storage HPPs:** Pumped-storage hydro-electric power plants (PSPs) work as energy storage devices and not as an energy source. Within PSPs water is pumped from a lower reservoir into an upper reservoir during off-peak hours. The water is released during peak-load hours or at other times when the demand exceeds production and drives the turbines. The pumping process consumes energy and, therefore, PSPs are net-electricity consumers. However, they provide effective large-scale electricity storage and contribute to the stability of the grid, which makes it easier to integrate fluctuating electricity sources, such as PV or wind (IPCC, 2012, p. 452; IRENA, 2012b, p. 9). PSPs have a general round-trip efficiency rate between 70 and 85% and currently represent 99% of all on-grid electricity storage (IEA, 2012a, p. 13).

These three technologies are not defined by clear boundaries as applications might often overlap and incorporate aspects from other hydropower technologies. This increases flexibility and efficiency, i.e., run-of river projects that incorporate storage technologies. The World Energy Council emphasizes that no standard exists that completely differentiates each typology from the others (WEC, 2013).

In general, hydro-electric power based electricity generation is the most efficient electricity generation technology with over 90% mechanical efficiency in the turbines and 99% in the generator (IEA, 2012a, p. 46; IPPC, 2012, p. 452). The capacity factor of HPPs varies greatly and can be as low as 23% and as high as 95% with an average value of 50% (based on an assessment of 142 worldwide Clean Development Mechanism, CDM, projects). The huge variation in capacity factors is an indicator of how a HPP can be employed in the energy mix (base- vs peak-load) as well as for water availability (IPCC, 2012, p. 445; IRENA, 2012d, p. 10; IEA-ETSAP & IRENA, 2015, p. 5). Therefore, a general categorization of a capacity factor for HPPs is difficult.

HPPs could have large-scale environmental and social impacts mostly associated with their reservoir. For example, with regards to environmental impacts, dams could be a barrier for fish migration or the seasonal flows and patterns of rivers could be changed impacting local biodiversity and ecosystems. HPPs could also induce the replacement of local communities. However, proper designed HPPs could also be driving force for socio-economic development. Hence, the negative and positive impacts of HPPs are strongly determined by local, site-specific factors (IPCC, 2012, p. 461-462).

For this publication, it is assumed that future utility-scale HPPs (with a size of > 1 MW) in the MENA-region will be based on the reservoir HPP technology. This assumption is based on currently planned projects, such as the "M'Dèz-El Menzel Hydropower Complex" in Morocco with a planned capacity 170 MW (AFDB, 2011, p. 1). Furthermore, the majority of currently operational utility-scale HPPs in Morocco - even though sometimes called "small-scale" HPPs (see Footnote 39) - are also based on this technology[42]. Another indicator is that there exist strong seasonal fluctuations in rivers that might limit the application of the RoR HPPs technology as well as the high need in these arid regions to secure fresh-water supply and irrigation. PSPs are not considered, because they do not constitute an electricity generation technology; rather they are a storage device.

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[42]   Only five out of the 21 currently operational HPPs (except PSP) listed in the Annex are not reservoir based HPPs, but RoR HPPs (based on World Bank, 1984, p. 84; Chraibi, 2014; ISL, 2016; GEO, 2016).

Nuclear power

Nuclear Power Plants (NPPs) are based on the thermal energy that is released by uranium fission reactions.[43] A coolant fluid, sometimes called "reactor coolant," constantly removes the thermal energy from the fission reaction. The fluid then drives a turbine-powered electricity generator directly or transfers the heat to another fluid (water or steam) that powers the turbine. In this regard, NPPs are very similar to conventional thermal power plants based on the Rankine cycle using water or steam, but some are also based on Brayton cycle using helium or carbon dioxide (see Figure 38) (Simbolotti, 2010, p. 2; Michaelides, 2012, p. 131-132; Breeze, 2014, p. 360).
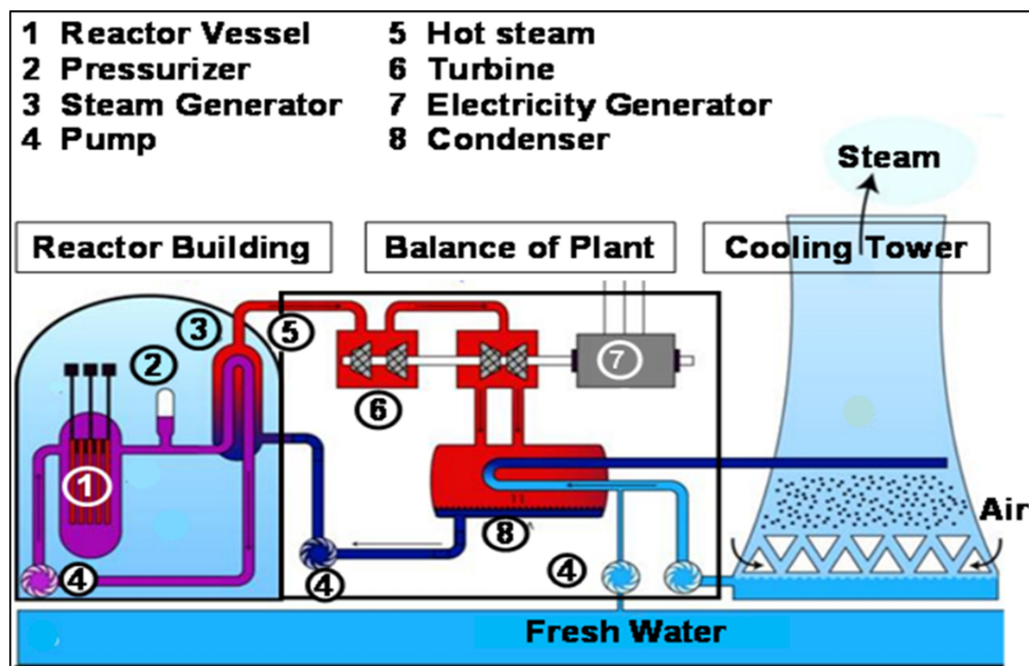

Figure 38: Schematic overview of a NPP.

Source: IEA-ETSAP, 2010a, p. 2.

The basic elements of a NPP are (based on Michaelides, 2012, p. 132-136): the reactor fuel, whereas current thermal nuclear reactors mostly use uranium-235 as their fuel[44]; the fuel moderator (common, heavy water or graphite) that slows down

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[43] For a detailed description of nuclear fission see Michaelides, 2012, p. 110-129).
[44] The fuel itself is processed into small cylindrical pellets placed into the fuel elements, which are long, thin tubes with an air gap between the fuel pellets and the cladding material. Reactors must be re-charged with new fuel elements every 18 to 24 months. During that time, the reactor stops producing electricity (Michaelides, 2012, p. 133).

the fast neutrons from the fission reaction; the coolant fluid/reactor coolant (common or heavy water or, for gas cooled reactors, carbon dioxide, helium, or argon); the control system and safety devices; and the radiation shield, whereas the purpose of the shield (normally simply thick walls made out of concrete and steel) is to prevent the radiation from escaping out of the reactor environment.

NPPs can be classified according to the energy level of their neutrons (thermal or fast), to the coolant applied (water, gas, or liquid metal), or to their moderator type (water, heavy water, or graphite), where 82% of all NPPs nowadays are thermal reactors using water as a coolant as well as a moderator (Simbolotti, 2010, p. 1; IEA, 2015, p. 25). While it is beyond the scope of this study to describe all different kinds of NPPs in detail, some key features of the different reactor types are described below.

\ **Light-Water Reactors**: Light-water reactors (LWRs) can be distinguished into Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs).

BWRs are arguably the simplest form of NPPs as no additional steam generators are required, which reduces the cost of the power plant. The steam that drives the turbine is condensed and recycled for the nuclear core (Breeze, 2014, p. 361). PWRs also use water as coolant and moderator, but the water is kept under pressure in order to prevent it from boiling. Additionally, it uses two separated water circles, the primary and the secondary. The heat from the primary water cooling system is transferred via a heat exchanger to heat the water in the secondary cycle. This allows for the contaminated water to be maintained securely in a closed system. One common disadvantage of BWRs and PWRs is that the temperature of the steam that drives the turbine is relatively low (300 °C), which is below other fossil-fired power plants (550 °C). Accordingly, the efficiency of these plants is between 30 and 34% and is considerably lower than in power plants (40 to 45%). PWRs are the most widespread form of NPPs making up 63% of all LWRs currently operational, dominating the market in the US, France, and Japan; and they make up 58 out of 70 NPPs currently under construction (Michaelides, 2012, p. 143; Breeze, 2014, p. 362; IEA, 2015, p. 25).

\ **Pressurized Heavy Water Reactors:** Pressurized Heavy Water Reactors (PHWR) also called CANDU (Canadian deuterium uranium) reactor is an attempt made by Canada to use unenriched natural uranium to drive the reactor. Furthermore, the reactor uses heavy water as a coolant and moderator. The CANDU has higher capital costs because the heavy water

that is only applied once is more expensive, but lower operational costs as the natural uranium - the fuel - is cheaper compared to conventional PWRs. The efficiency of PHWRs is relatively low with values close to 30% (Michaelides, 2012, p. 140-143; Breeze, 2014, p. 363-364).

\ **Gas-cooled Reactors:** Gas-cooled Reactors (GCRs) use gas as a coolant and graphite as a moderator. Natural uranium (used within the Magnox type) as well as enriched uranium (used in the Advanced Gas Reactor, AGR) could be used as a fuel. Temperatures that can be reached within this type of reactor are significantly higher than in water-cooled reactors and, hence, superheated steam with a temperature between 400 and 500 °C can be generated, resulting in higher thermodynamic efficiencies between 33-36%. However, dimensions and volume of GCRs is higher when compared to water-cooled reactors. There are also attempts to build another version of GCRs, called High Temperature Gas Cooled Reactors (HTGCRs). However, these kinds of GCRs have not reached a commercial state (Michaelides, 2012, p. 145-147; Breeze, 2014, p. 364-365).

\ **Other reactor types**: Other types of reactors include the RBMK (Russian acronym) reactor that uses water as a coolant and graphite as a moderator. This type of reactor was designed and used in Russia and is known to have major design flaws that contributed to the Chernobyl accident. Nuclear fast breeder reactors aim to use uranium-238 instead of uranium-235 as it is much more abundant. However, unsolved technical problems remain with this type of reactors and, hence, no commercial reactor has ever been built. Advanced, or third-generation, reactors are designed to be cheaper reactors that are also safer, due to standardization and passive safety features. Advanced boiling water reactors (ABWR) are third-generation reactors that are mainly used in Japan and Taiwan (Michaelides, 2012, p. 147-148; Breeze, 2014, p. 367-370).

NPPs are in general designed as base-load plants (IEA, 2015, p. 21). Hence, they operate with high capacity factors. For example, US NPPs operate on average with a capacity factor of around 90% and NPPs in the Republic of Korea even achieved capacity factors of 96.5% on average in recent years (Vine & Juliani, 2014, p. 7; IEA, 2015, p. 17).

Major drawbacks of NPPs are associated with the unresolved problem of Nuclear Waste Material (NWM) in the form of the used fuel, contaminated internal reactor structure including the cooling water, and contaminated mechanical equipment. The fuel is a significant source of NWM and will remain radioactive for hundreds of

thousands of years. The reprocessing, storage facilities, and safe transportation of NWM are still technically and socially contested issues. Additionally, proliferation of highly-enriched weaponized uranium connected to geopolitically friction, the catastrophic impacts of a nuclear meltdown and its associated safety issues, as well as the potential target of NPPs for terrorist attacks are major international security concerns. NPPs emit only few GHGs during their operation, however, and no other air pollutants (Breeze, 2014, p. 158-161).

Currently, there exist no commercially operated NPPs in the target countries (Morocco and Jordan), though all target countries are considering the nuclear option in the mid- to long-term future (IEA, 2014b, p. 114; IEA, 2015, p. 15). Yet, other NPPs currently operational or under construction in the region, like the Bushehr nuclear power plant in Iran and the Barakah nuclear power plant in the United Arab Emirates, are PWRs (IAEA, 2016a; IAEA, 2016b). Based on this information and statements made by the IEA that trends further consolidated reactor technology towards LWRs (IEA, 2015, p. 26), a PWR NPP is assumed as the reference power plant for this publication.

Coal-fired power

Coal-fired power plants convert the chemical energy that is embedded in coal into heat, i.e., the fuel is burned and the heat released during the combustion is captured. The heat is then used to generate steam which drives a steam turbine generator to produce electricity.

A conventional coal-fired power plant consists of the following components: a fuel handling system, which processes the coal into a form that can be burned (usually crushing the coal); a combustion system with the boiler, where the coal burned through addition of air and the heat is captured by tubes filled with water within the boiler; a steam turbine

Four different types of coal with different properties can be differentiated (Breeze, 2014, p. 31-32):

Anthracite coal, that is the hardest coal with the highest percentage of carbon (up to 98%), little volatile matter and moisture, and high energy density. Anthracite is relatively expensive and slow burning, which makes it difficult to use without other fuels for electricity production.

Bituminous coal is the most abundant type of coal, but contains huge amounts of volatile matter, less carbon (40 to 70%) and more moisture content (5 to 10%) than anthracite. However, it burns relatively easy which makes it well suited for electricity production.

Sub-bituminous coal is also sometimes called soft coal. It contains 35 to 45% carbon and 15 to 30% water, but has nonetheless good burning qualities

Lignite contains the lowest amount of carbon (20 to 35%), the highest moisture content (30 to 50%) and huge amounts of volatile matter. These properties make lignite relatively uneconomical to transport, which is why it is mostly used locally.

system, which often consists of multiple turbines for high pressure

(HP), intermediate pressure (IP), and low pressure (LP) and which converts the heat contained in the steam into mechanical energy; a condenser, which condenses the steam output from the LP turbine back to water; a flue-gas cleaning system, which removes some impurities, such as sulfur dioxide (SO_x), nitrogen oxide (NO_x), and heavy metals as remnants of the combustion process, before the flue gas is released to the atmosphere; and a generator, which is coupled to the turbine via a turbine shaft and converts the rotary mechanical motion coming from the turbine into electricity (AC) (Breeze, 2014, p. 34-36) (see Figure 39).
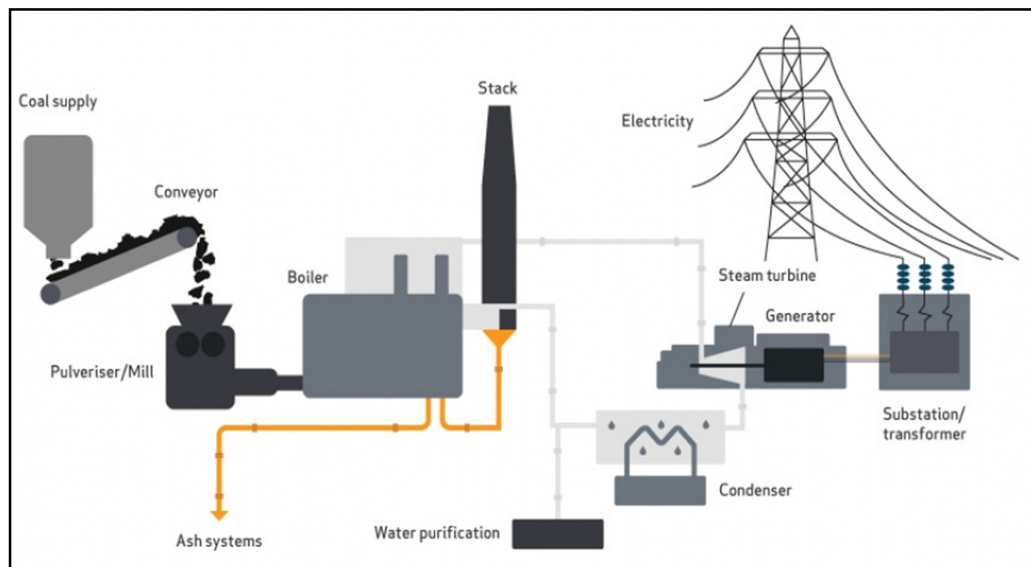

Figure 39: Schematic overview of a coal-fired power plant.

Source: WorldCoal, 2016.

Usually, the coal is cleaned and processed before being used. The cleaning focuses on removing the moisture as well as incombustible material. Moisture is either removed through solar drying before transport or through heating at the power plant site. Ash is removed by crushing the coal, and incombustible material is separated via gravity-based filtering methods, since other, more chemical-based methods, have been developed but have not found commercial application so far (Breeze, 2014, p. 34).

Based on different technical features, three major types of coal-fired power plants can be distinguished and are described below (Burnard & Bhattacharya, 2011, p. 11).

\ **Pulverized Coal-Fired power plants:** Pulverized Coal-Fired power plants (PCs) (see Figure 48) as per the boiler technology are the most widely spread type, accounting for 90% of all operating coal-fired power plants. PCs burn a fine coal powder within the boiler where a high-temperature fireball (1,500 to 1,700 °C) is created. In modern PCs the temperature and pressure within the boiler is so high that the water enters a "supercritical" state, which is a thermodynamic expression for when the distinction between a liquid and a gaseous phase is no longer possible. Conventional PCs, instead, use a steam drum that allows for the phase to change from liquid to gas and are called "subcritical." Supercritical PCs operate at higher steam exit temperature (540 to 600 °C) compared to subcritical PCs (typically around 540 °C, with 38% efficiency) and, consequently, are more efficient (up to 41%). There exist also PCs that operate at even higher temperatures (around 600 °C), "ultra-supercritical" PCs, which have shown efficiencies up to 45%, advanced ultra-supercritical PCs are under development with the goal to achieve an efficiency of around 50% (Burnard & Bhattacharya, 2011, p. 11-15; IEA, 2012b, p. 21; Breeze, 2014, p. 39).

\ **Fluidized Bed Combustion power plants:** Fluidized Bed Combustion power plants (FBCs) are an alternative to PCs. FBCs are solid-state reactors that mimic the behavior of liquid-phase reactors in that the application of high-pressure air provokes small solid particles to behave like a liquid. This process takes place in a fluidized bed. The main advantages of FBCs are that they can utilize a wider range of fuels than PCs and operate at temperatures significantly lower than PCs, which minimizes the production of sulfur dioxide and nitrogen oxide. Three types of FBCs can be distinguished: bubbling fluidized bed combustion (BFBC), which is basically a conventional boiler where the combustion chamber has been replaced by a fluidized bed; circulating fluidized bed combustion (CFBC), where the particles are fluidized at high-speed using high-velocity air; and the pressurized fluidized bed (PFB), which is similar to BFBC, but uses a bubbling bed which is under pressure allowing for higher efficiencies. Commercial FBCs have not reached efficiency levels of ultra-supercritical PCs, but efficiencies of CFBC plants are comparable to supercritical PCs with an efficiency of around 43% (Burnard & Bhattacharya, 2011, p. 14-15; IEA, 2012b, p. 22-23; Breeze, 2014, p. 43-46).

\ **Integrated Gasification Combined Cycle power plants**: Integrated Gasification Combined Cycle power plants (IGCCs) are based on the gasification of coal where a gasifier converts coal into a mixture of hydrogen

and carbon monoxide or another type of "fuel gas." This process creates heat, which can be used to generate steam and drive a steam-turbine. Additionally, the cleaned gas can be burned in a gas turbine to generate electricity as well, and the exhaust heat from the gas turbine can be used to generate more steam. While their capital and operational costs are higher than those of PCs, IGCCs can in theory reach efficiencies like those of ultra-supercritical PCs (around 46 to 47 per cent), while existing IGCCs have shown efficiencies of around 42 to43 per cent. Furthermore, they have inherently lower emissions than PCs, because the gas is cleaned before being burned. There exist only very limited operating experience worldwide for IGCCs as only a limited number of commercial projects have been realized (Burnard & Bhattacharya, 2011, p. 16-22; IEA, 2012b, p. 23-24; Breeze, 2014, p. 46-48).

PCs are operating as base-load power plants with capacity factors of around 80% for both, PCs and CFBCs and slightly lower values of IGCCs (around 70%) (IEA, 2012b, p. 18, 32). Concerns for coal-fired power plants are mostly associated with the high amount of emissions as a result of the combustion process of the fuel (Breeze, 2014, p. 48).

For this publication, it is assumed that coal-fired power plants will be based on the PC-technology as it is the most widespread and common technology. Additionally, it is assumed that these power plants will use bituminous coal, which is the major type of coal being used in the MENA countries with operating coal-fired power plants (IEA, 2016).

Gas-fired power

Gas-fired power plants utilize the kinetic energy of motion of a flowing gas or the potential energy of a gas under pressure to generate electricity via a gas turbine. Most gas-fired power plants use natural gas as a fuel, while other gases and fuels could also be used including distillate fuel oil, hydrogen, and gases produced by gasification, such as the gases in IGCC power plants. Natural gas is usually extracted from gas fields with the main component methane (approximately 70 to 90%) and other components, such as ethane, propane, or butane (up to 20%) and small amounts of carbon dioxide (up to 8%), oxygen, nitrogen, and hydrogen sulfide. Normally before transport or usage, the natural gas is cleaned of impurities and is then referred to as dry natural gas. Natural gas can be transported via pipelines or, as liquefied natural gas (LNG), without pipelines.

The most important part of a gas-fired power plant is the gas turbine. The modern gas turbine consists of a compressor, a combustion chamber, and a turbine stage that is in principle a thermodynamic heat engine. The compressor draws in and compresses air. The high-pressure air then enters the combustion chamber where it is mixed with the natural gas and burned. This process heats the air up to 1,600 °C and also creates NO_x. The hot pressurized combustion gas than enters the turbine stage and spins the blades of the turbine. The rotating blades fulfill two functions: first, they drive the compressor to draw even more pressurized air into the combustion chamber and, second, they spin the generator to generate electricity (Breeze, 2014, p. 72-76).

As the exhaust gas that leaves the turbine still has relatively high temperature of around 400 to 500 °C, two basic types of gas-fired power plants have evolved:

\ **Open-Cycle Gas Turbines:** Within Open-Cycle Gas Turbines (OCGTs) the exhaust gas is discharged into the atmosphere.

\ **Combined-Cycled Gas Turbines**: In Combined-Cycled Gas Turbines (CCGTs) (see Figure 40) the exhaust gas is re-used in a heat recovery steam generator to generate steam that drives a steam-turbine generator to generate additional electricity. Consequently, OCGTs have much lower efficiencies ranging between 35 and 42% than CCGTs with efficiencies between 52 and 60%. Consequently, CCGTs have become the gas-fired technology of choice (Seebregts, 2010, p. 1-2).
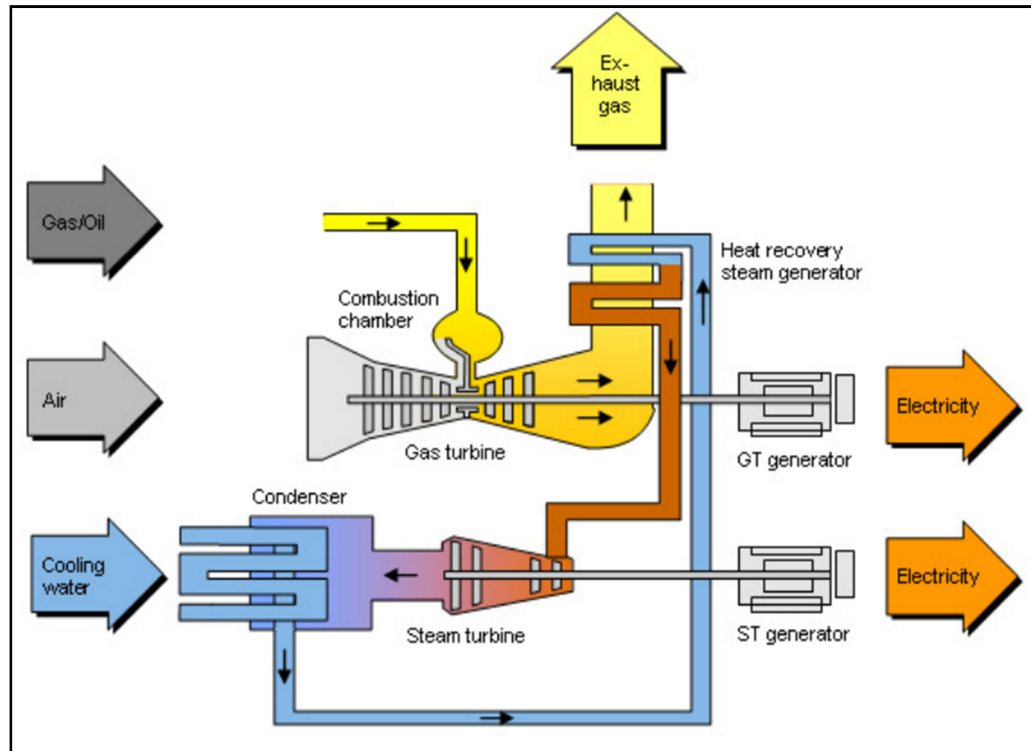
Figure 40: Schematic overview of a CCGT power plant.

Source: Seebregts, 2010, p. 2.

CCGT is a mature and fully commercial technology. The size of a CCGT power plant varies depending on the size of the turbine from a few megawatts to up to 400 MW. Thanks to their modularity and flexibility they can be adapted to the electricity demand and grid requirements and, hence, be used as base-load, intermediate-load, or peak-load power plants, whereas larger turbines are often used as base-load plants (Seebregts, 2010, p. 2; Breeze, 2015, p. 71). Consequently, the span of the typical capacity factor is relative large ranging from 20 to 60% (Seebregts, 2010, p. 4). However, the exact usage of CCGTs is also determined by the availability of the natural gas and its current price as well as of the overall energy mix. For example, in the US CCGTs plants are used as intermediate-load power plants with capacity factors of around 48 – 56% (EIA, 2016). Often, CCGTs are designed to react very fast to changing electricity demands and services. Modern CCGTs emit considerable less CO_2 and NO_x emissions than other fossil-fired power plants, e.g., coal-fired power plants (Seebregts, 2010, p. 1-2; Görner & Sauer, 2016, p. 34).

For this publication, a CCGT power plant is assumed as the reference plant as it represents the most common type of a gas-fired power plant.

Oil-fired power

The chemical energy that is embedded within oil can be utilized in a number of different ways to generate electricity. There are three different basic types of oil-fired power plants based on the conventional steam systems, the combustion-turbine, or the use of a diesel engine:

\\ **Oil-fired power plants based on a conventional steam system**: This type of power plants is similar to coal-fired power plants using the boiler technology. They work according to the same principles and characteristics as well as with the same composition as coal-fired power plants, but replacing coal as a fuel. However, their fuel storage and fuel feed is less complex (Görner & Sauer, 2016, p. 28).

\\ **Oil-fired power plants using a combustion-turbine**: In parallel, oil-fired power plants using a combustion-turbine are similar to gas-fired OCGTs or CCGTs, but replace the natural gas with oil for the ignition of the high-pressure air in the combustion chamber of the gas turbine.

\\ **Diesel engine-based power plants:** In diesel engine-based power plants an air-fuel[45] mix is introduced into a cylinder and ignited. This causes a controlled explosion within the cylinder and the high-pressure impulse forces the gas in the cylinder to expand, which moves a piston. The engine is directly connected to a generator that converts the mechanical energy into electricity. Diesel engines have efficiencies ranging between 30 and 48%, whereas larger engines have higher efficiencies. Diesel engines can burn a wide range of fuels, including biofuels and low-quality heavy-fuel oils, and can be as large as 65 MW (see Figure 41) (Breeze, 2014, p. 94-101).

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[45] In contrast to spark-ignition engines, the air admitted in diesel engines is compressed more highly during the compression stroke - usually with a compression ratio of up to 25:1. The compressed air becomes so hot that the admitted diesel at the end of the compression stroke ignites spontaneously (Breeze, 2014, p. 100).
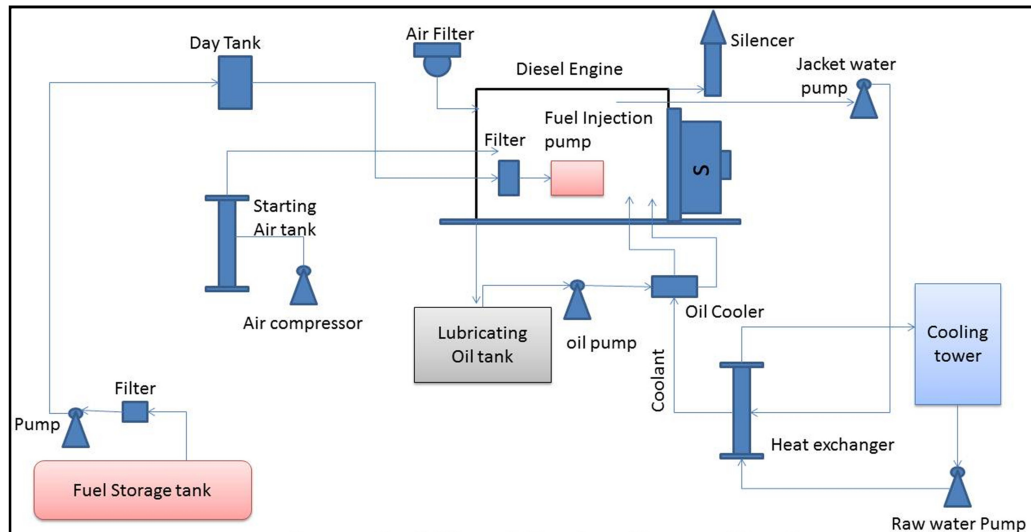
Figure 41: Schematic overview of a diesel engine-based power plant.

Source: Mechanical-Engineering, 2016.

The naturally occurring oil is called crude oil and is composed out of a mixture of different hydrocarbons. It can be classified according to its viscosity. **Light crude oil** is less viscous and flows more easily, and more viscous crudes are considered heavy. Light crude oils are considered more valuable as they require less processing at the refinery and yield a higher amount of valuable products, such as gasoline, diesel, and jet fuel. **Heavy crude oil**, in turn, is more commonly used to produce less valuable products, such as residual fuel oil and asphalt. In addition, crude oils are distinguished by their amount of impurities, e.g., sulfur, which makes the processing more difficult and costly. Crude oils with high amounts of sulfur are referred to as "sour" and crude oils with low amounts of sulfur are called "sweet." Consequently, light sweet crude is more expensive than heavy sour crude (Devold, 2013, p. 21-23; Levine et al., 2014, p. 13). Another distinction made between crude oils is based on the type of exploitation: if oil could be extracted and processed through traditional methods and techniques, it is referred to as **conventional oil**. If the use of alternative methods and techniques is needed, the oil is called **unconventional oil**. Unconventional sources of oil include very heavy crudes, oil/tar sands, and oil shale (BGR, 2009, p. 18).

Typically, oil-fired power plants are used as backup or peak-load plants (Görner & Sauer, 2016, p. 28). This is mainly due to the fact that the fuel is relatively expensive compared to other fossil fuels. In general, this type of power plant is not very common and widespread anymore. However, in parts of the world where oil is relatively abundant, oil-fired power plants are also used as base-load plants, e.g., in Saudi-Arabia, which has the world's largest oil-fired power plant in Riyadh, which uses a number of gas turbines with a total capacity of 3,000 MW, as well as the world's largest oil-fired CCGT power plant with a capacity of 5,600 MW (Power Technology, 2016a and 2016b).

Environmental concerns for oil-fired power plants are mostly associated with CO_2 emissions as well as other air pollutant emissions associated with the combustion of oil (Breeze, 2014, p. 106-107).

Morocco has a number of large-scale oil-fired power plants with up to 300-MW capacity that use steam turbines. As these types of oil-fired power plants also are the most widespread oil-fired power plants for utility-scale application, a conventional oil-fired power plant based on the boiler technology and a steam turbine is assumed as the reference power plant for this publication.

References

AFDB, African Development Bank. (2011). *Strategic Environmental and Social Assessment Summary*. Renewable Energy and Global Rural Electrification Project (PERG). Retrieved from http://www.afdb.org/fileadmin/uploads/afdb/Documents/Environmental-and-Social-Assessments/EESS-Renouvelable%20et%20PERG-Resume_English.pdf

BGR, Bundesanstalt für Geowissenschaften und Rohstoffe. (2009). Energierohstoffe 2009. Reserven, Ressourcen, Verfügbarkeit. Erdöl, Erdgas, Kohle, Kernbrennstoffe, Geothermische Energie. Hannover. Retrieved from http://www.bgr.bund.de/DE/Themen/Energie/Downloads/Energierohstoffe_2009_Teil1.pdf?__blob=publicationFile

Breeze, P. (2014). *Power Generation Technologies* (2nd ed.). Oxford: Elsevier Ltd.

Broehl, J., Labastida, R. R., & Hamilton, B. (2015). Executive Summary: World Wind Energy Market Update 2015. International Wind Energy Development: 2015-2019. Retrieved from http://www.provedor.nuca.ie.ufrj.br/estudos/navigant1.pdf

Burnard, K., & Bhattacharya, S. (2011). Power Generation from Coal. Ongoing Developments and Outlook. IEA. Retrieved from https://www.iea.org/publications/freepublications/publication/Power_Generation_from_Coal2011.pdf

Chraibi, A. F. (2014). Capacity Building Morocco. Presentation for Water Storage and Hydropower Development for Africa, Addis Ababa, 16-18 April 2013. Retrieved from http://academic.sun.ac.za/icold-africa/documents/presentations/symposium_April_2013/presentation_Morocco%5B1%5D.pdf

Devold, H. (2013). Oil and gas production handbook. An introduction to oil and gas production, transport, refining and petrochemical industry. Edition 3.0. Oslo. ABB Oil and Gas.

EIA, U.S. Energy Information Administration. (2016). Electric Power Monthly. Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_6_07_a

Firstsolar. (2015). First Solar Breaks Ground on Jordan's Largest PV Plant. Retrieved from http://www.firstsolar.com/en/About-Us/Press-Center/Blog/2015/June/First-Solar-Breaks-Ground-on-Jordans-Largest-PV-Plant

Frankl, P., Menichetti, E. and Raugei, M. (2005). Final report on technical data, costs and life cycle inventories of PV applications. Deliverable n° 11.2 – RS Ia. Retrieved from http://www.needs-project.org/RS1a/RS1a%20D11.2%20Final%20report%20on%20PV%20technology.pdf

Frass, L.M. (2014). *Low-Cost Solar Electric Power*. Cham: Springer International Publishing Switzerland.

Fraunhofer ISE, Fraunhofer Institute for Solar Energy Systems. (2016). *Photovoltaics Report*. Freiburg. Retrieved from https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Fraunhofer ISE & NREL, Fraunhofer Institute for Solar Energy Systems & National Renewable Energy Laboratory. (2016). *Current Status of Concentrator Photovoltaic (CPV) Technology*. Springfield. Retrieved from https://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/current-status-of-concentrator-photovoltaic-cpv-technology-in-englischer-sprache.pdf

GEO, Global Energy Observatory. (2016). Hydro in Morocco. Retrieved from http://globalenergyobservatory.org/form.php?pid=41650

Schinke, B., Terrapon-Pfaff, J., Borbonus, S., Viebahn, P., Fink, T., & Brand, B. (2015). *Energy and development: exploring the local livelihood dimension of the Noor I CSP project in Southern Morocco* (Final Report). Bonn/Wuppertal: Germanwatch/Wuppertal Institute for Climate, Environment and Energy. Retrieved from https://germanwatch.org/de/download/11797.pdf

Görner, K., & Sauer, D.W. (Eds). (2016). *Konventionelle Kraftwerke. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050"*. Retrieved from http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Konventionelle_Kraftwerke.pdf

IAEA, International Atomic Energy Agency. (2016a). PRIS – Power Reactors Information System. BUSHEHR-1. Retrieved from https://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=310

IAEA, International Atomic Energy Agency. (2016b). PRIS – Power Reactors Information System. BARAKAH-1. Retrieved from https://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1050

IEA, International Energy Agency. (2012a). Technology Roadmap. Hydropower. Retrieved from https://www.iea.org/publications/freepublications/publication/2012_Hydropower_Roadmap.pdf

IEA, International Energy Agency. (2012b). Technology Roadmap. High-Efficiency, Low-Emissions Coal-Fired Power Generation. http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHighEfficiencyLowEmissionsCoalFiredPowerGeneration_WEB_Updated_March2013.pdf

IEA, International Energy Agency. (2013). *Technology Roadmap. Wind Energy*. 2013 Edition. Retrieved from https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf

IEA, International Energy Agency. (2014a). *Technology Roadmap. Solar Photovoltaic Energy*. 2014 Edition. Paris. Retrieved from https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf

IEA, International Energy Agency. (2014b). *Morocco 2014. Energy Policies Beyond IEA countries*. Retrieved from https://www.iea.org/publications/freepublications/publication/Morocco2014.pdf

IEA, International Energy Agency. (2015). *Technology Roadmap. Nuclear Energy. 2015 Edition*. Retrieved from https://www.iea.org/media/freepublications/technologyroadmaps/TechnologyRoadmapNuclearEnergy.pdf

IEA, International Energy Agency. (2016). Morocco – Coal for 2013. Retrieved from https://www.iea.org/statistics/statisticssearch/report/?country=MOROCCO&product=coal&year=2013

IEA-ETSAP, & IRENA, International Energy Agency – Energy Technology Systems Analysis Programme & International Renewable Energy Agency. (2013a). *Concentrating Solar Power*. (Technology Brief E10). Retrieved from https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E10%20Concentrating%20Solar%20Power.pdf

IEA-ETSAP, & IRENA, International Energy Agency – Energy Technology Systems Analysis Programme & International Renewable Energy Agency. (2013b). *Solar Photovoltaics*. (Technology Brief E11). Retrieved from https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E11%20Solar%20PV.pdf

IEA-ETSAP, & IRENA International Energy Agency – Energy Technology Systems Analysis Programme & International Renewable Energy Agency. (2015). *Hydropower*. (Technology Brief E06). Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP_Tech_Brief_E06_Hydropower.pdf

IEA-ETSAP, & IRENA, International Energy Agency – Energy Technology Systems Analysis Programme & International Renewable Energy Agency. (2016). *Wind Power.* (Technology Brief E07). Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP_Tech_Brief_Wind_Power_E07.pdf

IFC, International Finance Corporation. (2015). *Utility-Scale Solar Photovoltaic Power Plants. A Project developer's guide*. Washington, DC. Retrieved from http://www.ifc.org/wps/wcm/connect/f05d3e00498e0841bb6fbbe54d141794/IFC+Solar+Report_Web+_08+05.pdf?MOD=AJPERES

IPCC, Intergovernmental Panel on Climate Change. (2012). *Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press. Retrieved from http://www.ipcc.ch/pdf/special-reports/srren/SRREN_Full_Report.pdf

IRENA, International Renewable Energy Agency. (2012a). *Concentrating Solar Power*. (Renewable Energy Technologies: Cost analysis series Volume 1: Power Sector. Issue 2/5). Retrieved from http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf

IRENA, International Renewable Energy Agency. (2012b). *Renewable Energy Technologies: Cost analysis series. Hydropower.* (Volume 1: Power Sector. Issue 3/5). Retrieved from http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf

IRENA, International Renewable Energy Agency. (2012c). *Solar Photovoltaics*. (Renewable Energy Technologies: Cost analysis series Volume 1: Power Sector. Issue 4/5). Retrieved from https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf

IRENA, International Renewable Energy Agency. (2012d). *Wind Power.* (Renewable Energy Technologies: Cost analysis series. Volume 1: Power Sector. Issue 5/5). Retrieved from https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf

ISL, Ingénierie. (2016). The Ouljet Essoltane hydroelectrical development. Retrieved from http://www.isl.fr/en/activites/projets/ouljet-essoltane-hydroelectrical-development

Kaltschmitt, M., & Rau, U. (2007). Photovoltaic Power Generation. In: M. Kaltschmitt, W. Streicher, & A. Wiese (Eds.), *Renewable Energy. Technology, Economics and Environment*. Berlin/Heidelberg: Springer.

Kosmadakis, G., Karellas, S., & Kakaras, E. (2013). Renewable and Conventional Electricity Generation Systems:
Technologies and Diversity of Energy Systems. In Michalena, E. & Hills, J. M. (2013) *Renewable Energy Governance. Complexities and Challenges.* London: Springer.

Levine, S., Taylor, G., Arthur, D., & Tolleth, M. (2014). *Understanding crude oil and product markets*. Washington, DC: American Petroleum Institute. Retrieved from http://www.api.org/~/media/files/oil-and-natural-gas/crude-oil-product-markets/crude-oil-primer/understanding-crude-oil-and-product-markets-primer-high.pdf

Mechanical-Engineering. (2016). Diesel Power Plant. Retrieved from http://mechanical-engineering-info.blogspot.de/2011/12/diesel-power-plant.html

Michaelides, E.E. (2012). *Alternative Energy Sources*. Berlin/Heidelberg: Springer.

Pitz-Paal, R. & Elsner, P. (Eds). (2015). *Solarthermische Kraftwerke. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050".* (Energiesysteme der Zukunft). Munich/Halle/Mainz: acatech/Deutsche Akademie der Naturforscher Leopoldina/Union der deutschen Akademien der

Wissenschaften. Retrieved from http://elib.dlr.de/100388/1/2015-11-17_Solarthermie_Gesamt.pdf

Power Technology. (2016a). Riyadh Crude Oil-Fired Power Plant, Saudi Arabia. Retrieved from http://www.power-technology.com/projects/riyadh/

Power Technology. (2016b). Shoaiba Oil-Fired Power Plant, Saudi Arabia. Retrieved from http://www.power-technology.com/projects/shoaiba/

Rech, B. & Elsner, P. (Eds). (2016). *Photovoltaik. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050".* Munich/Halle/Mainz: acatech/Deutsche Akademie der Naturforscher Leopoldina/Union der deutschen Akademien der Wissenschaften. Retrieved from http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Photovoltaik.pdf

Reuter, A. & Elsner, P. (Eds). (2016). *Windkraftanlagen. Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050".* Munich/Halle/Mainz: acatech/Deutsche Akademie der Naturforscher Leopoldina/Union der deutschen Akademien der Wissenschaften. Retrieved from http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Windkraftanlagen.pdf

Seebregts, A. J. (2010). *Gas-Fired Power*. (Technology Brief E02). Paris: IEA-ETSAP, International Energy Agency – Energy Technology Systems Analysis Programme. Retrieved from http://www.iea-etsap.org/web/e-techds/pdf/e02-gas_fired_power-gs-ad-gct.pdf

Simbolotti, G. (2010). *Nuclear Power*. (Technology Brief E03). Paris: International Energy Agency – Energy Technology Systems Analysis Programme. Retrieved from https://iea-etsap.org/E-TechDS/PDF/E03-Nuclear-Power-GS-AD-gct.pdf

Solarserver. (2016). New analysis: Thin-film PV catches up in solar technologies race. Retrieved from http://www.solarserver.com/solar-magazine/solar-news/archive-2016/2016/kw04/new-analysis-thin-film-pv-catches-up-in-solar-technologies-race.html

SPE, Solar Power Europe. (2015). Global Market Outlook. For Solar Power/2015 – 2019. Brussels. Retrieved from http://helapco.gr/pdf/Global_Market_Outlook_2015_-2019_lr_v23.pdf

Trieb, F., Schillings, C., O'Sullivan, M., Pregger, T. & Hoyer-Klick, C. (2011). Global Potential of Concentrating Solar Power. SolarPacer Conference Berlin. Retrieved from http://www.dlr.de/tt/en/Portaldata/41/Resources/dokumente/institut/system/projects/reaccess/DNI-Atlas-SP-Berlin_20090915-04-Final-Colour.pdf

Viebahn, P., Lechon, Y. & Trieb, F. (2011). The potential role of concentrated solar power (CSP) in Africa and Europe – A dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy, 39*, 4420-4430.

Vine, D. & Juliani, T. (2014). Climate Solutions: The Role of Nuclear Power. Retrieved from http://www.c2es.org/docUploads/nuclear-energy-brief-04-14-final.pdf

Weinrebe, G. & Ortmanns, W. (2007). Solar Thermal Power Plants. In: M. Kaltschmitt, W. Streicher, & A. Wiese (Eds.), *Renewable Energy. Technology, Economics and Environment*. Belin/Heidelberg: Springer.

World Bank. (1984). Morocco Power Sector Study. (Report No. 4135-MOR). Washinton, DC. Retrieved from http://www-wds.worldbank.org/servlet/WDSContentServer/IW3P/IB/2000/05/26/000178830_98101901001810/Rendered/PDF/multi_page.pdf

WorldCoal. (2016). Coal & Electricity. Retrieved from http://www.worldcoal.org/coal/uses-coal/coal-electricity

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