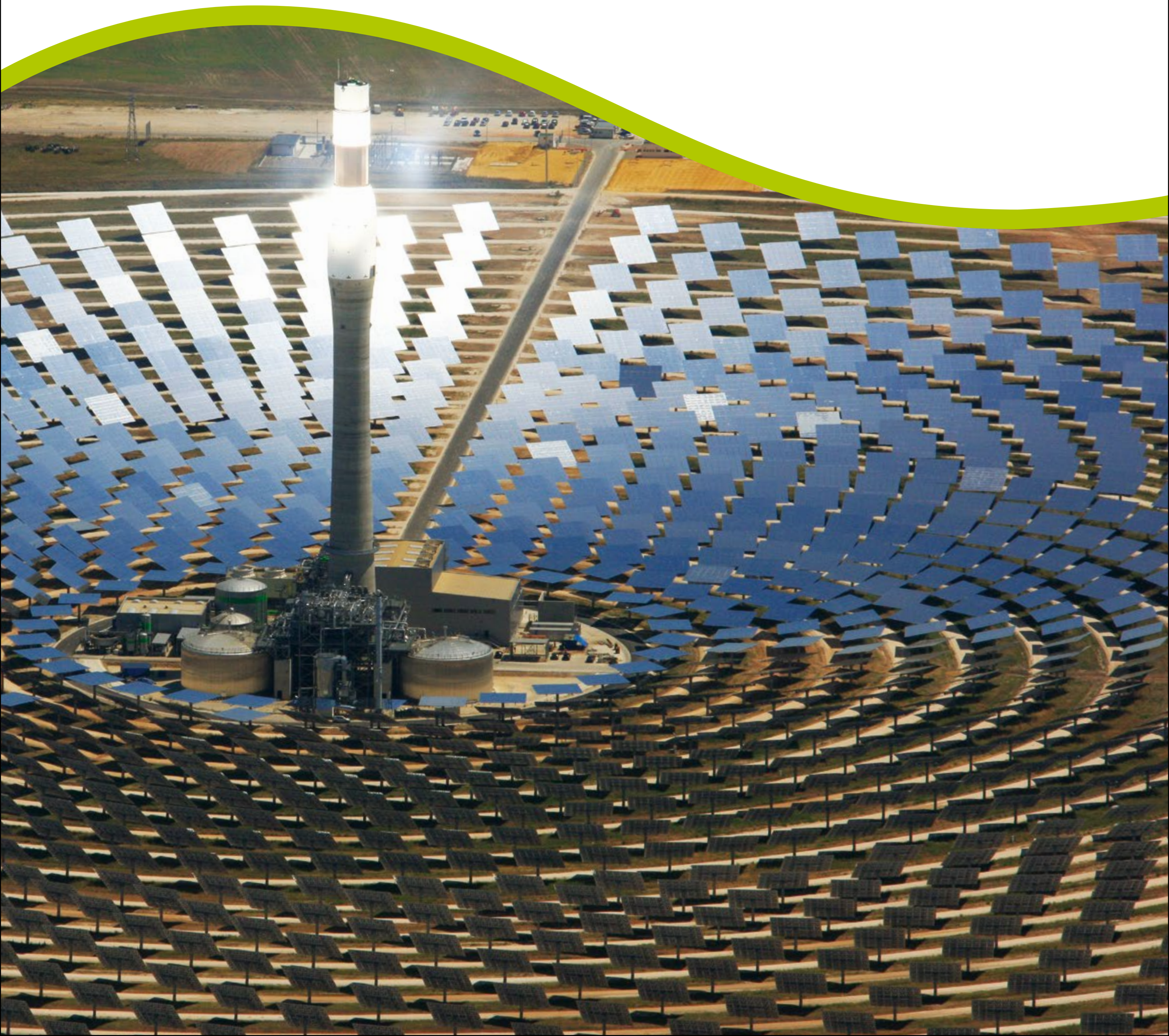
Renewable Energies

Future renewable energy costs: solar-thermal electricity

How technology innovation is anticipated to reduce the cost of energy from European solar-thermal electricity plants



KIC InnoEnergy

KIC InnoEnergy is a European company dedicated to promoting innovation, entrepreneurship and education in the sustainable energy field by bringing together academics, businesses and research institutes.

KIC InnoEnergy's goal is to make a positive impact on sustainable energy in Europe by creating future game changers with a different mindset, and bringing innovative products, services and successful companies to life.

KIC InnoEnergy is one of the first Knowledge and Innovation Communities (KICs) fostered by the European Institute of Innovation and Technology (EIT). It is a commercial company with 28 shareholders that include top-ranking industries, research centres and universities, all of which are key players in the energy field. More than 150 additional partners contribute to the company's activities to form a first-class and dynamic network that is always open to new entrants and furthers KIC InnoEnergy's pursuit of excellence. Although KIC InnoEnergy is profit-oriented, it has a "not for dividend" financial strategy, reinvesting any profits it generates back into its activities.

KIC InnoEnergy is headquartered in the Netherlands, and develops its activities across a network of offices located in Belgium, France, Germany, the Netherlands, Spain, Portugal, Poland and Sweden.

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Executive summary

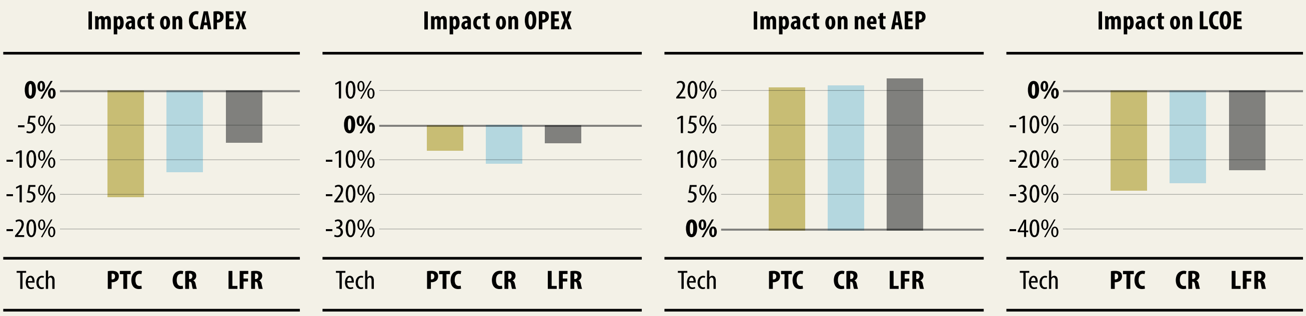
KIC InnoEnergy is developing credible future technology cost models for four renewable energy generation technologies using a consistent and robust methodology. The purpose of these cost models is to enable the impact of innovations on the levelised cost of energy (LCOE) to be explored and tracked in a consistent way across the four technologies. While the priority is to help focus on key innovations, credibility comes with a realistic overall LCOE trajectory. This report examines how technology innovation is anticipated to reduce the LCOE from European solar-thermal electricity (STE) plants over the next 12 to 15 years.

For this STE report, input data is closely based on the KIC InnoEnergy technology strategy and roadmap work stream published in October 2014. The output of that work was an exhaustive and comprehensive set of discrete innovations and groups of innovations together with their potential impact on known reference plants, built on expert vision and knowledge. For this report, the temporal scope of KIC InnoEnergy technology strategy and roadmap, five years ahead, has been extended to 12 to 15 years according to the methodology set up for this series of reports.

At the heart of this study is a cost model, developed for KIC InnoEnergy by BVG Associates, in which elements of baseline STE plants are impacted on by a range of technology innovations. These power plants are defined in terms of the applied technology type: parabolic trough collector (PTC); central receiver (CR); and linear Fresnel reflector (LFR). Each type is analysed at three points in time at which the projects reach the final investment decision (FID): 2014 [the baseline]; 2020; and 2025). In this study, the plants' lifetimes are set to 25 years for the purpose of LCOE calculation. These plants are representative of the European market.

The combined impact that technology innovations over the period are anticipated to have on projects with different combinations of Technology Types is presented in Figure 0.1.

Figure 0.1 **Anticipated impact of all innovations by Technology Type FID in 2025, compared with an STE plant with the same capacity with FID in 2014.** (Site type 2050DNI).



Source: KIC InnoEnergy

The study concludes that LCOE savings of at least 28.7% are anticipated for PTC technology, with a capacity factor of 27.4%. Numerous innovations generate small improvements in LCOE through changes in capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP). The baseline parameter (fully detailed in Appendix A) for this prediction is a 100MW plant situated in Spain, with a direct normal irradiation (DNI) of 2,050kWh/m^2 per year and, for PTC and CR technology types, a storage of 1GWht in order to operate the plant for an additional four hours at nominal power.

For CR technology, the anticipated impact is predicted to be an approximate 27.0% reduction in LCOE. The capacity factor of the baseline CR plant is expected to be 26.3%. Other baseline parameters remain the same as applied to PTC technology.

For LFR technology, LCOE is expected to lower by 23.6%, comparing current projects to those with FID in 2025. The estimated capacity factor of 18.8% for LFR plants is significantly lower than for other Technology Types. Also, the reference plant for this technology is assumed to operate without thermal storage. Other baseline parameters stay the same. The potential of LFR technology is to be seen in the lower investment costs compared to other Technology Types. However, the efficiency of LFR plants is currently lower than competing Technology Types (as shown by the capacity factor) and higher operations, maintenance and service (OMS) costs per kWhe generated are a challenge to overcome.

For all the Technology Types, the impacts from STE technology innovations (excluding transmission, decommissioning, pre-FID risk, supply chain and finance effects) contribute an anticipated reduction in the LCOE of at least 23.6%. Figure 0.2 shows that well over half of the total anticipated technology impact is achieved through seven innovations. The largest potential is expected to rest on the improvement of component manufacturing, excluding supply chain effects such as volume and competition. As the market for modern STE technologies is relatively young, competition is not very strong in this field and the potential optimisation of production processes remains largely untapped. By analysing existing operational experience and implementing innovative changes in production and assembly lines, a significant decrease in capital expenditures is possible. It is also expected that pure supply chain effects, such as economies of scale and competition, will emerge as a function of market growth, delivering an additional reduction in LCOE.

Figure 0.2a **Anticipated impact of technology innovations for an STE plant using PTCs with FID in 2025, compared with an STE plant with FID in 2014.**

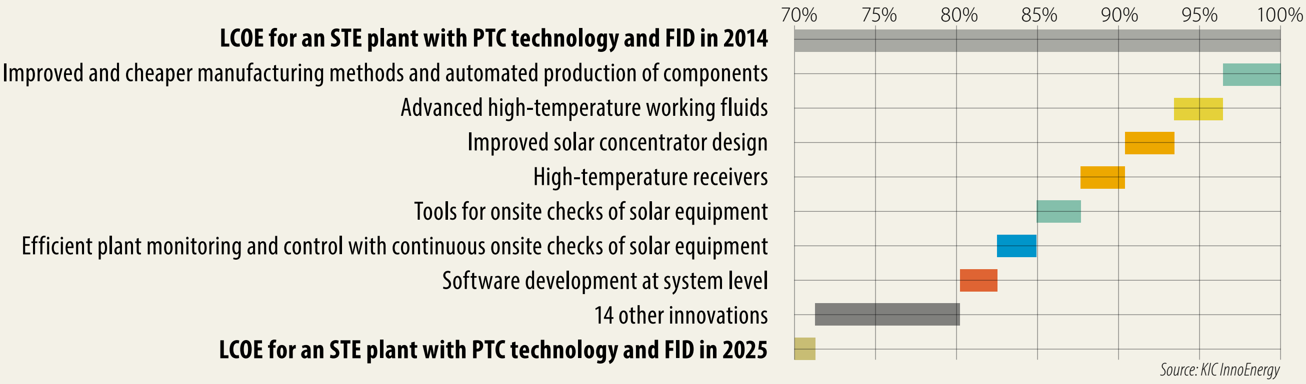


Figure 0.2b **Anticipated impact of technology innovations for an STE plant using a CR with FID in 2025, compared with an STE plant with FID in 2014.**

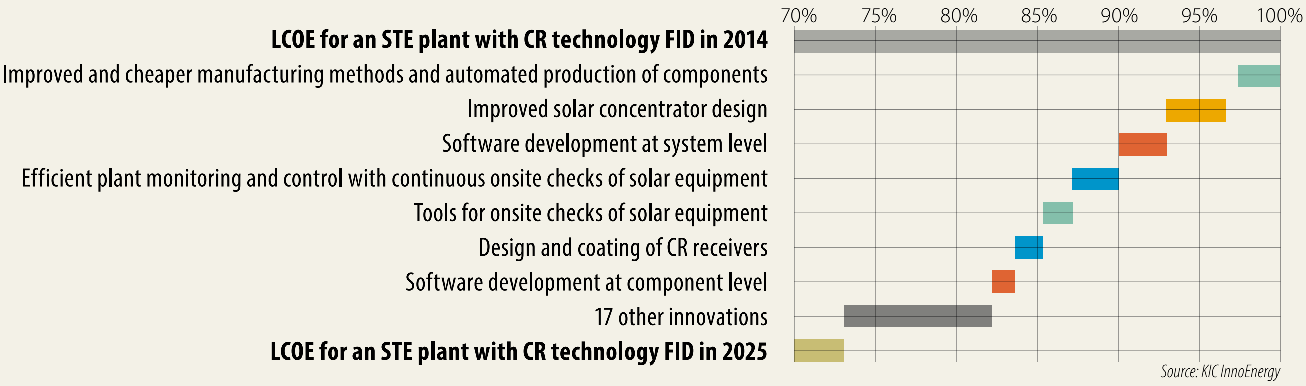
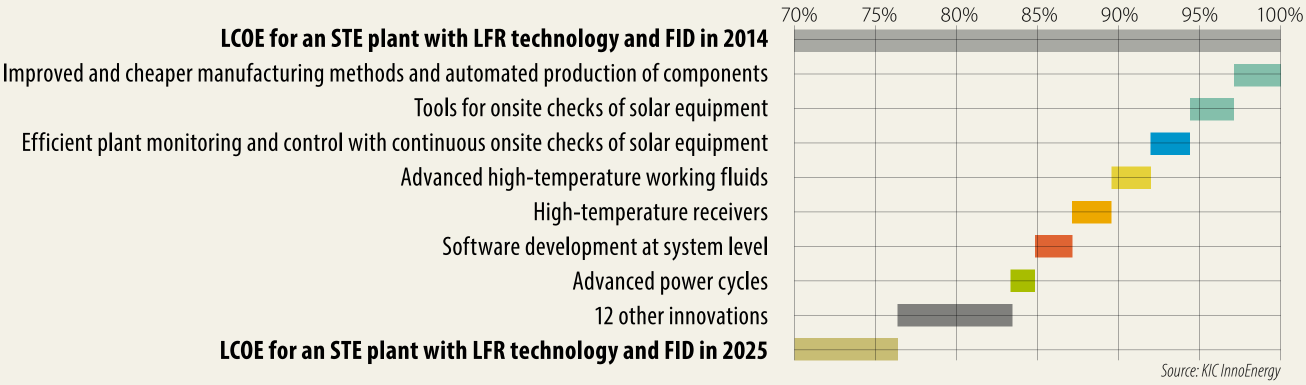


Figure 0.2c **Anticipated impact of technology innovations for an STE plant using LFR with FID in 2025, compared with an STE plant with FID in 2014.**



Between 19 and 24 technology innovations for each Technology Type were identified as having the potential to cause a substantive reduction in LCOE through a change in the design of hardware, software or process. Technology innovations are distinguished from supply chain innovations, which are addressed separately. Many more technical innovations are in development, so some of those described in this report may be superseded by others. Overall, however, industry expectation is that the LCOE will reduce by the aggregate level described. In most cases, the anticipated impact of each innovation has been significantly moderated downwards in order to give overall LCOE reductions in line with industry expectations. The availability of this range of innovations with the potential to impact LCOE further gives confidence that the picture described is achievable.

To calculate a realistic LCOE for each scenario, real-world effects of supply chain dynamics, pre-FID risks, cost of finance, transmission and decommissioning are considered in addition to technology innovations.

In plant development, the innovations are mainly based on the implementation and improvement of software, either on a component level or on a plant level. In this sector, the reduction in LCOE is predicted to be at least 4.6%. The dominant improvements relate to well-validated and verified software models that support the engineering process.

Innovations around concentrators and receivers result in an anticipated impact of at least 7.1% LCOE reduction. A significant share of the cost reduction – up to 4.5% – is contributed by the improvement of the solar concentrator design. Other innovations enable moves towards high-temperature receivers and better efficiency of both the receiver as well as the concentrators. Sometimes sites with a high direct normal irradiance (DNI) also have harsh environmental conditions (e.g., sand storms, great differences between daily maximum and minimum temperatures), making durability of key components crucial if such sites are to be exploited effectively.

Improvements in heat transfer fluids (HTFs) and storage solutions result in an expected LCOE reduction varying from 2.3% for CR to 5.6% for PTC. The use of new and improved working fluids along with the cost reduction of storage systems towards more competitive price levels is the main driver for optimisation in this section. The introduction of direct steam generation (DSG) in once-through operation mode is expected to play an important role for LFR (with an anticipated 3.1% reduction in LCOE).

The cumulative impact of the innovations in balance of plant (BoP) varies from 1.4% to over 2%, however, this result is controversial. Some innovations result in an increase in the LCOE (which is not modelled here), which derives from the implementation of efficient dry-cooling systems. This is tolerated as these systems lower the water consumption and make STE possible in areas with high DNI but where water is a scarce resource. Other innovations refer to the adoption of new thermodynamic cycles and the improvement of thermodynamic efficiency for currently used cycles.

The anticipated impact of innovation in the field of construction is at least 8.5%. The majority of LCOE reduction within this section, around 4%, is provided by improvements in the manufacturing process, excluding supply chain effects such as competition and economies of scale. Further cost reductions arise from improvements to, and optimisation of, the commissioning process.

In OMS, software development has strong potential to lower LCOE. An efficient plant monitoring concept makes up half of the 3.1% of overall anticipated reductions. Another large impact is expected to come from the development of models and methodologies to predict long-term behaviour of key components and degradation in extreme environments. Cost-efficient sun-tracking as well as effective cleaning systems are assumed to have a moderate effect in this area. Innovations in this section deliver LCOE reduction by lowering OPEX for the plant and raising AEP, while CAPEX stays almost the same.

Overall, reductions in CAPEX per megawatt installed over the period are anticipated to be between 8% (LFR) and 15% (PTC). OMS costs are anticipated to reduce by 5% (LFR) to 12% (CR). The biggest anticipated reduction of LCOE is caused by an increase in AEP in the range of 20% (CR and PTC) and 22% (LFR).

Although CAPEX, OPEX and AEP are unique to each Technology Type, the overall LCOE reductions modelled are similar. PTC has shown to present the greatest potential for innovations in the future; however, as CR plants already achieved lower LCOE in 2014, CR is predicted to be cheaper in 2025 as well. LFR technology has a lower CAPEX than PTC currently; however, its lower efficiency leads to a higher LCOE. LCOE reduction for LFR is not expected to become higher than the other Technology Types within the next 10 years, but it has the potential to become a competitive alternative to PTC through efficiency increases.

There is a range of innovations not discussed in detail in this report because either their anticipated impact is still negligible on projects reaching FID in 2025 or their evaluation is difficult because no reference plant exists. Among these are new process concepts, such as the coupling to solar desalination plants, which are especially interesting for arid regions with high DNI. Thermochemical reactions within an absorber of a CR plant also offer potential for the development of concentrated solar power. It would therefore be possible to directly produce solar fuels such as hydrogen with a significantly lower carbon footprint than is currently possible via natural gas reformation. The unrealised potential of innovations modelled in the project at FID in 2025, coupled with this further range of innovations not modelled, suggests there are significant further cost reduction opportunities when looking to 2030 and beyond.

Glossary

AEP. Annual energy production.
Anticipated impact. Term used in this report to quantify the anticipated market impact of a given innovation. This figure has been derived by moderating the potential impact through applying various real-world factors. For details of methodology, see section 2.
Balance of plant (BoP). Support structure and array electrical, see Appendix A.
Baseline. Term used in this report to refer to "today's" technology, as would be incorporated into a project.
Capacity factor (CF). Ratio of annual energy production to annual energy production if the plant is generating continuously at rated power.
CAPEX. Capital expenditure.
CR. Central receiver.
CSP. Concentrated solar power.
DECEX. Decommissioning expenditure.
DNI. Direct normal irradiation.
DSG. Direct steam generation.
FEED. Front end engineering and design.
FID. Final investment decision, defined here as that point of a project life cycle at which all consents, agreements and contracts that are required in order to commence a project construction have been signed (or are at or near execution form) and there is a firm commitment by equity holders and, in the case of debt finance or debt funders, to provide or mobilise funding to cover the majority of construction costs.
Generic WACC. Weighted average cost of capital applied to generate LCOE-based comparisons of technical innovations across scenarios. Different from Scenario-specific WACC.
GWHt. Thermal gigawatt hour.
HTF. Heat transfer fluid.
kWhe. Kilowatt hour electrical.
LCOE. Levelised Cost of Energy, considered here as pre-tax and real in mid-2014 terms. For details of methodology, see section 2.
LFR. Linear Fresnel reflector.
MW. Megawatt.
MWh. Megawatt hour.
OMS. Operations, planned maintenance and unplanned (proactive or reactive) service in response to a fault.
OPEX. Operational expenditure.
Other effects. Effects beyond those of power plant innovations, such as supply chain competition and changes in financing costs.
Potential impact. Term used in this report to quantify the maximum potential technical impact of a given innovation. This impact is then moderated through application of various real-world factors. For details of methodology, see section 2.
PTC. Parabolic trough collector.
RD&D. Research, development and demonstration.
Scenario. A specific combination of technology type and year of FID.
Scenario-specific WACC. Weighted average cost of capital associated with a specific scenario. Used to calculate real-world LCOE incorporating other effects, ref. section 2.4.
STE. Solar-thermal electricity.
Technology Type. Term used in this report to describe a concept that could be implemented in order to realise an STE project. For details of methodology see section 2.
TES. Thermal energy storage.
WACC. Weighted average cost of capital, considered here as real and pre-tax.
WCD. Works completion date.

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Foto: ACS Cobra

1. Introduction

1.1. Framework

As an innovation promoter, KIC InnoEnergy is interested in evaluating the impact of visible innovations on the cost of energy from various renewable energy technologies. This analysis is critical in understanding where the biggest opportunities and challenges are from a technology point of view.

In publishing a set of consistent analyses of various technologies, KIC InnoEnergy seeks to help in the understanding and definition of innovation pathways that industries could follow to maintain the competitiveness of the European renewable energy sector worldwide. In addition, it seeks to help solve the existing challenges at the European level: reducing energy dependency; mitigating climate change effects; and facilitating the smooth evolution of the generation mix for the final consumers.

With a temporal horizon out to 2025, this work includes a range of innovations that might be further from the market than normally expected from KIC InnoEnergy. This constitutes a longer term approach, complementary to the KIC InnoEnergy technology mapping focusing on innovations reaching the market in the short to mid-term (up to five years ahead).

1.2. Purpose and background

The purpose of this report is to document the anticipated future solar thermal electricity cost of energy to projects reaching their financial investment decision (FID) in 2025, by reference to robust modelling of the impact of a range of technical innovations and other effects. This work is based on KIC InnoEnergy technology strategy and roadmap work stream published in October 2014. This work involved significant industry experts, as detailed in the above report, and this has been augmented by taking into consideration the existing literature in the field, including the ESTELA Strategic Research Agenda[1]

1 http://www.estelasolar.eu/fileadmin/ESTELAdocs/documents/Publications/ESTELA-Strategic_Reseach_Agenda_2020-2025_Jan2013_Full_HD.pdf

and ERKC Thematic Research Summary[2], as well as continued dialogue with players across industry, right up until publication of this report.

The study does not consider the market share of the different technology types considered. The actual average levelised cost of energy (LCOE) in a given year will depend on the mix of such parameters for projects reaching FID in that year.

1.3. Structure of this report

Following this introduction, this report is structured as follows:

Section 2 Methodology. This section describes the scope of the model, project terminology and assumptions, the process of technology innovation modelling, industry engagement and the treatment of risk and health and safety.

Section 3 Baseline STE plants. This section summarises the parameters relating to the three baseline STE plants for which results are presented. Assumptions relating to these STE technologies are presented in Section 2.

The following six sections consider each element of the STE plant in turn, exploring the impact of innovations in that element.

Section 4 Innovations in STE plant development. This section incorporates the STE plant design, consenting, contracting, land rent and developer's project management activities through to the works completion date (WCD).

Section 5 Innovations in concentrators and receivers. This section incorporates the reflectors, heliostats, receiver and receiver tubes as well as the piping within the solar field itself.

Section 6 Innovations in the heat transfer fluid and thermal energy storage. This section incorporates the heat transfer fluid (HTF) and piping used to transfer the heat from the receiver (tube) to the non-solar equipment and the thermal energy storage (TES).

Section 7 Innovations in balance of plant. This section incorporates the components of the power cycle: the pre-heater / steam generator / super-heater (not for direct steam generation [DSG]); the turbine; the condenser/cooler; the generator; and the elements needed for power control.

Section 8 Innovations in construction. This section incorporates the innovations that may apply to the manufacturing of the components at the factory site (supply chain effects as volume is not considered here), the transportation of all elements and the construction processes on the designated plant site as well as the supportive actions during commissioning.

Section 9 Innovations in operations, maintenance and service. This section incorporates all activities after the WCD until decommissioning.

Section 10 Summary of the impact of innovations. This section presents the aggregate impact of all innovations, exploring the relative impact of innovations in different STE elements.

Section 11 Conclusions. This section includes technology-related conclusions.

Appendix A. Details of methodology. This appendix discusses project assumptions and provides examples of methodology use.

Appendix B. Data tables. This appendix provides tables of data behind figures presented in the report.

2 http://setis.ec.europa.eu/energy-research/sites/default/files/docs/ERKC%20TRS%20Concentrating%20Solar%20Power_print.pdf


Foto: Solana Abengoa

2. Methodology

2.1. Scope of model

The basis of the model is a set of baseline elements of capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP) for a range of different representative Technology Types with given direct normal irradiation (DNI), impacted on by a range of technology innovations. Analysis is carried out at a number of points in time (years of FID), thus describing various potential pathways that the industry could follow, each with an associated reduction of LCOE.

2.2. Project terminology and assumptions

2.2.1. Definitions

A detailed set of project assumptions were established in advance of modelling. These are presented in Appendix A, covering technical and non-technical global considerations and STE-specific parameters.

2.2.2. Terminology

For clarity, when referring to the impact of an innovation that lowers costs or the LCOE, terms such as reduction or saving are used, and the changes are quantified as positive numbers. When these reductions are represented graphically or in tables, reductions are expressed as negative numbers as they are intuitively associated with downward trends.

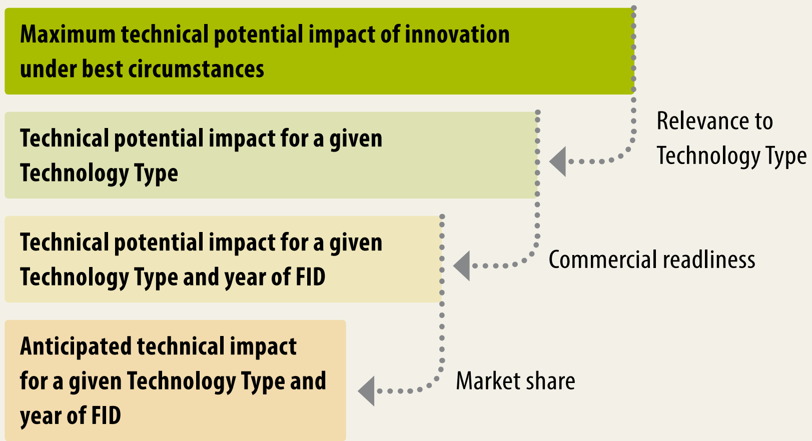
Changes in percentages (for example, losses) are expressed as a relative change. For example, if losses are decreased by 5% from a baseline of 10%, then the resultant losses are 9.5%.

2.3. Technology innovation modelling

The basis of the model is an assessment of the differing impact of technology innovations in each of the STE elements on each of the baseline STE plants, as outlined in Figure 2.1. This section describes the methodology, developed by BVG Associates, analysing each innovation in detail. An example is given in Appendix A.

Figure 2.1 **Process to derive impact of innovations on the LCOE.**

Figure 2.2 **Four-stage process of moderation applied to the maximum potential technical impact of an innovation to derive anticipated impact on the LCOE.**



2.3.1. Maximum technical potential impact

Each innovation may impact a range of different costs or operational parameters, as listed in Table 2.1. The maximum technical potential impact on each of these is recorded separately for the Technology Type most suited to the given innovation. Where relevant and where possible, this maximum technical impact considers timescales that may go well beyond the final year of FID considered in this study.

Frequently, the potential impact of an innovation can be realised in a number of ways, for example, through reduced CAPEX or OPEX or increased AEP. The analysis uses the implementation resulting in the largest reduction in the LCOE, which is a combination of CAPEX, OPEX and AEP.

Table 2.1 **Information recorded for each innovation.** (%)

Impact on cost of		Impact on
• Project up to WCD	• Balance of Plant (BoP)	• Gross AEP
• Solar field	• Operation and planned maintenance, and	• Losses
• Receiver and heat transfer system	• Resource and service	
• Thermal storage system		

2.3.2. Relevance to Technology Type

The maximum technical potential impact of an innovation compared with the baseline may not be realised on every Technology Type. In some cases, an innovation may not be relevant to a given Technology Type at all. For example, sensible heat storage concepts are unlikely to have an impact on LFR plants, so the relevance of this innovation to LFR is set to 0%. In other cases, the maximum technical potential may only be realised on some plant types, with a lower technical potential realised on others. In this way, relevance indicators for a given Technology Type may be between zero and 100% with, at least one Technology Type having 100% relevance.

This relevance is modelled by applying a factor specific to each Technology Type independently for each innovation. The factor for a given Site Type and Turbine Size combination is applied uniformly to each of the technical potential impacts derived above.

2.3.3. Commercial readiness

In some cases, the technical potential of a given innovation will not be fully realised even on a project reaching FID in 2025. This may be for a number of reasons:

- Long research, development and demonstration period for an innovation,
- The technical potential can only be realised through an ongoing evolution of the design based on feedback from commercial-scale manufacture and operation, or
- The technical potential impact of one innovation is decreased by the subsequent introduction of another innovation.

This commercial readiness is modelled by defining a factor for each innovation specific to each year of FID, defining how much of the technical potential of the innovation is available to projects reaching FID in that year. If the figure is 100%, this means that the full technical potential is realised by the given year of FID.

The factor relates to how much of the technical potential is commercially ready for deployment in a project of the scale defined in the baseline, taking into account not only the supplier offering the innovation for sale but also the customer's appetite for purchase. Reaching this point is likely to have required full-scale demonstration. This moderation does not relate to the share of the market that the innovation has taken but rather how much of the full benefit of the innovation is available to the market.

2.3.4. Market share

Each innovation is assigned a market share for each Technology Type and year of FID. This is a market share of an innovation for a given Technology Type for projects reaching FID in a given year; it is not a market share of the innovation in the whole of the market that consists of a range of projects with different Technology Types.

The resulting anticipated impact of a given innovation, as it takes into account the anticipated market share on a given Technology Type in a given year of FID, can be combined with the anticipated impact of all other innovations to give an overall anticipated impact for a given Technology Type and year of FID. At this stage, the impact of a given innovation is still captured in terms of its anticipated impact on each capital, operational and energy-related parameter, as listed in Table 2.1.

These impacts are then applied to the baseline costs and operational parameters to derive the impact of each innovation on LCOE for each Technology Type and year of FID, using a generic weighted average cost of capital (WACC).

The aggregate impact of all innovations on each operational and energy-related parameter in Table 2.1 is also derived, enabling a technology-only LCOE to be derived for each Technology Type and FID year combination.

2.4. Treatment of other effects

To derive a real-world LCOE, this technology-only LCOE is factored to account for the impact of various other effects, defined for each combination of Technology Type and year of FID as follows:

- Scenario-specific WACC, taking into account risk (or contingency)
- Transmission fees, covering transmission capital and operating costs and charges related to the infrastructure from input to substation to the transmission network
- Supply chain dynamics, simplifying the impact of the supply chain levers such as competition and collaboration
- Insurance and contingency costs, both relating to construction and operation insurance and typical spend of construction phase contingency
- The risk that some projects are terminated prior to FID, thereby inflating the equivalent cost of work carried out in this phase on a project that is constructed. For example, if only one in three projects reaches FID, then the effective contribution to the cost of energy of work carried out on projects prior to FID is modelled as three times the actual cost for the project that is successful, and
- Decommissioning costs, as described in Appendix A.

A factor for each of these effects was obtained from the KIC InnoEnergy technology strategy and roadmap work stream published in October 2014 and the consultation to experts lead afterwards.

The factors are applied as follows:

- Scenario-specific WACC is used in place of the generic WACC to calculate a revised LCOE, and
- Each factor is applied in turn to this LCOE to derive the real-world WACC, that is, a 5% effect to account for transmission costs (the first factor in Table A.4) is applied as a factor of 1.05.

These factors are kept separate from the impact of technology innovations in order to clearly identify the impact of innovations, but they are needed in order to be able to compare LCOE for different scenarios rationally.

The effects of changes in construction time are not modelled.

2.5. Treatment of health, safety and environmental impacts

As solar-thermal electricity (STE) is similar to the power block of conventional power plants (steam or gas turbine), the issues related to the health and safety of operation personnel are well known and the measures to be taken are well defined. It is important, however, to recognise that the large collector fields will be different from the usual electricity plants. The health and safety of operational staff is of primary importance to the STE industry. This study incorporates into the cost of innovations any mitigation required in order to at least preserve existing levels of health and safety. Many of the innovations that are considered to reduce the LCOE over time have an intrinsic benefit to health and safety performance, for example the increased reliability of equipment and hence less time working in the solar field.

Another important issue for power plants using STE will be their environmental impact. Topics for the minimisation of the environmental impact that are considered in this report are:

- Implementation of dry-cooling systems at higher costs in order to save water,
- Improvement of cleaning methods for lower water consumption in the operation of an STE plant,
- Innovations related to efficiency improvements in order to lower the demand for land for solar collectors, and
- Substitution of biologically hazardous thermal oil with alternative HTFs.

Specificity of the methodology: differences between anticipated and potential impacts of innovation

This report presents the evolution of the economic parameters of different STE plants from the present day to 2025 and how a number of technology innovations are expected to impact upon them, including the increase or decrease of CAPEX, OPEX, the energy generated and an overall reduction in the LCOE from those plants over time.

The methodology developed for the study presented in this report goes beyond the traditional cost-benefit and technical analysis commonly used for such works and seeks to explore and track the impact of such innovations in a wider context, taking into consideration their different levels of development. This recognises that effects will be evident at different times and accepted by the market at different stages due to their progressive incorporation. Those specific points could well explain why the results presented here may differ from other reference studies. This broader scope is of special interest for KIC InnoEnergy as it highlights the close relationship needed between technology development and innovation and market acceptance.

It is important to note that this study's time horizon is 2025. Therefore, many of the listed innovations will not have reached their full potential impact by that date. This, together with the effect of a range of innovations not discussed in detail in this report (because their anticipated impact is still negligible in the next 10 years), means that further relevant cost reductions can be expected in the long term.


Foto: ACS Cobra

3. Baseline solar-thermal electricity plants

The modelling process described in Section 2 will:

- Define a set of STE plants and derive costs and energy-related parameters for each,
- For each of a range of innovations, derive the anticipated impact on these same parameters for each baseline STE plant for a given year of FID, and
- Combine the impact of a range of innovations to derive costs and energy-related parameters for each of the baseline STE plants for each year of FID.

This section summarises the costs and other parameters for the baseline STE plants. The baselines were developed from the analysis undertaken to deliver the KIC InnoEnergy technology strategy and roadmap report, based on the technical parameters of the baseline STE power plants (see Appendix A).

It is recognised that there is significant variability in costs between projects due to the limited track record of the technology itself and supply chain and technology effects, even within the portfolio of a given developer.

The baseline costs presented in Table 3.1, Figure 3.1 and Figure 3.2 are values obtained from cost data currently available from recent projects or commercial bids and are for projects reaching FID in 2014.

As such, they incorporate real-life supply chain effects such as the impact of competition. All results presented in this report incorporate the impact of technology innovations only, except for when the LCOE are presented in Figure 3.3 and in Section 10.3, which also incorporate the other effects discussed in Section 2.4.

As there are already commercial STE plants in operation with a unit power higher than 100MW and there are also plants of less than 100MW, the assumption of a power plant with 100MW seems reasonable. "Commercially available" means that it is technically possible to build such

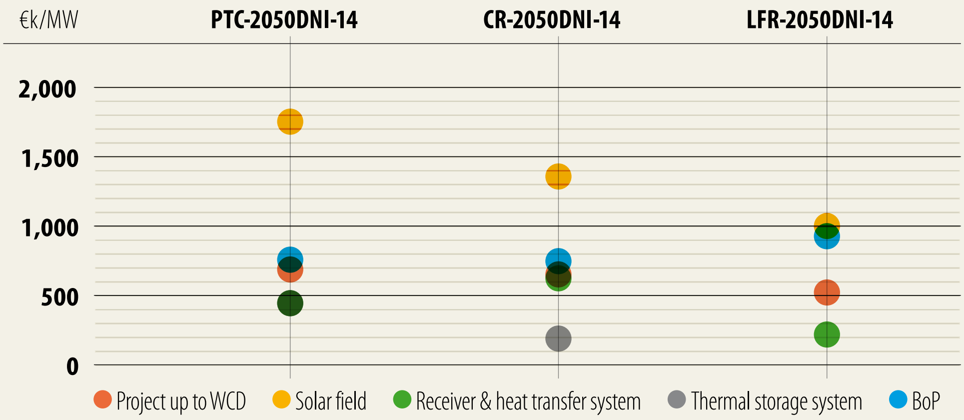
STE plants and that they have been sufficiently prototyped and demonstrated so they have a reasonable prospect of sale into a project. Baseline STE plants considered for this study have been defined, taking into consideration the state-of-the-art of the three technologies analysed. Some parameters have been assumed in order to allow the analysis of some innovations. For example, a working temperature of 500 °C has been assumed when analysing the impact of receivers and working fluids for parabolic trough collectors (PTC) with higher temperature, while a 650 °C working temperature has been assumed for central receiver (CR) plants.

Table 3.1 **Baseline parameters.**

Type	Parameter	Units	PTC-2050DNI-14	CR-2050DNI-14	LFR-2050DNI-14
CAPEX	Project up to WCD	€k/MW	687	651	534
	Solar field	€k/MW	1,755	1,360	1,000
	Receiver and heat transfer system	€k/MW	450	638	225
	Thermal storage system	€k/MW	450	200	-
	BoP	€k/MW	750	750	938
OPEX	Operation and planned maintenance	€k/MW/yr	56	52	49
	Resources and service	€k/MW/yr	15	12	11
AEP	Gross AEP	MWh/yr/MW	2,727	2,614	1,875
	Losses	%	12.0	12.0	12.0
	Net AEP	MWh/yr/MW	2,400	2,300	1,650
	Net capacity factor	%	27.4	26.3	18.8

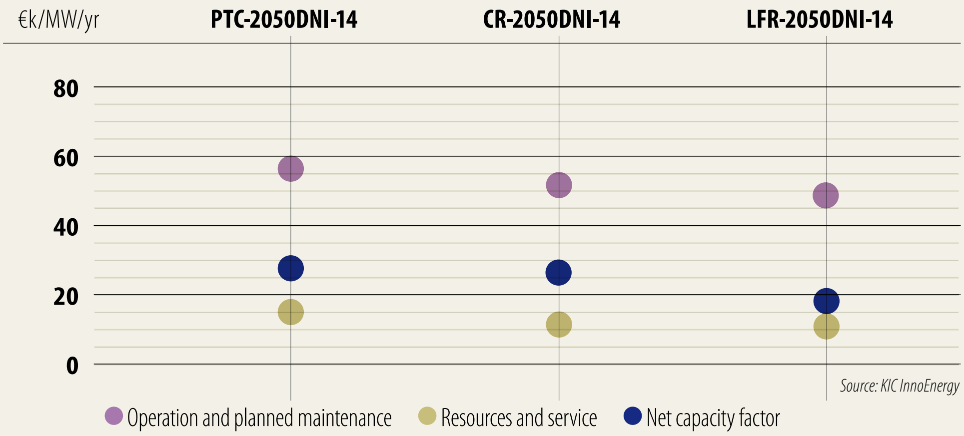
Source: KIC InnoEnergy

Figure 3.1 **Baseline CAPEX by element.**
Note: Receiver data points are partially overlapped by thermal storage system data points (for values see Appendix B. Data supporting tables).



Source: KIC InnoEnergy

Figure 3.2 **Baseline OPEX and net capacity factor.**
The timing profile of CAPEX and OPEX spend, which is important in deriving the LCOE, is presented in Appendix A.



These baseline parameters are used to derive the LCOE for the three baseline Technology Types. A comparison of the relative LCOE for each of the baseline STE plants is presented in Figure 3.3.

At this time, CR provides the lowest LCOE of the three Technology Types. PTC may have the best capacity factor, but it also has the highest investment costs. LFR plants are the cheapest in terms of CAPEX, but their significantly lower power output raises the LCOE above the level of PTC and CR technology.

Figure 3.3 **Relative LCOE and net capacity factor for baseline STE plants with other effects incorporated.** Ref. Section 2.4.

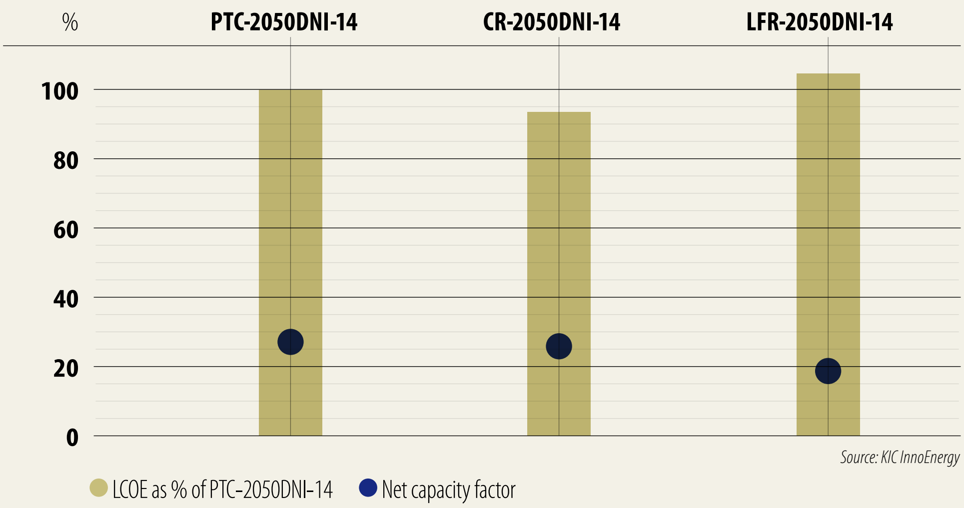


Foto: Solana Abengoa

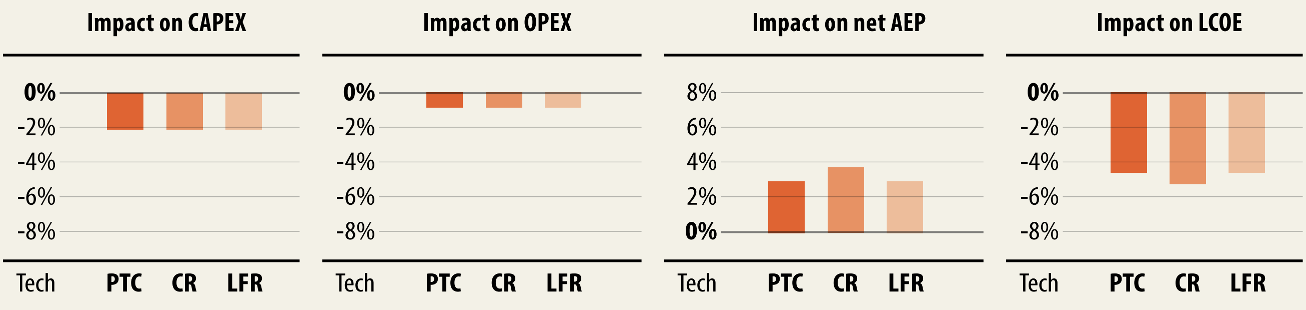
4. Innovations in STE plant development

4.1. Overview

Innovations in STE plant development are anticipated to reduce the LCOE by around 5% between FID 2014 and 2025, with the largest savings anticipated for CR power plants. The savings are dominated by improvements in AEP but also include a slightly lower CAPEX.

Figure 4.1 shows that all Technology Types achieve approximately the same advantage from this area of innovation. With significant savings on CAPEX for the solar field and better overall efficiency, it is possible to cut LCOE by at least 4.6%.

Figure 4.1 **Anticipated impact of STE plant development innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).

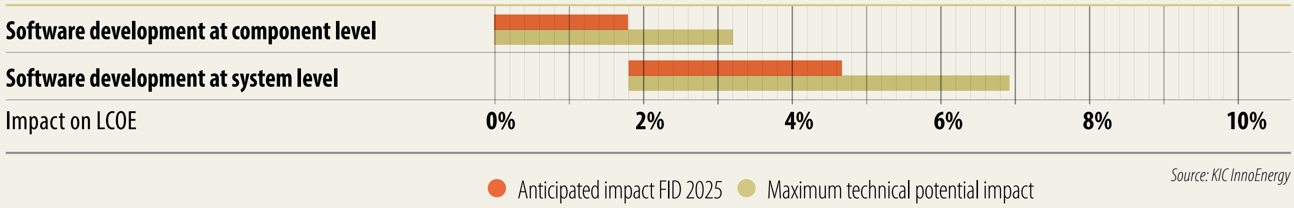


Source: KIC InnoEnergy

Figure 4.2 to Figure 4.4 and Table 4.1 to Table 4.3 show that the individual innovation with the largest anticipated impact by FID 2025 is software development on the system level. Software implementation for both component design and plant optimisation offers potential for cost reduction: however, the verification and validation of these software tools will be necessary in order to achieve the set goals.

4.1.1. Parabolic trough collector

Figure 4.2 **Anticipated and potential impact of STE plant development innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

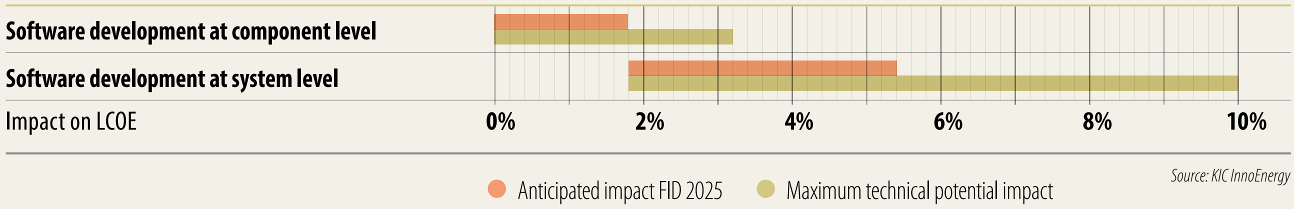
Table 4.1 **Anticipated and potential impact of STE plant development innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Software development at component level	3.8%	0.0%	0.0%	3.2%	2.1%	0.0%	0.0%	1.8%
Software development at system level	0.0%	1.3%	5.1%	5.1%	0.0%	0.7%	2.9%	2.9%

Source: KIC InnoEnergy

4.1.2. Central receiver

Figure 4.3 **Anticipated and potential impact of STE plant development innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

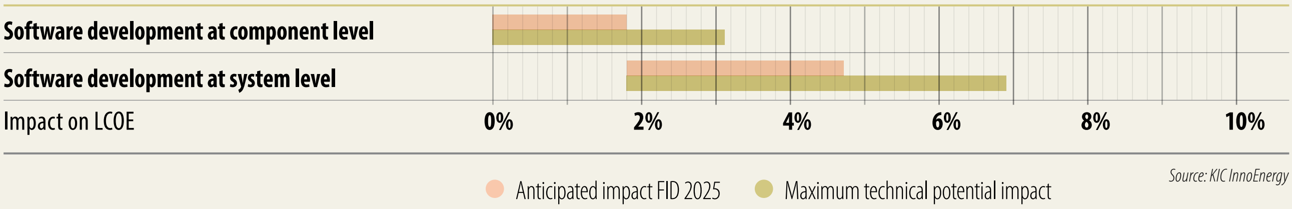
Table 4.2 **Anticipated and potential impact of STE plant development innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Software development at component level	3.8%	0.0%	0.0%	3.2%	2.1%	0.0%	0.0%	1.8%
Software development at system level	0.0%	1.7%	8.5%	8.1%	0.0%	0.7%	3.6%	3.6%

Source: KIC InnoEnergy

4.1.3. Linear Fresnel reflector

Figure 4.4 **Anticipated and potential impact of STE plant development innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 4.3 **Anticipated and potential impact of STE plant development innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Software development at component level	3.8%	0.0%	0.1%	3.1%	2.1%	0.0%	0.1%	1.8%
Software development at system level	0.0%	1.3%	5.1%	5.1%	0.0%	0.7%	2.9%	2.9%

Source: KIC InnoEnergy

4.2. Innovations

Innovations in STE plant development span a range of technical modelling and optimisation improvements. A subset of the more important of these has been modelled here.

Software development at the component level

Practice today: Presently, the design of components for STE plants is supported by the use of modelling and simulation. Since many projects are still being researched, many components have their own models, which are not yet optimised.

Innovation: To improve the future design of components (for example, CRs, heliostat fields, TES systems, dry-cooling condensers and others), their dynamic behaviour must be accurately

modelled. In particular, transient processes resulting in operation outside of the nominal design envelope must be included in these models in order to achieve improved plant performance.
Relevance: The innovation is equally relevant for all Technology Types.
Commercial readiness: About half of the benefit of this innovation will be available for projects with FID in 2020, rising to about 80% for projects with FID in 2025.
For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 2.6% reduction in LCOE for PTC and CR technologies and 2.5% for LFR technology.
Market share: Market share is anticipated to be about a half of projects with FID in 2020. This is anticipated to rise to 70% for projects with FID in 2025.

Software development at the system level

Practice today: Although many commercial projects using STE have been implemented, there are still opportunities to improve the software development for such systems. The complex processes involved render efforts to find a good model for the behaviour of an STE plant.
Innovation: Ongoing software development campaigns will deliver improved algorithms utilising all relevant data sources to provide verified and validated models of plant behaviour. These models will allow developers and operators to optimise both the configuration of the plant and operation processes against the lifetime performance of the plant. Furthermore, probabilistic methods could be used not only to calculate deterministic values but also to track their stability when input variables change. This is anticipated to result in decreases in OPEX and losses and an associated increase in AEP.
Relevance: The innovation is equally relevant for all Technology Types.
Commercial readiness: For PTC and LFR, about half of the benefit of this innovation will be available for projects with FID in 2020, rising to about 80% for projects with FID in 2025. For CR technology, the commercial readiness is anticipated to be 30% for projects with FID in 2020 and 60% for projects with FID in 2025.
For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 5% reduction in LCOE for all technologies.
Market share: Market share is anticipated to be about a half of projects with FID in 2020. This is anticipated to rise to 70% for projects with FID in 2025.

Foto: Gemasolar

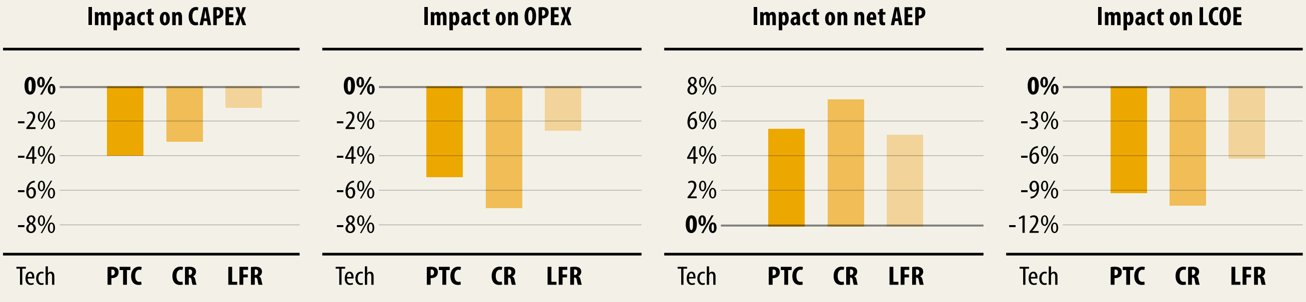
5. Innovations in concentrators and receivers

5.1. Overview

Innovations in the area of concentrators and receivers are anticipated to reduce the LCOE by between 6% and 10% between FID 2014 and 2025. The savings are dominated by improvements in AEP, but significant savings are also evident within OPEX.

Figure 5.1 shows that the impact on LCOE is greatest for a CR power plant. This is because some of the significant innovations in this area are anticipated to be applied only to this Technology Type. Furthermore, it is evident that the reduction is potentially higher for CR power plants once the technology is fully commercially available. One should also recognise that some of the innovations are applicable to all the Technology Types while others apply specifically to one type of STE plant.

Figure 5.1 **Anticipated impact of STE plant development innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).

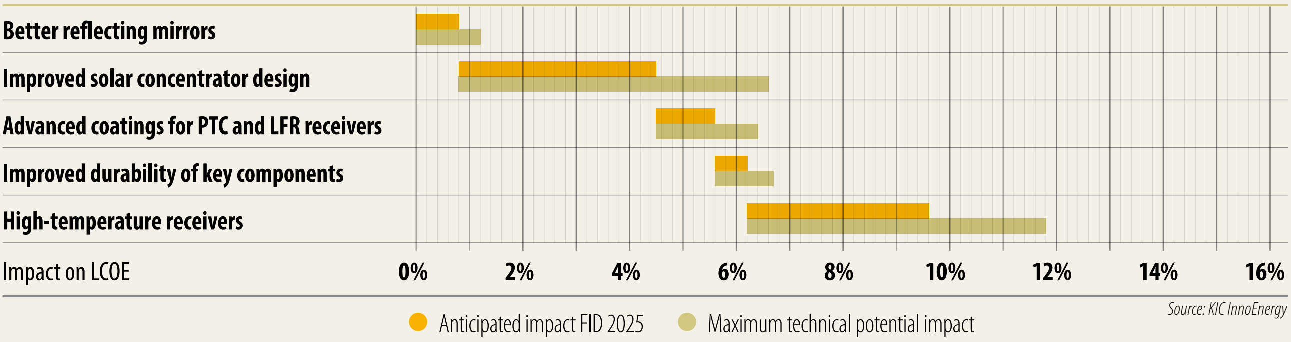


Source: KIC InnoEnergy

Table 5.2 to Figure 5.4 and Table 5.1 to Table 5.3 show that the innovation anticipated to have the biggest impact is the improvement of the design of solar concentrators including cheaper materials and increased efficiency. For LFR plants, the impact of this innovation is only surpassed in terms of impact on LCOE by the utilisation of high-temperature receivers.

5.1.1. Parabolic trough collector

Figure 5.2 **Anticipated and potential impact of concentrator and receiver innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 5.1 **Anticipated and potential impact of concentrator and receiver innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Better reflecting mirrors	0.0%	0.0%	1.3%	1.2%	0.0%	0.0%	0.8%	0.8%
Improved solar concentrator design	6.2%	3.7%	0.0%	5.8%	4.0%	2.4%	0.0%	3.7%
Advanced coatings for PTC and LFR receivers	0.0%	-0.4%	2.0%	1.9%	0.0%	-0.2%	1.1%	1.1%
Improved durability of key components	0.0%	6.2%	0.1%	1.1%	0.0%	3.5%	0.0%	0.6%
High-temperature receivers	0.0%	-0.8%	6.0%	5.6%	0.0%	-0.5%	3.6%	3.4%

Source: KIC InnoEnergy

5.1.2. Central receiver

Figure 5.3 **Anticipated and potential impact of concentrator and receiver innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

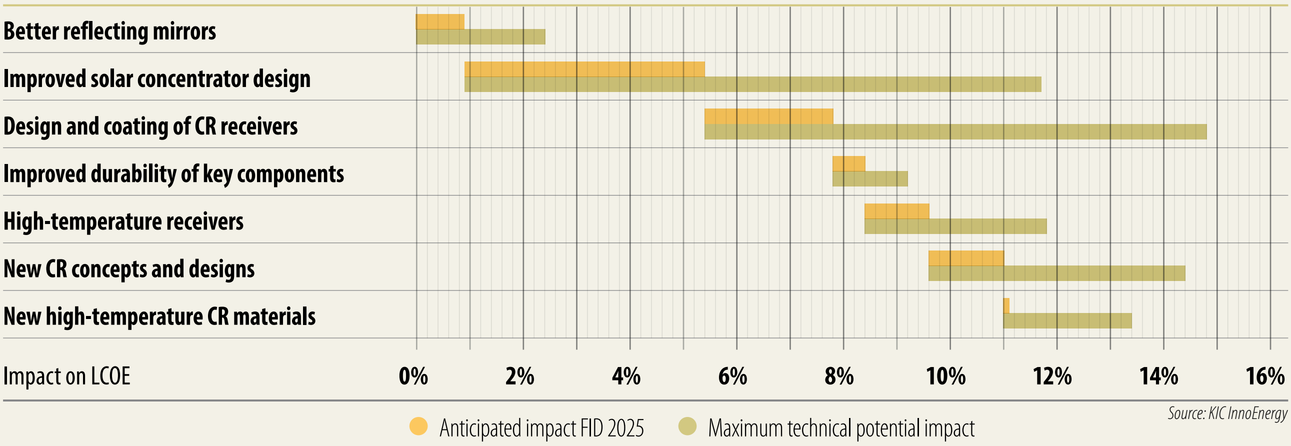


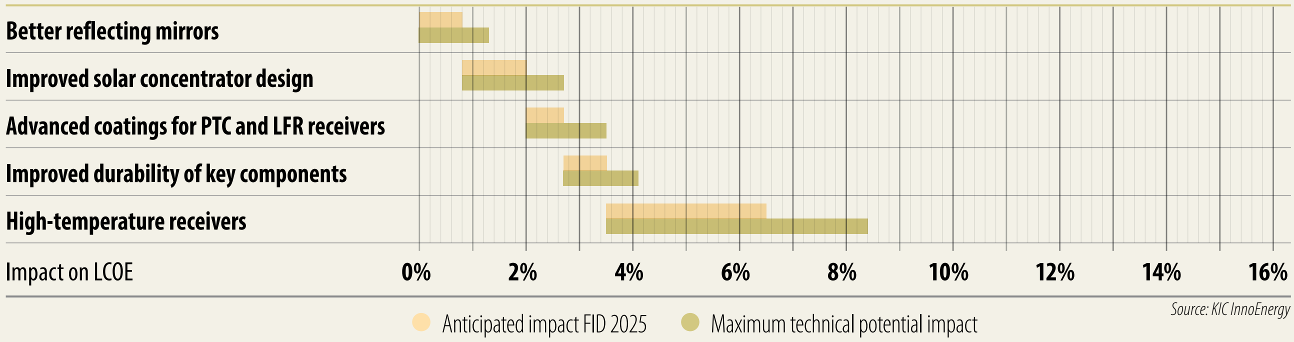
Table 5.2 **Anticipated and potential impact of concentrator and receiver innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Better reflecting mirrors	0.0%	0.0%	2.2%	2.2%	0.0%	0.0%	0.9%	0.9%
Improved solar concentrator design	8.8%	6.6%	2.7%	10.8%	3.6%	2.7%	1.1%	4.5%
Design and coating of CR receivers	-3.2%	0.0%	13.3%	9.4%	-0.7%	0.0%	2.8%	2.2%
Improved durability of key components	0.0%	8.3%	0.1%	1.4%	0.0%	3.5%	0.0%	0.6%
High-temperature receivers	-0.7%	0.0%	4.1%	3.4%	-0.2%	0.0%	1.4%	1.2%
New CR concepts and designs	1.6%	2.8%	3.2%	4.8%	0.4%	0.8%	0.9%	1.4%
New high-temperature CR materials	0.3%	0.4%	2.1%	2.4%	0.0%	0.0%	0.1%	0.1%

Source: KIC InnoEnergy

5.1.3. Linear Fresnel reflector

Figure 5.4 **Anticipated and potential impact of concentrator and receiver innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 5.3 **Anticipated and potential impact of concentrator and receiver innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Better reflecting mirrors	0.0%	0.0%	1.3%	1.3%	0.0%	0.0%	0.8%	0.8%
Improved solar concentrator design	2.3%	0.1%	0.0%	1.9%	1.5%	0.1%	0.0%	1.2%
Advanced coatings for PTC and LFR receivers	0.0%	0.0%	1.3%	1.3%	0.0%	0.0%	0.7%	0.7%
Improved durability of key components	0.0%	6.2%	0.1%	1.4%	0.0%	3.5%	0.1%	0.8%
High-temperature receivers	-0.5%	-1.8%	6.0%	4.9%	-0.3%	-1.1%	3.6%	3.0%

Source: KIC InnoEnergy

5.2. Innovations

Innovations in concentrators and receivers are primarily focused on maximising the collected energy and the temperature that can be achieved. A subset of the more important of these has been modelled here.

Mirrors with higher reflectivity

Practice today: STE technologies all rely on reflecting DNI towards a certain spot or line in order to get a higher spectral flux density. For this reason, all commercial STE plants need large areas of reflecting material to concentrate the solar irradiation.

Innovation: Development of mirror technology incorporating new or improved coating materials (for example, glass) with higher transmittance, improving the reflectivity of the mirror material itself, or producing new mirror designs for an STE plant will reduce losses. These improvements will result in higher AEP.

Relevance: The innovation is equally relevant to all Technology Types.
Commercial readiness: For both PTC and LFR, it is assumed that 50% and 80% of the potential of this innovation is commercially available for projects with FID in 2020 and 2025 respectively. Heliostats for CR plants will be able to use only 30% of the benefit of this innovation for projects with FID in 2020 and 50% in 2025.
For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 1% reduction in LCOE for all technologies.
Market share: Market share is anticipated to be 50% for PTC and LFR, and 60% for CR, projects with FID in 2020. For projects with FID in 2025, the market share for all Technology Types is anticipated to be 80%.

Improved solar concentrators design

Practice today: The design of solar concentrators is based mainly on a steel construction with a concrete foundation. The mirrors used in PTCs have a certain shape to focus the solar radiation at a focal line where the receiver tube is located. LFR concentrators are composed of a set of parallel rows of almost flat mirrors set at angles to direct radiation towards the overhanging receiver tube. CR technology uses a field of individual heliostats to obtain the necessary flux density.
Innovation: For PTC systems, research projects are analysing the use of lightweight materials and larger units with the potential to reduce the total specific investment cost (i.e., €/m^2), including material, manufacturing, transport and installation costs. The potential in improving CR plants lies in both advanced heliostat field layouts and new heliostat designs with lower specific cost (i.e., €/m^2). Implementing a two-stage concentration could bring some advantages for LFR technology (e.g., a better intercept factor and lower thermal losses at the receiver). The benefits of this innovation mainly affect the CAPEX related to the solar field and, to a lesser extent, the planned maintenance.
Relevance: The innovation is equally relevant to all Technology Types.
Commercial readiness: For both PTC and LFR, 50% and 80% of the potential of this innovation is predicted to be commercially available for projects with FID in 2020 and 2025 respectively. The commercial readiness for CR technology is assumed to be only 20% for projects with FID in 2020 and 45% in 2025.
For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 4.6% reduction in LCOE for PTC technology, 5% for CR and 1.5% for LFR.
Market share: It is anticipated that half of projects using PTC and LFR with FID in 2020 will use this innovation, rising to 80% for projects with FID in 2025. For CR plants, the market share is anticipated to be 60% for projects reaching FID in 2020 and 90% in 2025.

Advanced selective coatings for PTC and LFR receivers

Practice today: Selective coatings reduce the heat transfer losses caused by radiation from the receiver tube. Incoming "short" wave lengths (approximately 0.3-1.5µm) can be absorbed by the receiver tube while, at longer wave lengths (2µm and higher), the reflectivity of the coating rises to high values therefore preventing the receiver tube from emitting too much heat radiation because its emissivity is low. Emissivity values of 10% at 400 °C are usual nowadays. Is spite of the current high absorptivities (α>95%) and low emissivities (ε<10% at 400 °C), there is still potential for improvement.

Concerning thermal stability, currently available selective coatings for PTC and LFR are usually unstable in hot air at temperatures higher than 500 °C.

Innovation: Coating improvements for receiver tubes of PTC and LFR plants would cover the increase of solar absorption ($\alpha S \geq 0.96$), meaning higher gain of energy and the reduction of thermal emissivity ($\varepsilon \leq 0.1$ @ 450 °C), meaning the thermal losses are mitigated. An optimal selective coating will also exhibit enhanced thermal stability enabling the receiver tubes to reach higher temperatures than present components resulting in an increase of the AEP.

Relevance: The innovation is only relevant for PTC and LFR technologies.

Commercial readiness: For both PTC and LFR, it is assumed that 50% and 80% of the potential of this innovation is commercially available for projects with FID in 2020 and 2025 respectively.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 1.5% reduction in LCOE for PTC technology and 1% for LFR.

Market share: PTC plants as well as LFR projects show the same behaviour: 40% of the projects with FID in 2020 and 70% of the projects reaching FID in 2025 will use the innovation.

Advanced design and selective coatings for CRs

Practice today: Commercial CR plants currently use metallic tubular receivers, operated either with DSG or liquid HTF.

Innovation: The development of selective coatings for CR receivers with improved thermal stability will enable higher temperature operation. Unlike PTC and LFR coatings it is considered unlikely that this improvement will be attended by an increase in emissivity or absorbtivity as high-temperature thermal stability is challenging to achieve without damaging the optical coefficients. Improved CR design will increase the heat transfer efficiency and consequently the AEP and lower the pressure drop experienced by the HTF as it passes through the receiver.

Relevance: The innovation is only relevant to CR technology.

Commercial readiness: For projects with FID in 2020, about 15% of the benefit of this innovation will be available, doubling for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 3% reduction in LCOE for CR technology.

Market share: Half of the projects with FID 2020 will make use of the innovation, rising to 70% in 2025.

Improved durability of key components

Practice today: Components of STE include concentrators and receivers/receiver tubes as well as storage tanks, HTF piping and fittings, pumps and heat exchangers. The performance of these plant items usually degrades as a function of time, solar irradiation and other environmental influences.

Innovation: The development and commercialisation of new materials and manufacturing methods offers opportunities to extend the lifetime and lower degradation during operation, thereby increasing the power output and reducing OPEX. Durability against erosion caused by solid particles carried by the air will enhance the long-term reflectivity/transmittance of mirrors, heliostats, and other glass surfaces resulting in higher plant efficiency and lower OPEX. Improved piping systems will increase the availability and reliability of the TES and pumps. Research is also underway to improve the aging characteristics of absorptive materials.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: For both PTC and LFR, it is assumed that 50% and 80% of the potential of this innovation is commercially available for projects with in FID 2020 and 2025 respectively. The commercial readiness for CR technology is assumed to be 40% for projects with FID in 2020 and 60% for projects with FID in 2025.

For a single plant with FID in 2025, the expected impact of this innovation is expected to bring a 0.7% reduction in LCOE for PTC and CR technology and 0.9% for LFR.

Market share: Market share is anticipated to be 30% for PTC and LFR projects with FID in 2020 and 50% for CR plants. For projects with FID in 2025 the market share for all Technology Types is anticipated to be 70%.

High-temperature receivers

Practice today: Currently, commercial CRs are working at working fluid temperatures below 570 °C. Plants currently operating at such high-temperatures mostly use molten salts and liquid water/superheated steam as HTF. The current temperature limit in PTC receiver tubes is approximately 400 °C, while the cost-efficient LFR systems usually operate in the lowest range with temperatures of about 270 °C - 350 °C.

Innovation: New receiver designs, with new materials able to withstand higher stresses and thermal cycling would allow higher working temperatures at the receivers , for PTC and LFR, the improvement of evacuated receiver tubes is considered to have significant potential benefits. Temperature increases in the receiver and then the HTF have a strong influence on the power output of the plant. For PTCs, the target receiver temperature could be 550 °C by 2020, CRs could reach up to 1,000 °C and 500 °C is an appropriate goal for LFRs.. Increases to maximum operating temperatures drive improvements in thermodynamic efficiency thus increasing the AEP for the plant.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: For both PTC and LFR, it is assumed that 50% and 75% of the potential of this innovation is commercially available for projects with FID in 2020 and 2025 respectively. The commercial readiness for CR technology is assumed to be 30% for projects with FID in 2020 and 50% for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 4.2% reduction in LCOE for PTC, 1.7% for CR and 3.8% for LFR.

Market share: It is anticipated that half of projects that reach FID in 2020 will use this innovation, rising to 80% for PTC and LFR and 70% for CR projects reaching FID in 2025.

New concepts for CRs

Practice today: Currently, steam and molten salt tubular receivers are mostly applied in commercial CR plants. Both concepts are based on metal tubes that contain the HTF. Therefore, the heat transfer from the concentrated solar radiation to the HTF takes place via the wall of the metal tube.

Innovation: To deliver performance increases, new innovative concepts for central receivers may be necessary. In direct absorption receivers, the incoming concentrated radiation is focussed directly on the darkened HTF that runs over a surface as a falling film. In the direct absorbtion design there is no temperature drop between the metal tube surface and the HTF. Another potential technology is the solid particle receiver, which also allows direct absorption of the radiation by the HTF. In this case, the HTF is a fluidised finely-ground solid. The use of liquid metals is another possible innovation that allows operation at high-temperatures as well as providing the very high heat transfer coefficients that are necessary to derive maximum benefit from the high flux densities in CRs. This innovation has a positive effect on almost all project elements, especially the CAPEX related to the receiver and HTF and the AEP.

Relevance: The innovation is only relevant to CR technology.

Commercial readiness: Commercial readiness is anticipated to be 20% for projects with FID in 2020, doubling for projects with FID in 2025.

For a single plant with FID in 2025, the expected impact of this innovation is expected to bring a 2% reduction in LCOE for CR technology.

Market share: Half of the projects with FID in 2020 will make use of the innovation and this share will rise to 70%for projects with FID in 2025.

New high-temperature CR materials

Practice today: As discussed above, current commercial CR systems use metallic tubes that contain the HTF and are heated up by concentrated radiation. Air receivers are still at experimental stage and consist of either ceramic elements or metallic tubes that heat up the air flowing through them.

Innovation: New materials need to be developed that can withstand higher temperatures and higher radiant flux densities (up to 1.5MW/m^2). Ceramic-based materials can make outlet temperatures higher than 1,000 °C possible; however, designing a pressurised receiver will be a necessary challenge. These new materials will allow the CR plant to operate at higher temperatures and hence higher thermodynamic efficiencies. These innovations are anticipated to raise the AEP of the CR plant.

Relevance: The innovation is only relevant to CR technology.

Commercial readiness: As the development of new material for CRs represents a great effort in terms of research, the benefit of the innovation is anticipated to be 5% for projects with FID in 2020 and 15% for projects with FID in 2025.

For a single plant with FID in 2025, the expected impact of this innovation is expected to bring a 0.4% reduction in LCOE for CR technology.

Market share: 20% of the projects with FID in 2020 will make use of the innovation, doubling for projects with FID in 2025.

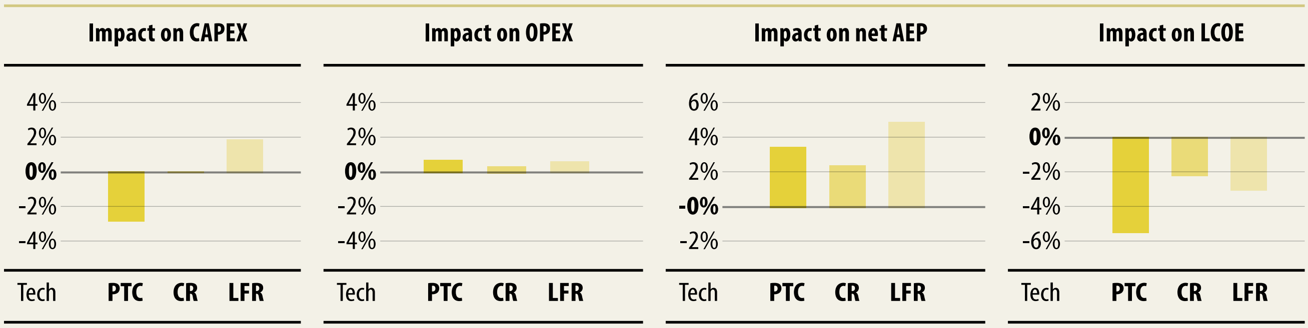
6. Innovations in the HTF and TES

6.1. Overview

Innovations in the area of HTF and TES are anticipated to reduce the LCOE by between 2.3% and 5.6% between FID 2014 and 2025. The savings are driven by improvements in AEP with limited improvements or even increases in CAPEX and OPEX.

Figure 6.1 shows that the impact on OPEX is broadly consistent between the Technology Types but CAPEX and AEP vary due to the different innovations modelled for each type of plant. LFR in particular benefits from just a few innovations.

Figure 6.1 **Anticipated impact of STE plant development innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).



Source: KIC InnoEnergy

Figure 6.2 to Figure 6.4 and Table 6.1 to Table 6.3 show that the individual innovations anticipated to deliver the greatest savings in this area are the development of advanced high-temperature working fluids in order to allow the power block to operate at higher conversion efficiencies.

This group of innovations includes topics with great future potential, especially for LFR technology, such as DSG at 500 °C with a once-through operation mode. In the case of CR, the use of pressurised gas as HTF is highlighted as having strong potential to reduce the LCOE.

6.1.1. Parabolic trough collector

Figure 6.2 **Anticipated and potential impact of HTF and TES innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in in 2014.**

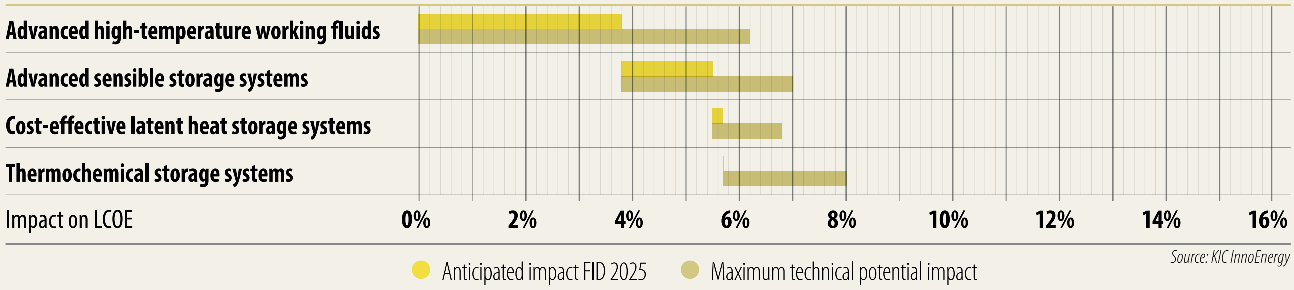


Table 6.1 **Anticipated and potential impact of HTF and TES innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Advanced high-temperature working fluids	1.2%	-1.2%	5.8%	6.2%	0.7%	-0.7%	3.5%	3.8%
Advanced sensible storage systems	3.8%	0.0%	0.0%	3.2%	2.0%	0.0%	0.0%	1.7%
Cost-effective latent heat storage systems	1.6%	0.0%	0.0%	1.3%	0.2%	0.0%	0.0%	0.2%
Thermochemical storage systems	2.7%	0.0%	0.0%	2.3%	0.0%	0.0%	0.0%	0.0%

Source: KIC InnoEnergy

6.1.2. Central receiver

Figure 6.3 **Anticipated and potential impact of HTF and TES innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in in 2014.**

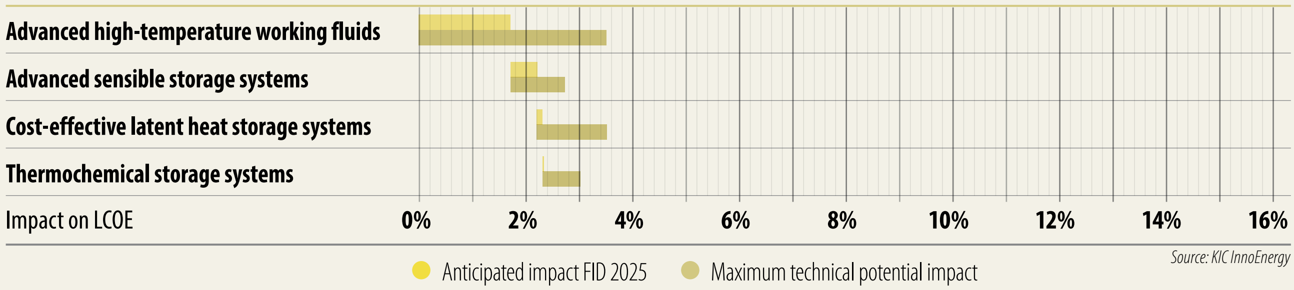


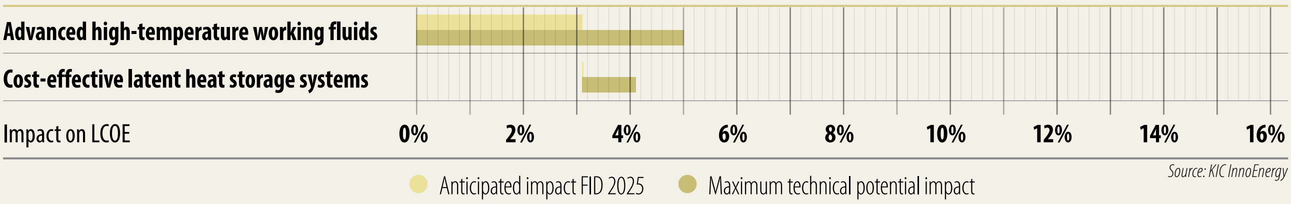
Table 6.2 **Anticipated and potential impact of HTF and TES innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Advanced high-temperature working fluids	-1.4%	-1.2%	5.0%	3.5%	-0.7%	-0.6%	2.4%	1.7%
Advanced sensible storage systems	1.2%	0.0%	0.0%	1.0%	0.6%	0.0%	0.0%	0.5%
Cost-effective latent heat storage systems	0.6%	4.8%	0.0%	1.3%	0.0%	0.2%	0.0%	0.1%
Thermochemical storage systems	0.8%	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%

Source: KIC InnoEnergy

6.1.3. Linear Fresnel reflector

Figure 6.4 **Anticipated and potential impact of HTF and TES innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in in 2014.**



Source: KIC InnoEnergy

Table 6.3 **Anticipated and potential impact of HTF and TES innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Advanced high-temperature working fluids	-3.2%	-1.0%	8.1%	5.0%	-1.9%	-0.6%	4.9%	3.1%
Cost-effective latent heat storage systems	1.2%	0.0%	0.0%	1.0%	0.1%	0.0%	0.0%	0.0%

Source: KIC InnoEnergy

6.2. Innovations

Innovations in HTFs and storage systems encompass a range of improvements of the medium that is responsible for the heat transfer from receiver to the TES and the power block, as well as developments in the field of TES systems. A subset of the more important of these has been modelled here.

Advanced high-temperature HTF

Practice today: Current commercial STE plants mainly use molten salt (CR), thermal oil (PTC) or water/steam (LFR and CR) as HTF. Maximum working fluid temperatures are 570 °C for CR plants and about 400 °C for LFRs and PTCs. Most commercial PTC STE plants use thermal oil at 395 °C as HTF. CR technology with DSG is already at a commercial level. LFR commercial plants are already using direct steam generation at moderate temperatures with no or small superheating (<400 °C).

Innovation: Innovations in this area include:

- The development of thermal oils with a higher chemical stability and therefore higher working temperatures. Widening the operational temperature band of molten salts also falls within this innovation. The higher working temperatures will allow processes with higher efficiency and consequently higher power output. Targets for CR could be a working temperature of 620 °C and 475-500 °C for PTC and LFR.
- Solid particles/fluidised bed as an HTF: this technology uses a solid/gas suspension that is expected to behave like a liquid. In order to absorb the radiation, particles either fall as a curtain or are transported within a fluidised bed through the beam. Solid particles would also offer a method of sensible heat storage from 100 °C potentially up to 1,000 °C. This wide range would offer possibilities in terms of energy density for TES.
- The use of pressurised gas as an HTF is viewed critically by part of the scientific community due to its poor heat transfer properties, but it offers many advantages. Using pressurised gas as an HTF would remove fluid-dependent temperature limits. Pressurised gas (e.g., air, N2, CO_2...) also has no special requirements regarding the material of the receiver tubes. In addition, using compressed air as an HTF would make a solar-assisted Brayton cycle possible. The efficiency would increase by using a hybrid heating technology (for example, both solar and conventional) in a gas turbine.
- DSG offers advantages over other HTFs. Steam can be piped directly into the steam turbine without the heat exchanger currently required. This results in higher process temperatures and therefore a higher efficiency. Despite this, there are still challenges to overcome concerning DSG: these include the implementation of the once-through operation mode (i.e., superheated steam production without decoupling the evaporating and superheating sections by means of a water/steam separator) to produce steam at 500 °C with PTC and LFR. Supercritical steam processes offer the potential to significantly increase the efficiency of CR plants.
- The use of molten salts as an HTF in PTC and LFR will allow for working temperatures up to 500 °C, thus achieving higher efficiencies at the power cycle.

This topic is closely coupled to the development of high-temperature receivers.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: Half of the benefits of this innovation are anticipated to be available for projects with FID in 2020 and up to 80% for PTC and LFR and 75% for CR projects with FID in 2025. For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 5% reduction in LCOE for PTC and 3% for CR and LFR technologies.

Market share: The same market share ratios are expected for both PTC plants as well as LFR projects: 60% of projects with FID in 2020 and 75% of the projects reaching FID in 2025 will use the innovation in one of its possible forms. For CR, the market share will rise from 45% for projects with FID in 2020 to 65% for projects with FID in 2025.

Advanced sensible heat storage systems

Practice today: State-of-the-art STE plants often make use of thermal storage systems (predominantly the "two-tank molten salt storage" which uses two tanks with molten salts at different temperature levels) to provide heat after the operation of the solar field has stopped. In direct systems, such as those used in the GEMASOLAR plant, which do not require an additional heat exchanger, temperatures up to 565 °C are achieved in the hot storage tank.

Innovation: The development of new storage mediums with improved thermal stability, such as molten salt mixtures will allow higher temperatures to be attained. Higher temperatures enable increased energy density to be achieved within the TES and hence lower the specific investment costs for the system. Operation of the TES at higher temperatures also has a positive impact on the efficiency of the plant and hence the AEP. The development of single-tank thermocline systems, where the HTF is partially replaced by cheaper filling materials in the tank, is also modelled. It is anticipated that thermocline systems will reduce the specific investment costs of the TES. Improvements to TES systems would have the potential to reduce CAPEX while improving efficiency and hence AEP.

Note: the use of storage systems strongly depends on the choice of the HTF as the heat has to be transferred between the two of them. Therefore this innovation is closely coupled to the thermal stability of the used HTF.

Relevance: The innovation is fully relevant to PTC and CR technologies, but is less relevant for LFR.

Commercial readiness: For both PTC and CR, the commercial readiness is anticipated to be 50% for projects with FID in 2020 and 80% for projects with FID in 2025.

For a single plant with FID 2025, this innovation is anticipated to achieve a 2.6% reduction in LCOE for PTC and 1% for CR technology.

Market share: PTC projects will have the same market share of 65% for projects with FID in 2020 and 2025, while 40% of the CR projects with FID in 2020 and 60% for projects with FID in 2025 will make use of this innovation.

Cost-effective latent heat storage systems

Practice today: Latent heat storage has not been implemented in commercial STE plants yet, but there are several research activities going on supporting the introduction and use of phase changing materials in TES technologies.

Innovation: The use of latent heat storage offers new possibilities for DSG. In order to implement energy storage for DSG systems, it is crucial to keep heat transfer processes at a relatively constant temperature level as otherwise the energy losses would not be affordable for the plant efficiency. This innovation includes activities to improve heat transfer from the heat conducting phase change materials. By overcoming this challenge, latent heat TES can achieve cost competitiveness with sensible heat technologies. The main effect of this innovation is a substantial decrease of CAPEX corresponding to the TES and to the HTF as well as some reduction in OPEX resulting in a positive impact on the LCOE.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: PTC and LFR technologies will be able to use 20% of the potential on projects with FID in 2020 and twice that value on projects with FID in 2025. For CR projects, 15% of the benefit will be available to projects with FID in 2020 and 25% for projects with FID in 2025. For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 0.5% reduction in LCOE for PTC, 0.3% for CR and 0.2% for LFR technology.

Market share: The market share for PTC projects will be 30% for projects with FID in 2020 and 2025. About 15% of the CR projects with FID in 2020 will make use of the innovation and this value will rise to 20% for CR projects with FID in 2025. For LFR projects, the market share will be 10% for projects with FID in 2020 and 25% for projects with FID in 2025.

Thermochemical storage systems

Practice today: To date, there are no known commercial systems for thermochemical TES in STE plants. Research into the application this technology started 40 years ago.

Innovation: Development projects assume potentials in energy density up to 10 times higher than a comparable sensible heat TES. Instead of raising the temperature of a certain substance and thus storing energy in it, thermochemical storage concepts are based on reversible chemical reactions. Energy is stored as the endothermic reaction progresses and is released as the exothermic reaction progresses. The ability to implement long-term energy storage is a significant advantage for such systems as there are almost no losses. This innovation is modelled as having a high impact on CAPEX.

Relevance: For both PTC and LFR, the innovation shows only 50% relevance as it is not fully applicable to all power plants of these Technology Types. For CR plants, the innovation is fully relevant.

Commercial readiness: The early stage of development is reflected in the low commercial readiness for PTC and LFR with no significance for projects with FID in 2020 and just 10% of the benefit available for projects with FID in 2025. For CR, it is assumed that 10% of the potential can be utilised by projects with FID in 2020, increasing to 25% for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 0.1% reduction in LCOE for PTC and 0.2% for CR technology.

Market share: As the technology is not expected to mature in the near future, the market share for PTC and LFR is very limited: no projects with FID in 2020 will use this innovation and only 5% of projects with FID in 2025 will use it. CR power plants show only slightly higher values, with 5% for projects with FID in 2020 and 15% for projects with FID in 2025.

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Foto: ACS Cobra

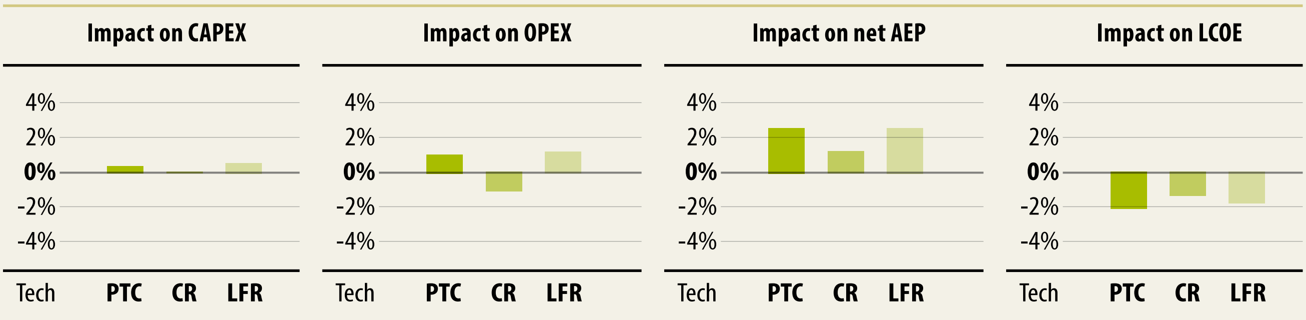
7. Innovations in BoP

7.1. Overview

Innovations in BoP are anticipated to reduce LCOE by between 1.4% and 2.1% between 2014 and 2025. The savings are dominated by improvements in AEP with minor improvements or even higher values anticipated in CAPEX and OPEX.

Figure 7.1 shows that the impact is slightly greater for PTC power plants but is fairly consistent for all technologies.

Figure 7.1 **Anticipated impact of BoP innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).

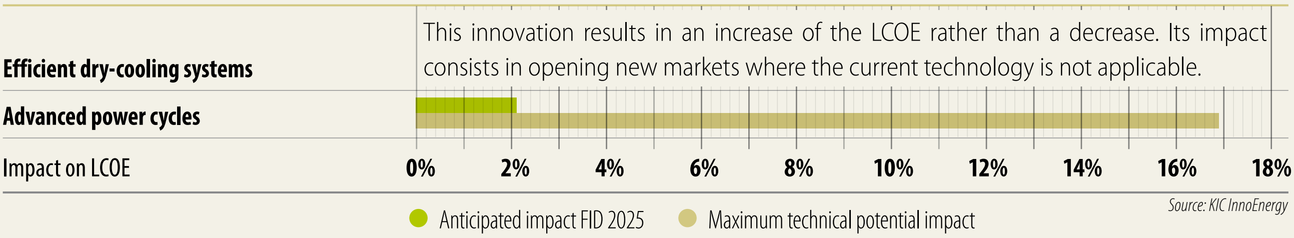


Source: KIC InnoEnergy

Figure 7.2 to Figure 7.4 and Table 7.1 to Table 7.3 show a significant difference between the impacts on CR and the other two Technology Types. While for PTC and LFR, the innovations in advanced power cycle will realise an anticipated reduction in LCOE of around 2% in the period, with further high potential reductions in the longer term. For the CR technology, the potential of this innovation is notably lower.

7.1.1. Parabolic trough collector

Figure 7.2 **Anticipated and potential impact of BoP innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

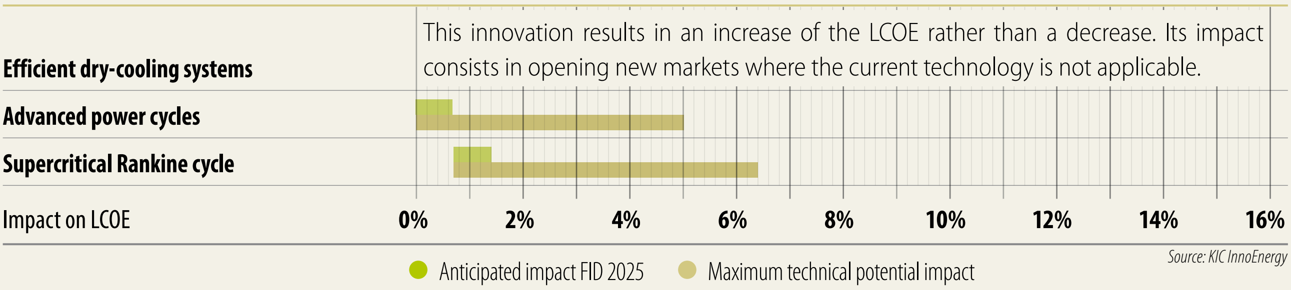
Table 7.1 **Anticipated and potential impact of BoP innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Efficient dry-cooling systems	-	-	-	-	-	-	-	-
Advanced power cycles	-2.7%	-10.0%	25.0%	16.9%	-0.3%	-1.0%	2.5%	2.1%

Source: KIC InnoEnergy

7.1.2. Central receiver

Figure 7.3 **Anticipated and potential impact of BoP innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

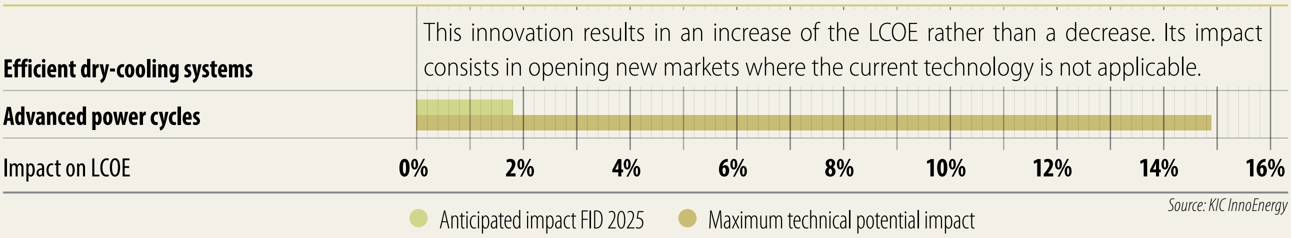
Table 7.2 **Anticipated and potential impact of BoP innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Efficient dry-cooling systems	-	-	-	-	-	-	-	-
Advanced power cycles	0.1%	5.3%	4.3%	5.0%	0.0%	0.7%	0.6%	0.7%
Supercritical Rankine cycle	0.1%	3.0%	5.4%	5.7%	0.0%	0.4%	0.6%	0.7%

Source: KIC InnoEnergy

7.1.3. Linear Fresnel reflector

Figure 7.4 **Anticipated and potential impact of BoP innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 7.3 **Anticipated and potential impact of BoP innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Efficient dry-cooling systems	-	-	-	-	-	-	-	-
Advanced power cycles	-5.2%	-11.4%	25.0%	14.9%	-0.5%	-1.1%	2.5%	1.8%

Source: KIC InnoEnergy

7.2. Innovations

Innovations in BoP are mostly centred on the applied power cycle within the STE plant as well as the opportunity of hybridisation with other fuels. A subset of the more important of these has been modelled here.

Efficient dry-cooling systems

Practice today: Cooling is used to remove waste heat from the steam coming from the turbine utilising the Rankine cycle. As at many conventional power plants, cooling is often achieved by evaporating water (wet cooling). Dry-cooling, however, uses large heat exchanger surfaces to cool down the steam to almost ambient temperature, lowering the water consumption significantly. Both wet-cooling (GEMASOLAR) and dry-cooling (Ivanpah) systems are already in use by commercial STE plants in the sub 1GW range. Although dry-cooling systems offer the advantage of lower water consumption, current systems are outperformed in terms of efficiency by wet systems and hence the LCOE rises. Despite this, reducing water consumption is a significant benefit both for the environment and for the commercial deployment of STE plants in arid countries with high solar radiation and a lack of water.

Innovation: Improving the efficiency of dry-cooling systems would make it possible to utilise STE in areas where water is already a scarce resource. The development of such systems is likely to increase the cost of the power plant with a negative effect on the LCOE which is not modelled here.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: PTC and LFR projects with FID in 2020 will be able to use 75% of the potential rising to 90% for projects with FID in 2025. For CR, 50% of the benefit will be available for projects with FID in 2020 and 80% for projects with FID in 2025.

Note that this innovation is responsible for an increase of LCOE and is thus not modelled here as the model used does not take such innovations into account.

Market share: As the efficiency of dry-cooling systems is usually lower than that of wet-cooling, the market is expected to be found in regions where water is a scarce resource. Therefore the market share for PTC and LFR is anticipated to be only 10% for projects with FID in 2020 and 30% for projects with FID in 2025. For CR power plants, it is assumed that 30% of the projects with FID in 2020 and 45% of projects with FID in 2025 will use this innovation.

Advanced power cycles with higher efficiencies

Practice today: Most of the active commercial STE plants work on a Rankine cycle operating with superheated steam. In smaller facilities, the BoP may also consist of an organic Rankine cycle (ORC) process. The implementation of an open Brayton cycle is the subject of demonstration projects currently underway.

Innovation: New power cycles should be considered for new technological approaches that have an impact on the overall plant efficiency. There are several technologies approaching a first prototype. By using supercritical CO_2 as an HTF it is possible to operate the STE plant in a closed Brayton cycle with high efficiencies. The use of the Brayton cycle within a combined cycle process is also an opportunity to maximise the power output of an STE plant. This innovation is closely related to the development of absorber and HTF technologies because of the dependency of conversion efficiency on the temperature levels.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: For all Technology Types, the available benefit of this innovation is anticipated to be 20% for projects with FID in 2020 and 40% for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 7.7% reduction in LCOE for PTC, 2.1% for CR and 6.8% for LFR technology.

Market share: The market penetration will be limited as this innovation is a challenging task to overcome. PTC and LFR will only show a market share of 10% and 25% for projects with FID in 2020 and 2025 respectively. With 20% for projects with FID in 2020 and 35% for projects with FID in 2025, CR technology is assumed to have slightly higher market shares.

Supercritical Rankine cycle

Practice today: The use of supercritical steam in commercial STE plants is not yet being implemented, however, researchers at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) generated supercritical steam in a solar concentrator for the first time in June 2014.

Innovation: The efficiency of conversion cycles within an STE plant usually increases with higher temperature and pressure levels as has already been seen in supercritical conventional power plants. Improved design of the overall STE plant and the plant equipment to allow operation at at least 600 °C and 25MPa will allow supercritical operation. Under ideal conditions operation at this temperature and pressure will allow thermal conversion efficiency of somewhere between 45-50%, while typical values for subcritical systems are between 40-45%. Hence, the application of supercritical steam cycles in STE plants would result in an increase in CAPEX and OPEX as well as in AEP bringing an overall positive impact con LCOE.

Relevance: The innovation is only relevant to CR technology as this is the only technology capable of generating steam at the temperatures required.

Commercial readiness: Only 20% of the benefit of these innovations is anticipated to be available for projects with FID in 2020, rising to 40% for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 2.3% reduction in LCOE for LFR technology.

Market share: The market penetration of this innovation is anticipated to be 15% for projects with FID in 2020, doubling for projects with FID in 2025.

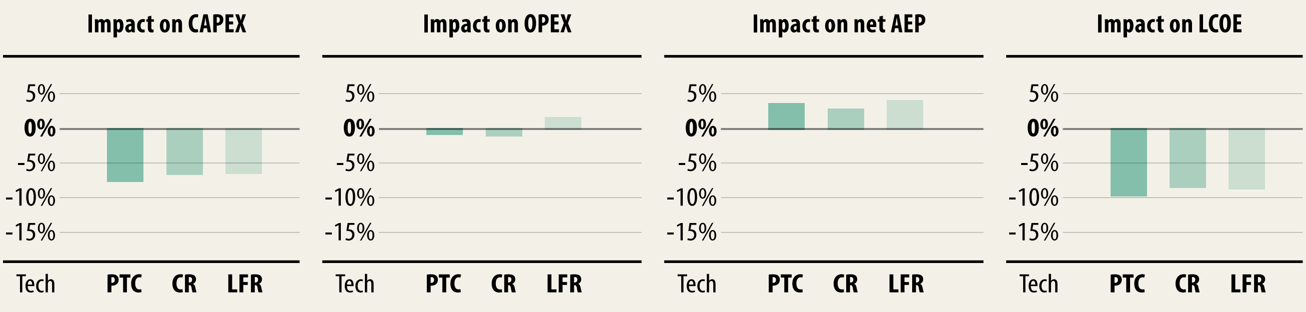

Foto: Abengoa Solar

8. Innovations in construction

8.1. Overview

Innovations in construction are anticipated to reduce the LCOE by 8-10% between 2014 and 2025. The savings are essentially due to improvements in CAPEX, rather than OPEX or AEP.
Figure 8.1 shows that the impact on CAPEX is dominating in this section, because many of the innovations reduce the costs of equipment and commissioning.

Figure 8.1 **Anticipated impact of construction innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).

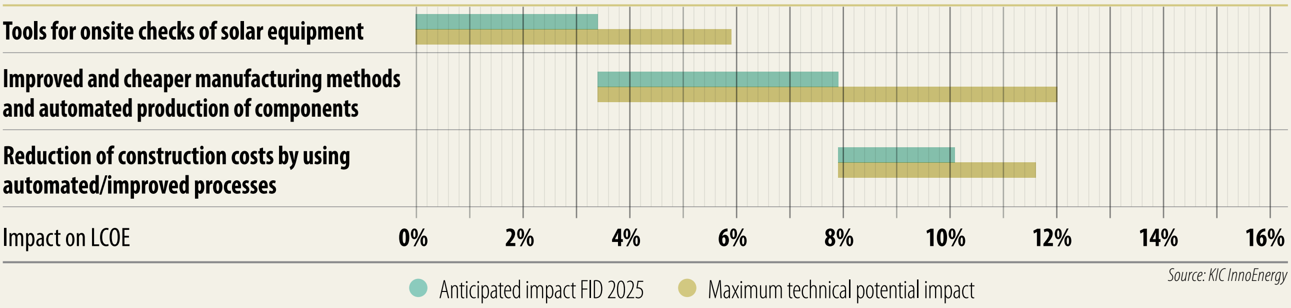


Source: KIC InnoEnergy

Figure 8.2 to Figure 8.4 and Table 8.1 to Table 8.3 show that the innovation with the largest anticipated impact is the improvement in manufacturing processes. This is caused by significant reductions to the CAPEX.
The other innovations that are anticipated to impact significantly by FID 2025 relate to improvements in the commissioning process. Overall, the innovations in this section show a very high potential to reduce the LCOE, but these will not be fully applicable by a 2025 time horizon and depend on market dynamism and growth.

8.1.1. Parabolic trough collector

Figure 8.2 **Anticipated and potential impact of construction innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

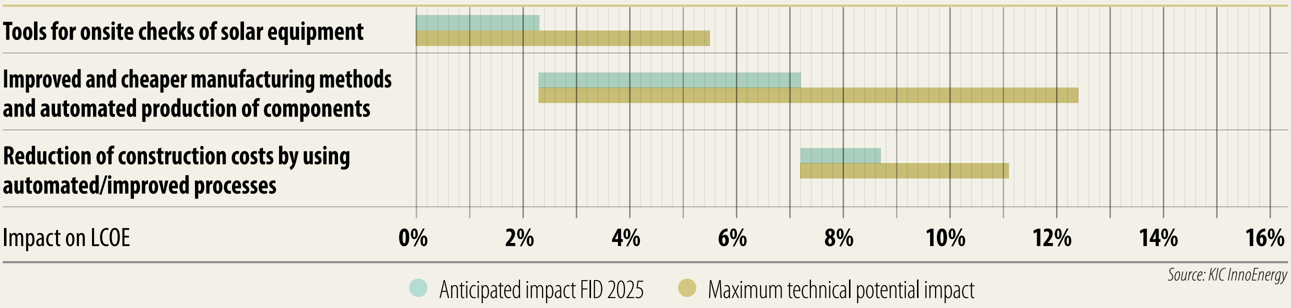
Table 8.1 **Anticipated and potential impact of construction innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Tools for onsite checks of solar equipment	-0.5%	-1.6%	7.0%	5.9%	-0.3%	-0.9%	3.9%	3.4%
Improved and cheaper manufacturing methods and automated production of components	10.2%	0.0%	0.0%	8.6%	5.4%	0.0%	0.0%	4.5%
Reduction of construction costs by using automated/improved processes	4.5%	0.0%	0.0%	3.7%	2.7%	0.0%	0.0%	2.2%

Source: KIC InnoEnergy

8.1.2. Central receiver

Figure 8.3 **Anticipated and potential impact of construction innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

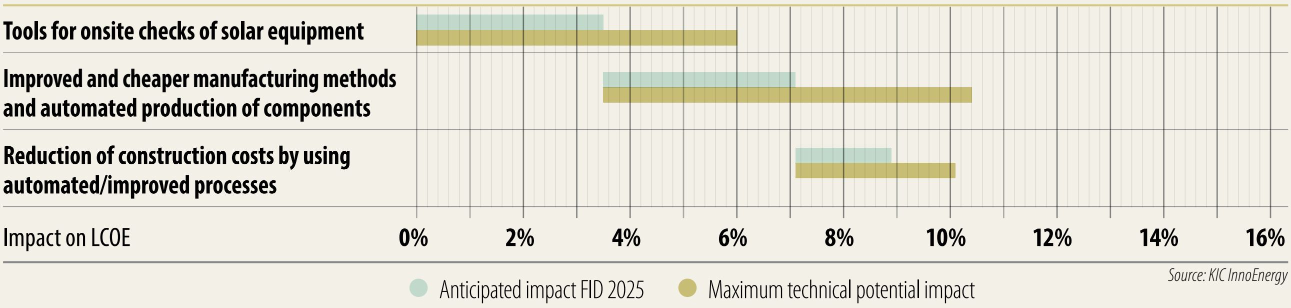
Table 8.2 **Anticipated and potential impact of construction innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Tools for onsite checks of solar equipment	-0.6%	-2.4%	6.7%	5.5%	-0.2%	-1.0%	2.7%	2.3%
Improved and cheaper manufacturing methods and automated production of components	10.6%	4.0%	0.6%	10.1%	5.1%	1.9%	0.3%	4.9%
Reduction of construction costs by using automated/improved processes	4.6%	0.0%	0.0%	3.9%	1.9%	0.0%	0.0%	1.5%

Source: KIC InnoEnergy

8.1.3. Linear Fresnel reflector

Figure 8.4 **Anticipated and potential impact of construction innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 8.3 **Anticipated and potential impact of construction innovations for an LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Tools for onsite checks of solar equipment	-0.6%	-3.1%	7.5%	6.0%	-0.3%	-1.7%	4.2%	3.5%
Improved and cheaper manufacturing methods and automated production of components	8.7%	0.0%	0.0%	6.9%	4.6%	0.0%	0.0%	3.6%
Reduction of construction costs by using automated/improved processes	3.7%	0.0%	0.0%	3.0%	2.2%	0.0%	0.0%	1.8%

Source: KIC InnoEnergy

8.2. Innovations

Innovations in construction are mostly focused on the improvement of production of components and faster and more precise sequences during commissioning. A subset of the more important of these has been modelled here.

Tools for onsite checks of solar equipment

Practice today: Most of the tools and procedures currently used on large solar fields were developed to evaluate prototypes of solar concentrators and other solar equipment. Therefore, most existing tools and procedures are considered too impractical, time-consuming and expensive to be used on large commercial solar fields.

Innovation: This innovation considers the development of efficient tools and procedures to improve the commissioning of STE plants and the periodic checking of the solar field performance. Onsite checks of optical, geometrical and thermal performance of the solar equipment should reduce the number of faulty components during the construction phase and guarantee a good performance during the lifetime of the facility. This innovation is responsible for slight increases in CAPEX and OPEX linked to the use of the tools but with relevant positive impact on the AEP.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: Half of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to 80% for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is anticipated to yield a 5% reduction in LCOE for all technologies.

Market share: It is estimated that 30% of projects with FID in 2020 will make use of the innovation. For projects with FID in 2025, the market share for PTC and LFR is predicted to rise to 70% while only 50% of the CR projects will use this innovation.

Improved manufacturing methods and automated production of components

Practice today: As STE is immature relatively recent and rapidly developing technology, the market has not yet created a competitive atmosphere that forces industry to improve its processes. Solutions for the commercial use of concentrated solar power are individually tailored and the potential to increase cost-efficiency is not fully exploited.

Innovation: Commercial pressure to move towards a cost-competitive STE technology will lead to improved manufacturing methods with increased automation and therefore less manpower. Besides the economies of scale (considered in the supply chain effect described in 2.4) there are developments to be integrated due to the lessons learned during every project. The innovative collector design ULTIMATE TROUGH® not only works with a wider panel to decrease the costs of components but it also uses a smaller number of different steel profiles for its structure, thus simplifying the manufacturing process. The Australian International University is also working on the reduction of heliostat cost by means of concurrent engineering with design and manufacturing engineers working closely together. Design optimization of solar concentrators will lead to a significant saving due to lower manufacturing cost (higher degree of automation), lower transport cost (i.e., better packaging), lower assembly cost (less manpower required for on-site assembly) and lower maintenance cost (i.e., fewer different components: steel profiles and fittings). As such, innovations in this field can impact on costs across the STE plant, which taken together can lead to a significant impacts on different elements of CAPEX.

Relevance: The innovation is equally relevant to all Technology Types.
Commercial readiness: PTC and LFR projects with FID in 2020 will be able to benefit from 30% of the potential of cost reductions and 70% for projects with FID in 2025. For CR, half of the benefit of this innovation is anticipated to be available for projects with FID in 2020, rising to 80% for projects with FID in 2025.
For a single plant with FID 2025, the expected impact of this innovation is anticipated to yield a 6% reduction in LCOE for PTC, 8.1% for CR and 4.9% for FLR technology.
Market share: It is anticipated that 40% of projects with FID in 2020 will make use of the innovation. The PTC and LFR market share will then rise to 75% for projects with FID in 2025. For CR plants, the value increases to 60% for projects with FID in 2025.

Reduction of construction costs by use of automated/improved processes

Practice today: Although the manufacturing processes for component manufacturing are becoming more and more automated, the on-site assembly still requires a lot of manpower to achieve the geometrical accuracy required for good optical performance of the solar concentrators.
Innovation: Collection of experience in assembly and onsite installation will establish best practice and improved procedures in plant manufacture and construction. For both manufacturing and construction, it will be necessary to implement standardised methods and therefore improve the construction process. Faster and highly automated assembly will result in a decrease of personnel costs and hence CAPEX during the construction phase.
Relevance: The innovation is equally relevant to all Technology Types.
Commercial readiness: For projects with FID in 2020 it is anticipated that 40% for PTC and LFR and 50% for CR technology of the estimated potential will be available. For projects with FID in 2025, the commercial readiness for the innovation is assumed to be 80% for all Technology Types.
For a single plant with FID 2025, the expected impact of this innovation is anticipated to yield a 3% reduction in LCOE for PTC, 3.1% for CR and 2.4% for LFR technology.
Market share: PTC and LFR projects show the same behaviour: 40% of the projects with FID in 2020 and 75% of the projects with FID in 2025 will use the innovation. For CR, the market share will rise from 30%for projects with FID in 2020 to 50% for projects with FID in 2025.

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Foto: ACS Cobra

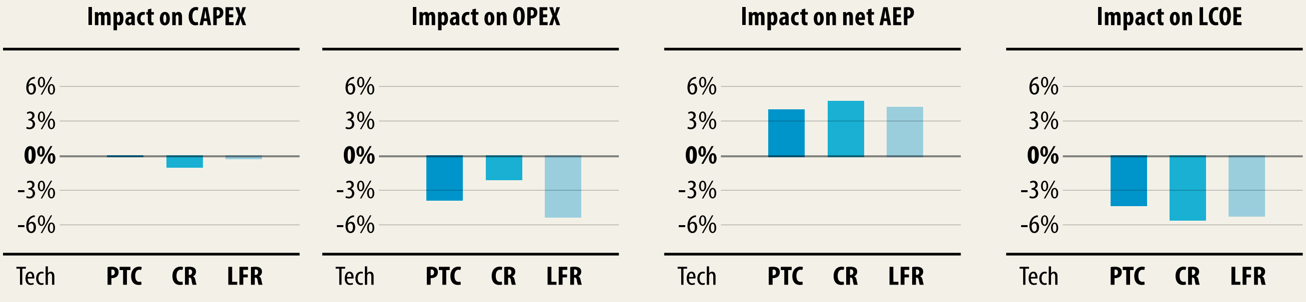
9. Innovations in plant operations, maintenance and service

9.1. Overview

Innovations in operations, maintenance and service (OMS) are anticipated to reduce the LCOE by around 5% between 2014 and 2025, with the largest savings anticipated for projects using CR technology. The savings are dominated by improvements in OPEX and power plant availability, and hence net AEP.

Figure 9.1 shows that the impact on OPEX is greater for LFR power plants. The LCOE reduction is greater for projects using CRs because AEP is a larger contributor to LCOE for STE plants.

Figure 9.1 **Anticipated impact of OMS innovations by Technology Type with FID in 2025, compared with a plant with the same nominal power with FID in 2014.** (Site type 2050DNI).

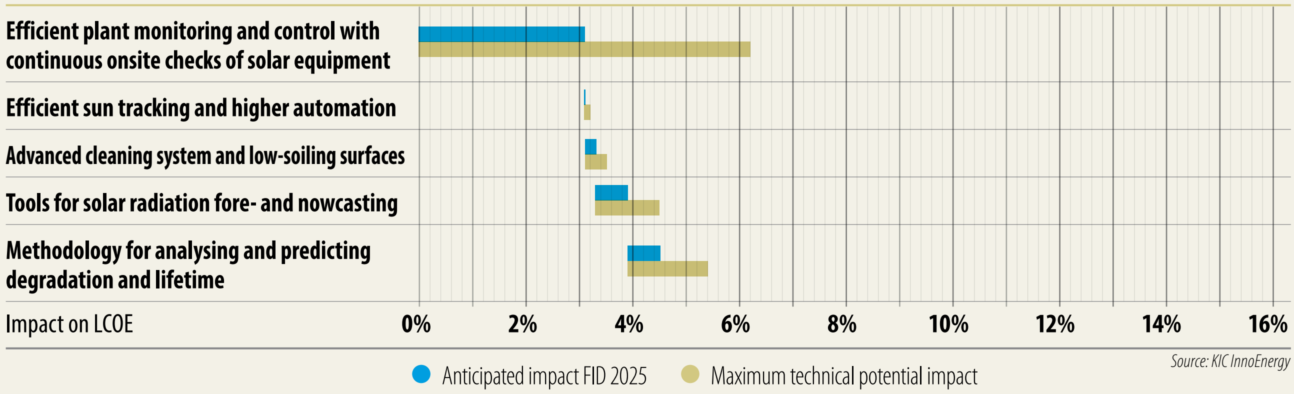


Source: KIC InnoEnergy

Figure 9.2 to Figure 9.4 and Table 9.1 to Table 9.3 show that the individual innovations with the largest anticipated impact by FID 2025 relate to the introduction of efficient plant monitoring that checks the condition of solar equipment. By improved control strategies and better interaction between single components of the power plant, the collected irradiation can be maximised and therefore the AEP increases. This not only improves the efficiency of the power plant but also lowers LCOE significantly.

9.1.1. Parabolic trough collector

Figure 9.2 **Anticipated and potential impact of OMS innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

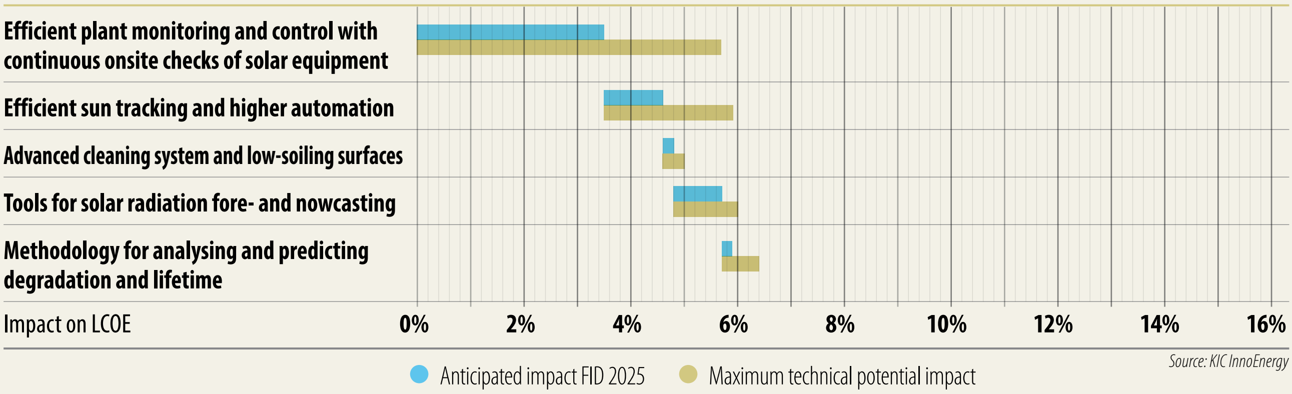
Table 9.1 **Anticipated and potential impact of OMS innovations for a PTC plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Efficient plant monitoring and control with continuous onsite checks of solar equipment	0.0%	1.2%	6.4%	6.2%	0.0%	0.6%	3.1%	3.1%
Efficient sun tracking and higher automation	0.1%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%
Advanced cleaning system and low-soiling surfaces	0.0%	2.5%	0.0%	0.4%	0.0%	1.4%	0.0%	0.2%
Tools for solar radiation fore- and nowcasting	0.0%	-0.3%	1.3%	1.2%	0.0%	-0.1%	0.6%	0.6%
Methodology for analysing and predicting degradation and lifetime	0.0%	5.0%	0.7%	1.5%	0.0%	2.0%	0.3%	0.6%

Source: KIC InnoEnergy

9.1.2. Central receiver

Figure 9.3 **Anticipated and potential impact of OMS innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

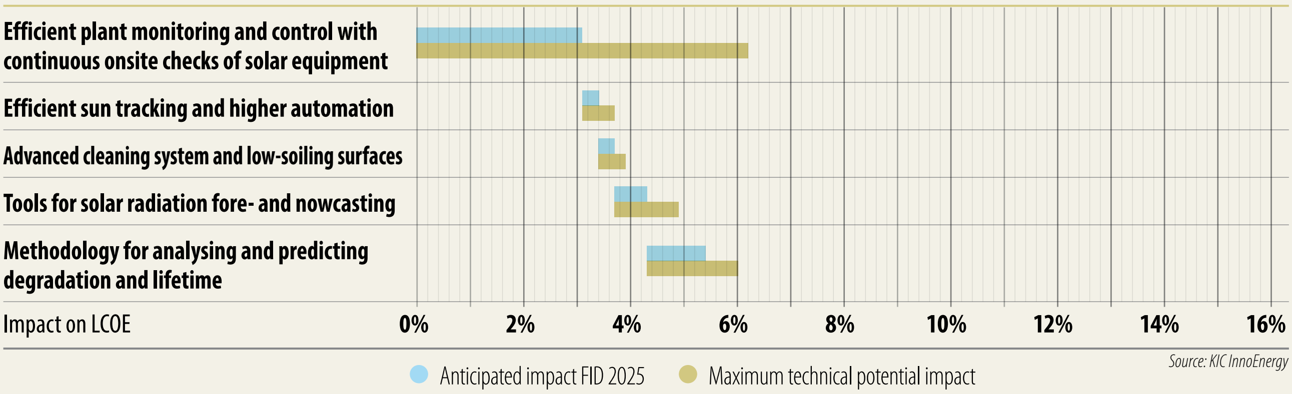
Table 9.2 **Anticipated and potential impact of OMS innovations for a CR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Efficient plant monitoring and control with continuous onsite checks of solar equipment	0.0%	1.3%	5.9%	5.7%	0.0%	0.8%	3.5%	3.5%
Efficient sun tracking and higher automation	2.5%	1.2%	0.2%	2.4%	1.1%	0.5%	0.1%	1.1%
Advanced cleaning system and low-soiling surfaces	0.0%	2.5%	0.0%	0.4%	0.0%	1.1%	0.0%	0.2%
Tools for solar radiation fore- and nowcasting	0.0%	-0.2%	1.3%	1.2%	0.0%	-0.2%	0.9%	0.9%
Methodology for analysing and predicting degradation and lifetime	0.0%	2.7%	0.3%	0.7%	0.0%	0.7%	0.1%	0.2%

Source: KIC InnoEnergy

9.1.3. Linear Fresnel reflector

Figure 9.4 **Anticipated and potential impact of OMS innovations for a LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**



Source: KIC InnoEnergy

Table 9.3 **Anticipated and potential impact of OMS innovations for a LFR plant of 100MW with FID in 2025, compared with a plant with the same nominal power on the same Site Type with FID in 2014.**

Innovation	Maximum Technical Potential Impact				Anticipated impact FID 2025			
	CAPEX	**OPEX**	**AEP**	**LCOE**	**CAPEX**	**OPEX**	**AEP**	**LCOE**
Efficient plant monitoring and control with continuous onsite checks of solar equipment	0.0%	1.3%	6.4%	6.2%	0.0%	0.6%	3.1%	3.1%
Efficient sun tracking and higher automation	0.6%	0.6%	0.0%	0.6%	0.3%	0.3%	0.0%	0.3%
Advanced cleaning system and low-soiling surfaces	0.0%	2.5%	0.0%	0.5%	0.0%	1.4%	0.0%	0.3%
Tools for solar radiation fore- and nowcasting	0.0%	-0.3%	1.3%	1.2%	0.0%	-0.1%	0.6%	0.6%
Methodology for analysing and predicting degradation and lifetime	0.0%	5.0%	0.7%	1.7%	0.0%	3.2%	0.4%	1.1%

Source: KIC InnoEnergy

9.2. Innovations

Innovations in STE plant OMS vary widely from highly practical to deeply technical. A subset of the more important of these has been modelled here.

Efficient plant monitoring and control with continuous onsite checks of solar equipment

Practice today: Currently, it is common to defocus a solar concentrator to control the amount of energy absorbed and therefore the temperature level. This technique reduces radiation capture and lowers the AEP.

Innovation: Improved control of HTF flow in the receiver will allow a reduction in the need for defocusing and hence reduce the associated losses. This innovation will incorporate advanced monitoring techniques and adapted operational strategies. The use of those techniques slightly increases the OPEX but by lowering the amount of radiation which is shed this innovation will substantially increase the AEP for the STE plant.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: All Technology Types are anticipated to show the same progress: half of the potential impact will be available for projects with FID in 2020. For projects with FID in 2025, the readiness rises to 80%.

For a single plant with FID 2025, the innovation is anticipated to achieve a 5% reduction in LCOE for all technologies.

Market share: PTC and LFR projects have the same prospect: 25% of the projects with FID in 2020 and 60% of the projects with FID in 2025 will use the innovation. For CR, the market share will rise from 50% for projects with FID in 2020 to 75% for projects with FID in 2025.

Cost-efficient sun tracking and higher automation

Practice today: State-of-the-art technology uses open-loop controllers that calculate the solar vector for each heliostat based on location and time. This approach does not entail tracking the actual position of the sun.

Innovation: The development of more computationally expensive tracking algorithms may increase the accuracy of the prediction from open-loop controllers; however, this entails an increased investment cost. Other solutions propose the incorporation of feedback from a charge-coupled device (CCD) sensor in closed-loop operation to correct inaccuracies in the open-loop prediction algorithms. Other technologies in CR plants should be able to aim the concentrated radiation precisely on a spot of the receiver to lower thermal stress and local temperature peaks.

By lowering the cost of sun tracking equipment with the same or improved tracking accuracy, the construction CAPEX for the solar concentrators can be lowered. This effect is especially significant for the large heliostat fields of CR plants. The reduction in tracking costs will also reduce OPEX.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: All Technology Types are anticipated to show the same progress: half of the potential impact will be available for projects with FID in 2020. This rises to 80% readiness for projects with FID in 2025.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 2% reduction in LCOE for CR technology and 0.5% for LFR. The impact on PTC is globally low and still negligible for projects with FID in 2025.

Market share: For PTC and LFR plants, the market share is anticipated to be 25% and 60% for projects with FID in 2020 and 2025 respectively. The market share for CR will rise from 35% for projects with FID in 2020 to 55% for projects with FID in 2025.

Advanced cleaning systems and low-soiling surfaces

Practice today: Soiling of reflecting surfaces in STE plants has a significant influence on the power output. In commercial power plants, mirrors and heliostats must be cleaned periodically to maintain or restore the reflectivity of the solar field. This is usually achieved by a tractor pulling a tank and compressor and two workers with cleaning nozzles.

Innovation: New concepts propose the use of tractor-mounted rotating-head rigs. These new methods for mirror cleaning reduce both water-use and the manpower required, and the associated operational costs. The costs can be further lowered by developing anti-soiling coatings for solar reflectors and receiver glass envelopes by decreasing the frequency of the cleaning required. This innovation, through a CAPEX increase, will allow further OPEX reduction.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: All Technology Types are anticipated to show the same progress: half of the potential impact will be available for projects with FID in 2020. For projects with FID in 2025, the readiness rises to 80%.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 0.3% reduction in LCOE for all technologies.

Market share: For PTC and LFR projects with FID in 2020, 30% and 40% are expected to utilise the innovation respectively. For projects with FID in 2025, the market share for both PTC and LFR is anticipated to be 70%. For CR, the market share will rise from 35% for projects with FID in 2020 to 55% for projects with FID in 2025.

Tools for solar irradiation fore- and nowcasting

Practice today: Weather forecasting is already used to predict the DNI and hence power generation for upcoming hours in order to forward plan operational strategy and support the grid balance. In addition, forecasting helps the operator to maximise the power output of the plant. Forecasting usually covers a time period of 24 hours and more, whereas nowcasting covers a range from one to six hours.

Innovation: A system based on numerical weather prediction, enhanced by satellite real-time images and data from meteorological stations, should allow prediction errors below 15% for nowcasting and 25% for forecasting. These improvements will allow operators to increase overall AEP by optimising safety margin on grid compliance.

Relevance: The innovation is equally relevant to all Technology Types.

Commercial readiness: All Technology Types are anticipated to show the same progress: half of the potential impact will be available for projects with FID in 2020. For projects with FID in 2025, the readiness rises to 80%.

For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 1% reduction in LCOE for all technologies.

Market share: It is predicted that 25% of the PTC and LFR power plants with FID in 2020 and 60% of those with FID in 2025 will deploy the innovation. Half of the CR projects with FID in 2020 will make use of the innovation and the share will increase to 90% for projects with FID in 2025.

Methodology for analysing and predicting degradation and lifetime

Practice today: Components of STE plants often have to operate in difficult conditions since high irradiance values are found in extreme environments, such as deserts. Currently, models and methods for simulating degradation processes or experimental setup for accelerated aging are rare although for some of the main components, such as the absorber or HTF, development of methodologies for lifetime assessment is underway. Aging analysis has not yet achieved commercialisation.

Innovation: Accelerated aging test procedures for components of STE plants can support the development of effective maintenance strategies by giving an accurate prediction of the through-life performance of components.

In order to accurately model the durability of these components, methods and standards have to be developed. The implementation of this methodology could reduce OPEX greatly.
Relevance: The innovation is equally relevant to all Technology Types.
Commercial readiness: All Technology Types are anticipated to show the same progress: half of the potential impact will be available for projects with FID in 2020. For projects with FID in 2025, the readiness rises to 80%.
For a single plant with FID 2025, the expected impact of this innovation is expected to bring a 1.2% reduction in LCOE for PTC, 0.5% for CR and 1.3% for LFR technologies.
Market share: The market share for PTC projects with FID in 2020 and 2025 is anticipated to be 30% and 50% respectively. For CR, the market share will rise from 15% for projects with FID in 2020 to 30% for projects with FID in 2025. Half the LFR projects with FID in 2020 are expected to make use of the innovation; by 2025, this share rises to 80%.

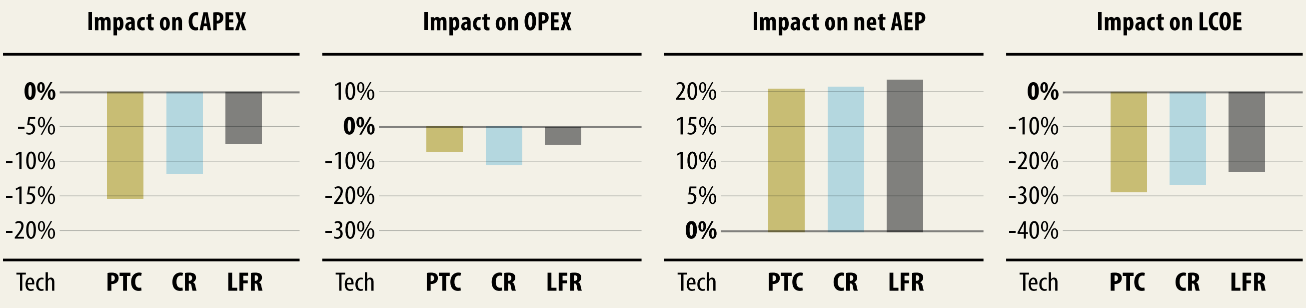
10. Summary of the impact of innovations

10.1. Combined impact of innovations

Innovations across all elements of STE plants are anticipated to reduce the LCOE by around 25% between projects with FID in 2014 and 2025. Figure 10.1 shows that the savings are generated through a balanced contribution of reduced CAPEX and OPEX and increased AEP.

It is important to note that the impact shown in Figure 10.1 is an aggregate of the impact shown in Figure 4.1 to Figure 9.1 and as such excludes any other effects such as supply chain competition. These are discussed in Section 10.3. The largest like-for-like reductions available for the same Technology Type are for projects using PTCs. Nonetheless, both of the other Technology Types score almost same total impact on LCOE for projects with FID in 2025. In the case of PTC, the higher reduction in CAPEX leads to an advantage compared with the other technologies.

Figure 0.1 **Anticipated impact of all innovations by Technology Type FID in 2025, compared with an STE plant with the same capacity with FID in 2014.** (Site type 2050DNI).

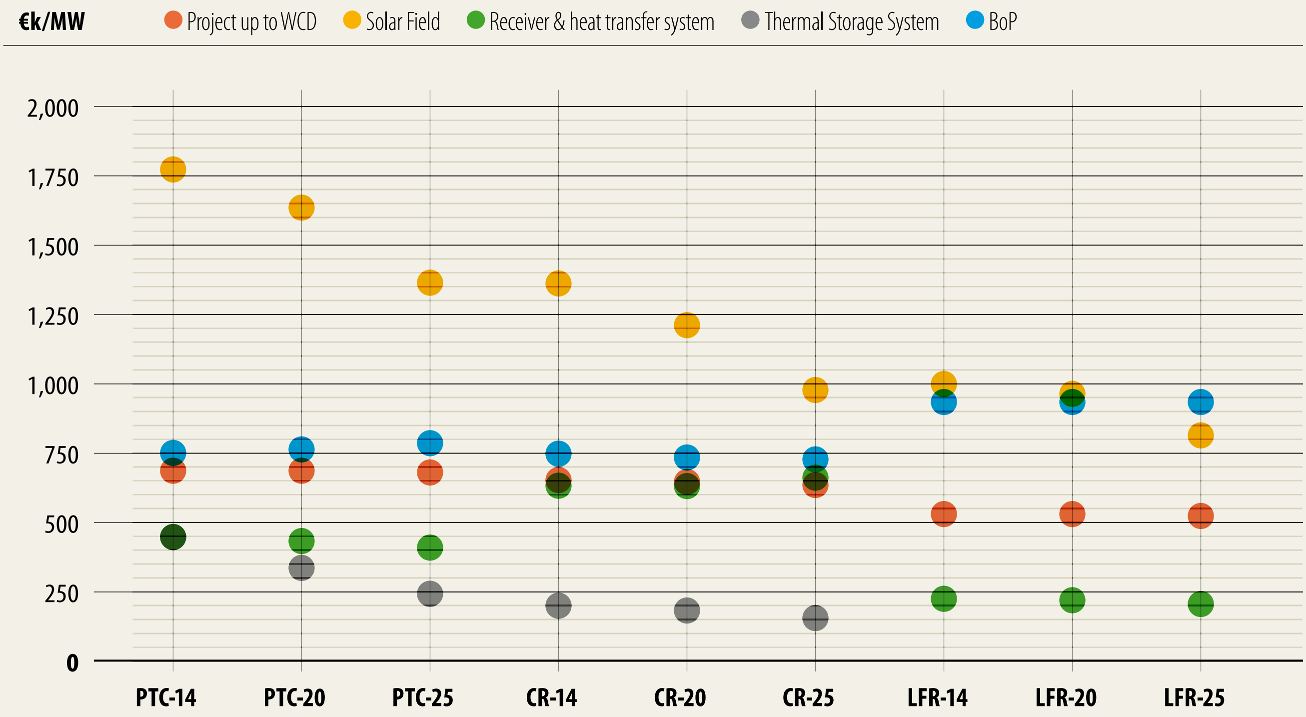


Source: KIC InnoEnergy

10.2. Relative impact of cost of each STE plant element

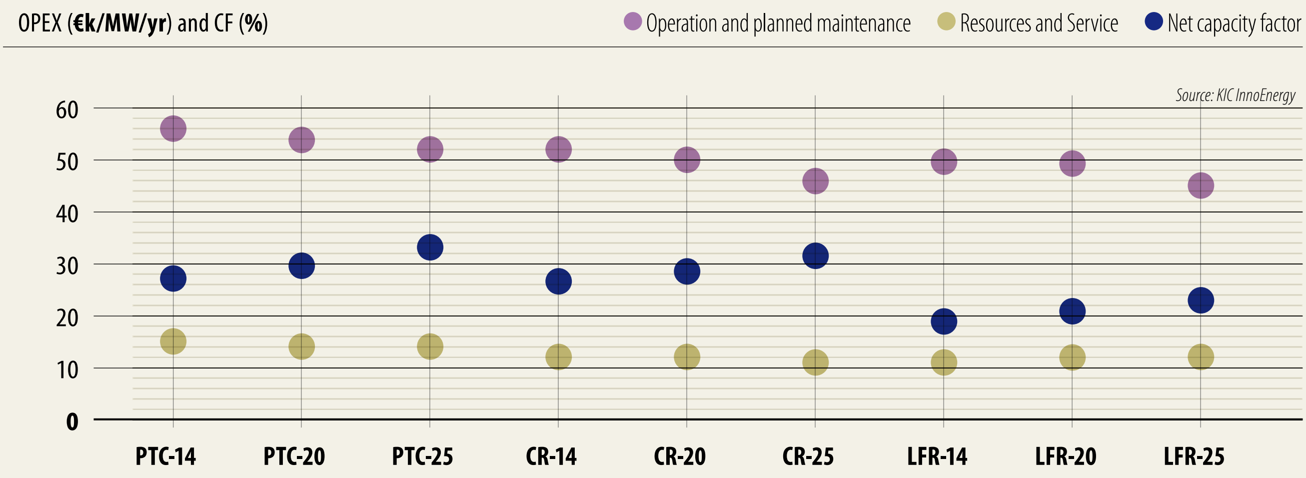
In order to explore the relative cost of each STE plant element, Figure 10.2 shows the cost of all CAPEX elements for all scenarios and Figure 10.3 reflects the same for OPEX and net capacity factor. These figures show the reduction in costs and increases in capacity factor over time for a given Technology Type, as well as the relative costs between different technologies.

Figure 10.2 **CAPEX for STE plants with FID 2014, 2020 and 2025.** (Site type 2050DNI).



Source: KIC InnoEnergy

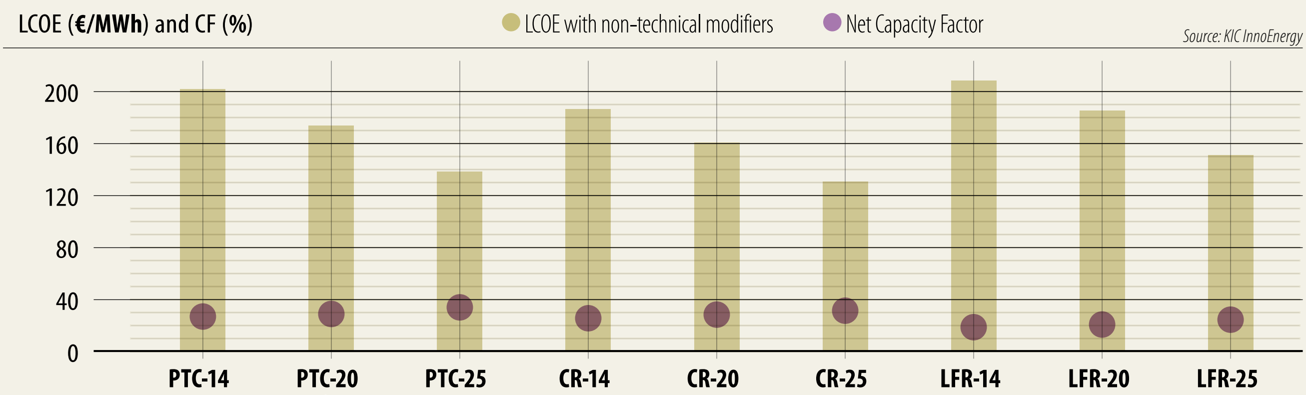
Figure 10.3 **OPEX and net capacity factor STE plants with FID 2014, 2020 and 2025.** (Site type 2050DNI).



10.3. LCOE including the impact of other effects

In order to compare LCOE, Figure 10.4 also incorporates the other effects discussed in Section 2.4. It shows that, with the benefit of increasing capacity factor over time, all three Technology Types experience almost the same trend. It is also evident that, for any time horizon, CR technology is the option with the lowest LCOE.

Figure 10.4 **LCOE for STE plants with FID 2014, 2020 and 2025 with other effects incorporated.** Ref. Section 2.4.[3]



The contribution of innovations in each element to this LCOE reduction is presented in Figure 10.5 to Figure 10.7. It shows that innovations in construction and manufacturing have the dominant effect on LCOE, but innovations in many other elements are also important.

3 Note that those values might be different from other existing references in the literature (see International Energy Agency 2014 Technology Roadmap for Solar Thermal Electricity, or Laurence Berkeley National Laboratory study "Utility-Scale Solar 2013", etc.). The differences are explained by the selection of the studied scenarios, with limited DNI and limitation in the power plant.

Figure 10.5 **Anticipated impact of technology innovations for an STE plant using PTCs with FID in 2025, compared with an STE plant with FID in 2014.**

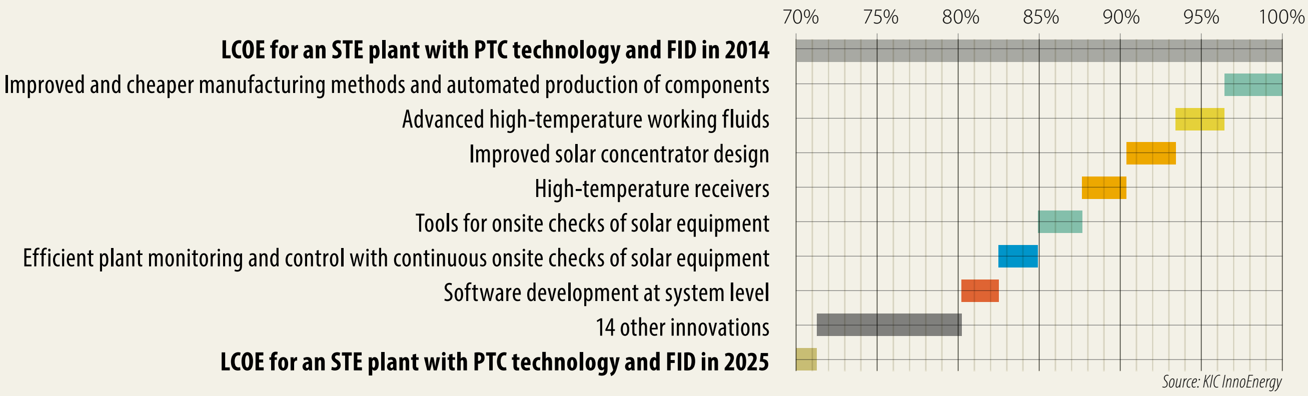


Figure 10.6 **Anticipated impact of technology innovations for an STE plant using a CR with FID in 2025, compared with an STE plant with FID in 2014.**

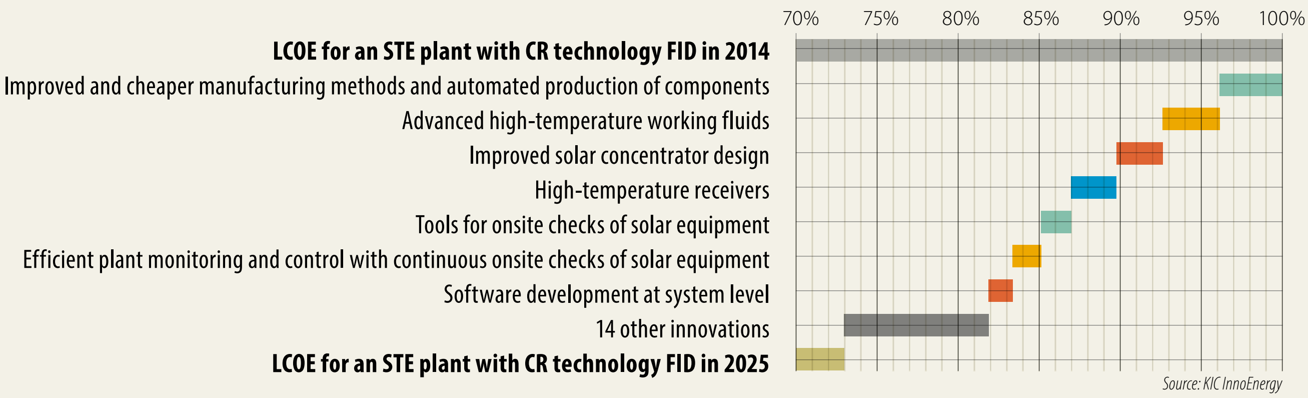
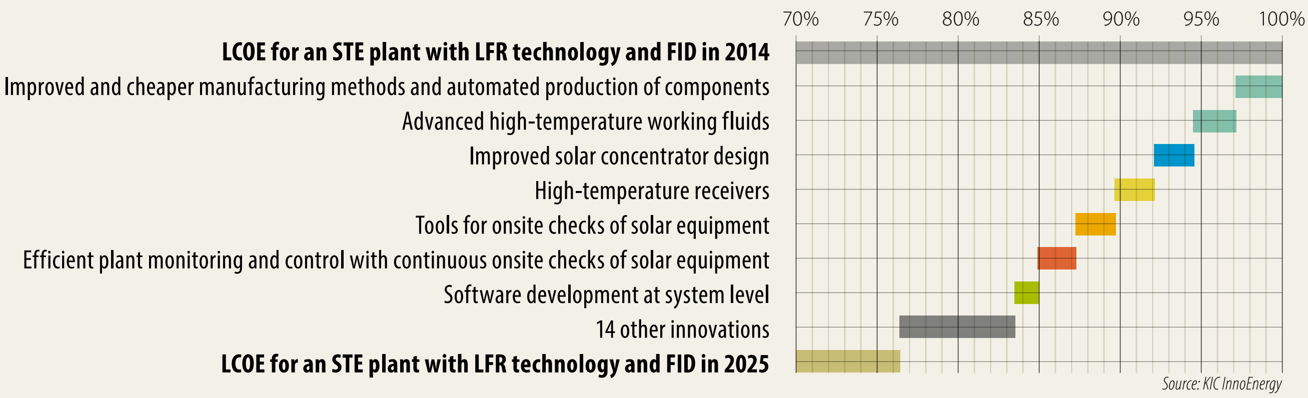


Figure 10.7 **Anticipated impact of technology innovations for an STE plant using LFRs with FID in 2025, compared with an STE plant with FID in 2014.**



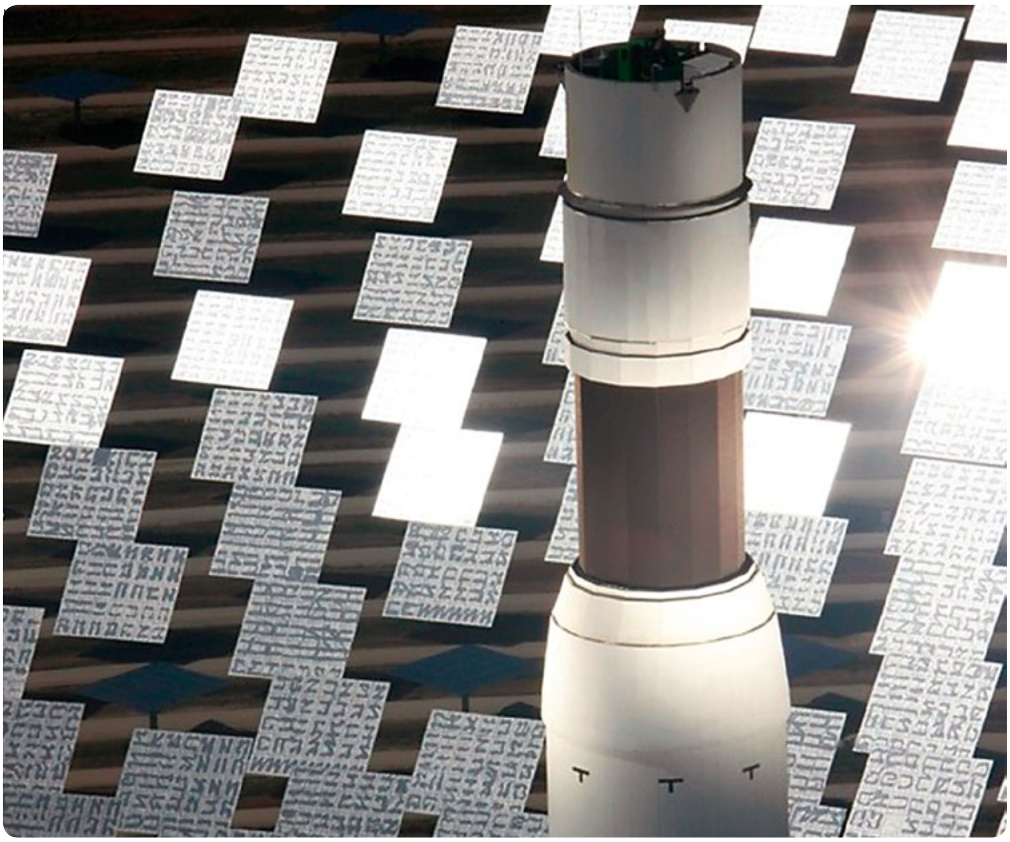


Foto: Torresol Energy

11. Conclusions

Sections 4.1 to 9.1 consider a large number of innovations with the potential to reduce the LCOE by FID 2025. Within these, a number of distinct themes emerge, which will be the focus of the industry's efforts to reduce costs:

- The improvement of production processes and the introduction of automated manufacturing methods of the components of an STE plant present high potential for LCOE reduction but will be mainly driven by the progressively increased deployment of the technology and are then related to market growth.
- The achievement of higher temperatures on one hand of the receiver/ receiver tubes of the solar part of the power plant and the HTF.
- Improved operational strategies with efficient plant monitoring and control to maximise the harvested irradiation and therefore increase the power output, and
- The implementation of computer aided development on both component and system level for an optimal plant design.

Although high-temperature receivers, advanced working fluids and higher conversion efficiencies are listed under a range of distinct innovations, they are closely linked. The potential of some topics to reduce LCOE has therefore been analysed taking into consideration the influence of those other items that are somehow technically linked.

The analysis carried out in this report has assessed the impact of a list of selected innovations on the LCOE, mainly based on the CAPEX, OPEX and AEP. The results obtained are therefore very useful to detect those innovations with a higher potential for LCOE reduction, however, both the impact of the analysed improvements on the LCOE and other important aspects such as the environmental impact must be considered. For example, there are improvements with a low or negative impact on the LCOE but with a significant reduction of the environmental impact. Such improvements would be very helpful to make STE plants feasible in more countries, especially in those with high DNI and a lack of water. Therefore, the interest of RD&D topics for the STE sector should not be based only on their potential impact on the LCOE, but also on other aspects such as water consumption and environmental hazards. A good example of this type of innovation is the development of more efficient dry-cooling systems, which would have a negative impact on the LCOE while significantly reducing water consumption. Another example is the automated cleaning systems for the solar fields. On this topic, all innovation able to increase the efficiency in land use could also help STE technology in building a more popular image.

The innovations linked to the construction of the plant elements and commissioning have been highlighted as of the highest relevance given that they can bring significant cost reductions, especially in term of CAPEX. They are based on the development of dedicated production tools for a better manufacturing of key elements: mirrors, heliostats, tubes, and others. They require significant investment in production facilities and therefore their implementation is conditioned by the market perspectives in the short to mid-term that should be sufficiently predictable to anticipate a return on investment.

Among the other innovations with a less significant impact on the LCOE, energy storage (basically thermal energy) should be kept as a key priority as it ensures a key feature of STE (at least for PTC and CR technology) through dispatchability. This quality could contribute to the implementation of all renewable energies in electric grids in the future as it will be necessary to provide enough balance capacity to compensate fluctuations in generation and/or demand and it would reduce the competitiveness gap as the electricity can be dispatched when the prices are higher.

Overall, the study demonstrates the existence of a very high cost reduction potential on a longer term, taking into account the innovations listed in this report, and further innovations with very low market projection today that may have a significant impact in the future.

Beyond those technical considerations, the evolution of the market also has to be taken into account. The development of new STE plants is being driven more and more by tendering processes where LCOE along the whole project life is key for the preparation of bids. Then there is an increased awareness among developers that the LCOE is a key measure in evaluating technology choices, hence including a more thorough assessment of OPEX to complete the assessment of CAPEX, recognising that the certain and immediate CAPEX, even if it remains a powerful driver, has to be balanced with the uncertain OPEX over time.

The evolution of market structure will also see the emergence of new problems not always linked to the parameters that have been studied in this report. The adaptability of the STE technology to new geographical and climatic conditions is key. The developers will have to face, for example, the availability of infrastructure, such as the grid and communications, or skills, such as in the construction and operation phases, with new challenges in perspective that can also be addressed from the technology perspective, simplifying design and construction processes and improving plant reliability and automated operation.

Between 19 and 24 technology innovations (depending on the STE technology) have been identified as having the potential to cause a substantive change in the design of hardware, software or process, with a resulting quantifiable impact on the LCOE. Many more technical innovations are in development and some of those described in this report may well be superseded by others. Overall, however, we anticipate that the LCOE reduction shown is achievable. In some cases, the anticipated impact of each innovation has been moderated downwards in order to give overall reductions in LCOE consistent with past trends.

The availability of such a range of innovations with the potential to impact LCOE more than shown gives confidence that the picture described is achievable. In addition, it is important to remember that LCOE reductions are available through the other effects considered in Section 2.4, although these are not anticipated to impact to the same degree as technology innovations.

NASA Earth Observatory image by Robert Simmon

12. About KIC InnoEnergy

KIC InnoEnergy is a European company dedicated to promoting innovation, entrepreneurship and education in the sustainable energy field by bringing together academics, businesses and research institutes.

KIC InnoEnergy's goal is to make a positive impact on sustainable energy in Europe by creating future game changers with a different mindset, and bringing innovative products, services and successful companies to life.

KIC InnoEnergy is one of the first Knowledge and Innovation Communities (KICs) fostered by the European Institute of Innovation and Technology (EIT). It is a commercial company with 28 shareholders that include top-ranking industries, research centres and universities, all of which are key players in the energy field. More than 150 additional partners contribute to the company's activities to form a first-class and dynamic network that is always open to new entrants and furthers KIC InnoEnergy's pursuit of excellence. Although KIC InnoEnergy is profit-oriented, it has a "not for dividend" financial strategy, reinvesting any profits it generates back into its activities.

KIC InnoEnergy is headquartered in the Netherlands, and develops its activities across a network of offices located in Belgium, France, Germany, the Netherlands, Spain, Portugal, Poland and Sweden.

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KIC InnoEnergy partners across Europe.

KIC InnoEnergy is committed to reducing costs in the energy value chain, increasing security and reducing CO_2 and other greenhouse gas emissions. To achieve this, the company focuses its activities around eight technology areas:

- **Electricity Storage**
- **Energy from Chemical Fuels**
- **Sustainable Nuclear and Renewable Convergence**
- **Smart and Efficient Buildings and Cities**
- **Clean Coal Technologies**
- **Smart Electric Grid**
- **Renewable Energies**, and
- **Energy Efficiency**

For more information on KIC InnoEnergy please visit: www.kic-innoenergy.com

KIC InnoEnergy is funded by the EIT. The EIT is an independent body of the European Union that was established in March 2008. Its mission is to increase European sustainable growth and competitiveness by reinforcing the innovation capacity within the European Union.

Appendix A

Further details of methodology

A detailed set of project assumptions was distributed to project participants in advance of their involvement in interviews and workshops. Assumptions that are relevant to the KIC InnoEnergy technology strategy and roadmap work stream are provided below.

A.1 Definitions

Definitions of the scope of each element are provided in Sections 4 to 9 and summarised in Table A.1, below.

Table A.1 **Definitions of the scope of each element.**

Parameter	Definition	Unit
CAPEX		
Project up to WCD	Development and consenting work paid for by the developer up to the point of WCD. INCLUDES • Internal and external activities such as environmental and wildlife surveys, resource evaluation (includes metering devices), land negotiation, and engineering (pre FEED) and planning studies up to FID. • Further site investigations and surveys after FID • Engineering (FEED) studies • Environmental monitoring during construction • Project management (work undertaken or contracted by the developer up to WCD) • Other administrative and professional services such as accountancy and legal advice, and • Land securing (cost related to establishment of contracts for land rent and acquisition in the planning phase of a project). EXCLUDES • Any reservation payments to suppliers • Construction phase insurance (included in "Other effects"), and • Suppliers' own project management.	€/MW
Solar field	Payment to solar field manufacturer for the supply of the collectors or heliostats (including support structure and trackers) to the installation site. INCLUDES • All production costs (raw material supply, workforce, energy, machinery, etc.) • Support structure • Delivery to site • Warranty, and • Commissioning costs. EXCLUDES • Receiver tubes for PTC and LFR • OMS costs, and • RD&D costs.	€/MW
Receiver and heat transfer system	INCLUDES • Payment to manufacturer for the supply of the heat transfer system including: - For PTC and LFR: HTF piping and fittings, receiver tubes, fluids, pumps, heat exchangers, etc. - For CR: tower, receiver, pumps, heat exchangers, etc. • Delivery to site • Warranty, and • Commissioning costs.	€/MW
	EXCLUDES • OMS costs, and • RD&D costs.	

Thermal storage system	Payment to manufacturer for the supply of the equipment required for the thermal storage (tanks and storage media). INCLUDES • Delivery to site • Warranty, and • Commissioning costs. EXCLUDES • OMS costs, and • RD&D costs.	**€/MW**
BoP	INCLUDES • Delivery to site and warranty of equipment of the power-block (steam generation system, power generation system, generator, grid connection devices) • On construction site transportation of all equipment of the power-block • All installation work for the power-block equipment • Commissioning work for all the installation, and • Land renting costs. EXCLUDES • Installation of substation / transmission assets • OMS costs, and • RD&D costs.	**€/MW**
OPEX		
OMS	Fixed operational costs. Starts once the plant starts producing electricity. Includes: • Operational costs relating to the day-to-day control of the STE plant • Condition monitoring if applied • Planned preventative maintenance, health and safety inspections, and • Reactive service in response to unplanned systems failure in the modules (solar field, receiver, etc.), electrical systems. Other OPEX includes fixed cost elements that are unaffected by technology innovations, INCLUDING • Contributions to community funds, and • Monitoring of the local environmental impact of the STE plant.	**€/MW/yr**
Resources and Service	Variable costs of operation. Dependent on the amount of energy produced. INCLUDES • Resources regarding electricity production (water for cooling), and • Unplanned / usage dependent service costs.	**€/MW/yr**
AEP		
Gross AEP	The gross AEP averaged over the STE plant life at output of the power block. Excludes electrical and availability losses. Includes any site specific adjustments from the standard specifications of equipment.	**MWh/yr/MW**
Losses	INCLUDES • Internal electricity consumption (7%) • Electrical losses to the metering point (2%), and • Losses due to lack of availability of plant elements (3%). EXCLUDES • Transmission losses.	**%**
Net AEP	The net AEP averaged over the STE plant life at the metering point at entry to the substation.	**MWh/yr/MW**

A.2 Assumptions

Baseline costs and the impact of innovations are based on the following assumptions for solar-thermal electricity.

Global assumptions

- Real (mid-2014) prices
- Commodity prices fixed at the average for 2013
- Energy prices fixed at the current rate, and
- Market expectation "mid-view".

STE plant assumptions

Site attributes are defined as follows, in line with the state of the market for today and the next years.

Table A.2 **Summary of Site Types.**

Site Type	**DNI** (kWh/m^{2}yr)	**Cloud losses** (%)	**Availability of water**	**Exemplary country**
2050DNI	2,050	2%	Yes	Southern Spain

General. The general assumptions are:

- A 100MW STE power plant
- The components are designed for an operational life of 25 years
- The CF is assumed to be 27.40% for PTC, 26.26% for CR and 18.84% for LFR
- The development and construction costs are funded entirely by the project developer, and
- A multi-contract approach is used to contracting for construction.

Spend profile

Table A.3 **CAPEX spend profile.**

Year	**-5**	**-4**	**-3**	**-2**	**-1**	**0**
CAPEX Spend	0%	0%	0%	5%	45%	50%

Year 1 is defined as year of first full generation.
AEP and OPEX are assumed as 100% for years one through 20.

Other assumptions for the baseline STE plants

- Thermal storage system: two-tank molten-salt system with a nominal capacity of 1,000MWht (except for LFR technology).
- Solar field size: 900,000m^2 of PTCs (1,090 collectors); 850,000m^2 of heliostats (7,083 heliostats); 1,003 100m^2 of LFR.
- PTCs: 12-module collectors with a focal length of 1.71m, a parabola width of 5.75m and an aperture of 825.7m^2.
- LFRs: solar field with 93 parallel rows, each with 10,786m^2 of collecting surface; single-tube receiver with secondary concentrator and saturated steam at 60 bar pressure.
- Heliostats: galvanised steel pylon supporting a 120m^2 reflecting surface composed of back-silvered thick glass mirrors.
- Reference case technologies:
  - PTC plant: solar field with VP-1 thermal oil at a maximum solar field outlet temperature of 393 °C
  - CR plant: molten salt in a CR at a maximum outlet temperature of 550 °C
  - LFR plant: 60 bar saturated steam at the solar field outlet
- Land cost: 2€/m^2.
- Promotion cost (including fee, taxes, interest during construction): 10% of total investment cost without promotion.

- Power block: 100MWe water/steam Rankine cycle with wet cooling system, and
- Decommissioning: no decommissioning cost has been considered because the cost of the dismantling will be covered with the incomes due to the residual value of the equipment.

A.3 Other effects

The table below corresponds to definitions made in Section 2.4. These figures are derived from the results of the KIC InnoEnergy technology strategy and roadmap work stream and the consultation to experts lead afterwards, they are provided for completeness. They do not form an integral part of the study.

DECEX includes:

- Planning work and design of any additional equipment required
- Removal of the plant and solar field foundations to meet legal obligations, and
- Further environmental work and monitoring.

Table A.4 **Summary of the impact of other effects.**

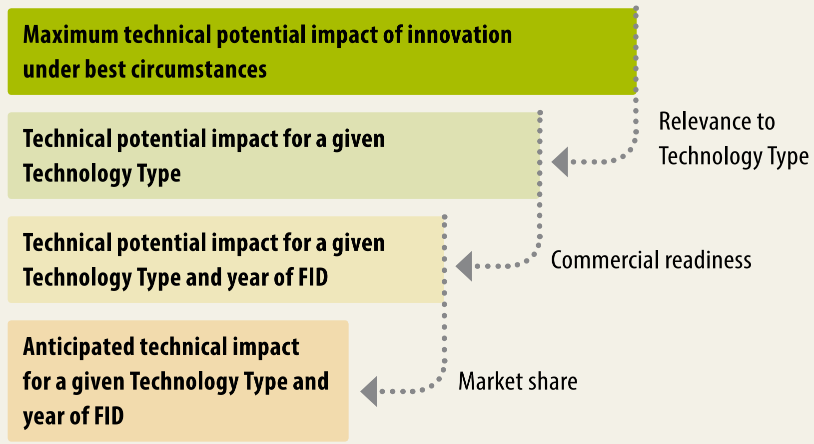
Tech-Site-FID	Transmission	Insurance and contingency	Pre-FID risk	Supply chain	Decommissioning costs	WACC
PTC-2050DNI-14	5.0%	8.2%	0.5%	-3.0%	0.5%	7.0%
CR-2050DNI-14	5.0%	8.6%	0.5%	-3.0%	0.5%	7.0%
LFR-2050DNI-14	5.0%	9.6%	0.5%	-3.0%	0.5%	7.0%
PTC-2050DNI-20	5.0%	7.2%	0.5%	-4.0%	0.5%	7.0%
CR-2050DNI-20	5.0%	7.6%	0.5%	-4.0%	0.5%	7.0%
LFR-2050DNI-20	5.0%	8.6%	0.5%	-4.0%	0.5%	7.0%
PTC-2050DNI-25	5.0%	6.2%	0.5%	-5.0%	0.5%	7.0%
CR-2050DNI-25	5.0%	6.6%	0.5%	-5.0%	0.5%	7.0%
LFR-2050DNI-25	5.0%	7.6%	0.5%	-5.0%	0.5%	7.0%

A.4 Example calculation of change in LCOE for a given innovation

The following example is intended to show the process of derivation and moderation of the impact of an innovation. There is some explanation of the figures used, but the focus is on methodology rather than content. The example used is the impact of improvements in “Improve solar concentrator design” for a 100MW PTC STE power plant.

To consider the impact of a technology innovation, a measure of LCOE is used, based on a fixed WACC. The CAPEX spend profile is annualised by applying a factor of 0.1281, which is based on a discount rate of 10%.

Figure A.5 **Four-stage process of moderation applied to the maximum potential technical impact of an innovation to derive the anticipated impact on the LCOE.**



Maximum technical potential impact

Based on work in the KIC InnoEnergy technology strategy and roadmap, we determine the maximum potential impact of improvements in solar concentrator design on a PTC plant to be 5.8% with 6.2% and 3.7% as respective impacts on CAPEX and OPEX.

Relevance to Technology Type

The relevance for the innovation on the PTC technology is anticipated to be 100% as this innovation can be applied to any type of power plant equally well.

Commercial readiness

As this innovation is considered to have a relatively short term impact, 80% of the benefits are anticipated to be available to project with FID in 2025 whereas, for longer term innovations, this percentage may fall to 10%. Due to the short track record of innovation in STE, there is relative uncertainty around the capacity of innovation developers to efficiently convert their work into marketable products.

Market share

For a 2025 time horizon, it is anticipated that 80% of PTC based projects will implement this innovation.

The anticipated LCOE impact is evaluated by comparing the LCOE calculated for the baseline case with the LCOE calculated for the target case. The target case includes the impact of the innovation on the costs for each element and AEP parameters, as well as the effects of relevance to Site Type and Turbine Size, commercial readiness and market share. Target case impacts are calculated as follows:

Impact for solar field CAPEX = Maximum potential impact (14.4%)
x Relevance to PTC technology (100%) = 14.4%
x Commercial readiness at FID in 2025 (80%) = 11.52%
x Market share for project with FID in 2025 (80%) = 9.22%

Impact for fixed OPEX = Maximum potential impact (4.7%)
x Relevance to PTC technology (100%) = 4.7%
x Commercial readiness at FID in 2025 (80%) = 3.76%
x Market share for project with FID in 2025 (80%) = 3.0%

The LCOE for the baseline and target cases then is calculated as in Table A.6. The anticipated impact of the innovation on the LCOE for this case is therefore (247.7 – 238.3) / 247.7 = -3.7%, or a 3.7% reduction in the LCOE.

Table A.6 **Calculation of the LCOE from cost and AEP data.**

Parameter	Baseline case PTC-2050DNI-14	Target case PTC-2050DNI-25
Solar field CAPEX (€k/MW)	1,755	1,755 x (1 – 0.0922) = 1,593.2
Other CAPEX (€k/MW)	2,337.05	2,337.05
Total CAPEX (€k/MW)	4,092.05	3,930.2
Fixed OPEX (€k/MW/yr)	56	56 x (1 – 0.03) = 54.3
Other OPEX (€k/MW/yr)	14.58	14.58
Total OPEX (€k/MW/yr)	70.58	68.9
Net AEP (MWh/yr/MW)	2,400	2,400
LCOE (€/MWh)	(4,092 x 0.101 + 70.58) x 1,000 / 2,400 = 201.3	(3930.2 x 0.101 + 68.9) x 1,000 / 2,400 = 193.7

Appendix B

Data supporting tables

Table B.1 **Data relating to Figure 3.1.**

Element	Units	PTC-2050DNI-14	CR-2050DNI-14	LFR-2050DNI-14
Project up to WCD	€k/MW	687	651	534
Solar field	€k/MW	1,755	1,360	1,000
Receiver and heat transfer system	€k/MW	450	638	225
Thermal storage system	€k/MW	450	200	-
BoP	€k/MW	750	750	938

Table B.2 **Data relating to Figure 3.2.**

Element	Units	PTC-2050DNI-14	CR-2050DNI-14	LFR-2050DNI-14
OMS	€k/MW/yr	56	52	49
Resources and Service	€k/MW/yr	15	12	11
Net Capacity Factor	%	27.4	26.3	18.8

Table B.3 **Data relating to Figure 3.3.**

Element	Units	PTC-2050DNI-14	CR-2050DNI-14	LFR-2050DNI-14
LCOE including other effects	€/MWh	201	187	209
LCOE as % of PTC-2050DNI-14	%	100.0	92.7	103.7
Net Capacity Factor	%	27.4	26.3	18.8

Table B.4 **Data relating to Figure 4.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	-2.1%	-2.1%	-2.1%
OPEX	-0.7%	-0.7%	-0.7%
AEP	2.9%	3.6%	2.9%
LCOE	-4.6%	-5.3%	-4.6%

Table B.5 **Data relating to Figure 5.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	-4.0%	-3.1%	-1.2%
OPEX	-5.2%	-7.0%	-2.5%
AEP	5.6%	7.3%	5.2%
LCOE	-9.2%	-10.3%	-6.3%

Table B.6 **Data relating to Figure 6.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	-2.9%	0.0%	1.9%
OPEX	0.7%	0.3%	0.6%
AEP	3.5%	2.4%	4.9%
LCOE	-5.6%	-2.3%	-3.1%

Table B.7 **Data relating to Figure 7.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	0.3%	0.0%	0.5%
OPEX	1.0%	-1.1%	1.1%
AEP	2.5%	1.2%	2.5%
LCOE	-2.1%	-1.4%	-1.8%

Table B.8 **Data relating to Figure 8.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	-7.7%	-6.7%	-6.4%
OPEX	-0.9%	-1.0%	1.7%
AEP	3.9%	3.0%	4.2%
LCOE	-9.9%	-8.5%	-8.7%

Table B.9 **Data relating to Figure 9.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	0.0%	-1.0%	-0.2%
OPEX	-3.9%	-2.1%	-5.4%
AEP	4.0%	4.8%	4.2%
LCOE	-4.4%	-5.7%	-5.3%

Table B.10 **Data relating to Figure 10.1.**

Impact of innovation on...	PTC Tech	CR Tech	LFR Tech
CAPEX	-15.3%	-11.8%	-7.4%
OPEX	-7.1%	-11.1%	-5.0%
AEP	20.5%	20.8%	21.8%
LCOE	-28.6%	-26.9%	-23.6%

Table B.11a **Data relating to Figure 10.2 and Figure 10.3.**

Element	Units	PTC-2050DNI-14	PTC-2050DNI-20	PTC-2050DNI-25
Project up to WCD	€k/MW	687	684	677
Solar field	€k/MW	1,755	1,635	1,361
Receiver and heat transfer system	€k/MW	450	441	409
Thermal storage system	€k/MW	450	338	248
BoP	€k/MW	750	755	771
Operation and planned maintenance	€k/MW/yr	56	54	52
Resources and Service	€k/MW/yr	15	14	14
Net capacity factor	%	27.4	29.5	33.0

Table B.11b **Data relating to Figure 10.2 and Figure 10.3.**

Element	Units	CR-2050DNI-14	CR-2050DNI-20	CR-2050DNI-25
Project up to WCD	€k/MW	651	648	643
Solar field	€k/MW	1,360	1,208	983
Receiver and heat transfer system	€k/MW	638	643	659
Thermal storage system	€k/MW	200	180	153
BoP	€k/MW	750	742	735
Operation and planned maintenance	€k/MW/yr	52	50	46
Resources and Service	€k/MW/yr	12	12	11
Net capacity factor	%	26.3	28.4	31.7

Table B.11c **Data relating to Figure 10.2 and Figure 10.3.**

Element	Units	LFR-2050DNI-14	LFR-2050DNI-20	LFR-2050DNI-25
Project up to WCD	€k/MW	534	532	526
Solar field	€k/MW	1,000	953	820
Receiver and heat transfer system	€k/MW	225	222	206
Thermal storage system	€k/MW	-	-	-
BoP	€k/MW	938	938	944
Operations and planned maintenance	€k/MW/yr	49	48	45
Resources and Service	€k/MW/yr	11	11	12
Net capacity factor	%	18.8	20.4	22.9

Table B.12a **Data relating to Figure 10.4.**

	Units	PTC-2050DNI-14	PTC-2050DNI-20	PTC-2050DNI-25
Net capacity factor	%	27.40	29.48	33.00
LCOE with non-technical modifiers	€/MWh	201.3	173.8	138.2

Table B.12b **Data relating to Figure 10.4.**

	Units	CR-2050DNI-14	CR-2050DNI-20	CR-2050DNI-25
Net capacity factor	%	26.26	28.42	31.71
LCOE with non-technical modifiers	€/MWh	186.5	160.8	131.1

Table B.12c **Data relating to Figure 10.4.**

	Units	LFR-2050DNI-14	LFR-2050DNI-20	LFR-2050DNI-25
Net capacity factor	%	18.84	20.41	22.95
LCOE with non-technical modifiers	€/MWh	208.9	184.1	151.1

Table B.13 **Data relating to Figure 10.5.**

Innovation	Relative impact of innovation on LCOE
LCOE for an STE plant with PTC technology and FID in 2014	100%
Improved and cheaper manufacturing methods and automated production of components	3.6%
Advanced high-temperature working fluids	3.0%
Improved solar concentrator design	3.0%
High-temperature receivers	2.7%
Tools for onsite checks of solar equipment	2.7%
Efficient plant monitoring and control with continuous onsite checks of solar equipment	2.4%
Software development at system level	2.3%
14 other innovations	8.9%
LCOE for an STE plant with PTC technology and FID in 2025	71.3%

Table B.14 **Data relating to Figure 10.6.**

Innovation	Relative impact of innovation on LCOE
LCOE for STE plant with CR technology and FID in 2014	100%
Improved and cheaper manufacturing methods and automated production of components	3.9%
Improved solar concentrator design	3.6%
Software development at system level	2.8%
Efficient plant monitoring and control with continuous onsite checks of solar equipment	2.8%
Tools for onsite checks of solar equipment	1.8%
Design and coating of CR receivers	1.7%
Software development at component level	1.4%
17 other innovations	8.9%
LCOE for STE plant with CR technology and FID in 2025	73.0%

Table B.15 **Data relating to Figure 10.7.**

Innovation	Relative impact of innovation on LCOE
LCOE for an STE plant with LFR technology and FID in 2014	100%
Improved and cheaper manufacturing methods and automated production of components	2.9%
Tools for onsite checks of solar equipment	2.7%
Efficient plant monitoring and control with continuous onsite checks of solar equipment	2.4%
Advanced high-temperature working fluids	2.4%
High-temperature receivers	2.4%
Software development at system level	2.3%
Advanced power cycles	1.4%
12 other innovations	7.1%
LCOE for an STE plant with LFR technology and FID in 2025	76.4%

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Future renewable energy costs: solar-thermal electricity
How technology innovation is anticipated to reduce the cost of energy from European solar-thermal electricity plants

The document is also available in an online format on the KIC InnoEnergy website: www.kic-innoenergy.com

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