European Commission

JRC SCIENCE AND POLICY REPORTS

ETRI 2014

Energy Technology Reference Indicator projections for 2010-2050

Joint Research Centre

Report EUR 26950 EN

European Commission

Joint Research Centre

Institute for Energy and Transport

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This publication is a Science and Policy Report by the Joint Research Centre of the European Commission.

JRC92496

EUR 26950 EN

ISBN 978-92-79-44403-6

ISSN 1831-9424

doi: 10.2790/057687

Luxembourg: Publications Office of the European Union, 2014

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ACKNOWLEDGEMENTS

We would like to gratefully acknowledge the following lists of authors, reviewers and contributors to the 2014 version of the Energy Technology Reference Indicators (ETRI) report.

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Marc Defrennes (ENER), Matthijs Soede (RTD), Kyriakos Maniatis (ENER), Maria Georgiadou (RTD), Patrick Van Hove (RTD), Jeroen Schuppers (RTD)

1.1.2 The following external reviewers are also gratefully acknowledged:

Johannes Trueby (IEA/GEE/EMU), Gregory Fayet (EDF), Thomas Nowak (EHPA), David Shropshire (IAEA)

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PREAMBLE

The European Union (EU) is tackling climate change, energy security of supply and economic competitiveness through a transformation of the energy system, with far-reaching implications on how we source and produce our energy, how we transport and trade it, and how we use it. The vision is to reduce carbon dioxide (CO_2) emissions from the EU by at least 85 % by 2050 compared to the 1990 levels.

The Strategic Energy Technology Plan (SET-Plan) is the technology pillar of the EU's energy and climate policy. SETIS, the SET-Plan Information System, supports the SET-Plan. This report contains assessments of energy technology reference indicators (ETRI) and it is aimed at providing independent and up-to-date cost and performance characteristics of the present and future European energy technology portfolio. Together with the SETIS Technology Map[a] they provide:

- techno-economic data projections for the modelling community and policy makers, e.g.:
    - capital and operating costs;
    - thermal efficiencies and technical lifetimes;
- greenhouse gas emissions, and water consumptions;
- an overview of the technology, markets, barriers and techno-economic performance;
- a useful tool for policymakers for helping to identify future priorities for research, development and demonstration (RD&D);

The ETRI report covers the time frame 2010 to 2050. This first version of the report focuses on electricity generation technologies, but it also includes electrical transmission grids, energy storage systems, and heat pumps.

Data was mainly collected from the open literature and then evaluated using a systematic and transparent approach. For the capital cost projection a reference value and an upper and lower range are given together with an assessment on the reliability of the data. The data were reviewed both within the European Commission and by external organisations.

The ETRI reference report will be updated on a biannual basis. The scope of technologies covered by the ETRI project will be broadened with each release. A spread sheet containing the indicators of this report can be downloaded from the SETIS website.

[a] Joint Research Centre (JRC), 2014, 2013 Technology Map, ISBN 978-92-79-34720-7, doi: 10.2790/99812

2 Methodology

This report presents performance characteristics of existing and future electricity generation technologies, smart grid technologies, energy storage systems, and heat pumps for the time period from 2010 to 2050. The data were primarily collected from the open literature using both primary and secondary sources. Sometimes data were complemented with expert judgements or were derived from other similar technologies. If a parameter could not be established with a reasonable certainty, then it is marked by a hyphen ('-'). Parameters not applicable for a certain time frame are marked by an 'n/a'.

The data for each technology refer to sizes and configurations which are typical of average geographic locations within the European Union. The most relevant types of each technology were selected for presentation in this report.

All cost data are given in euro of year 2013. Neither taxes nor subsidies were incorporated in the economic estimations presented in this report.

2.1 Definition of parameters

The definitions of the parameters used in this report are presented in Table 1. More detailed discussions about critical parameters can be found in Section 3.2.

2.1.1 Parameters collected

Table 1. Description of parameters collected.

Technical parameters		Description
Net electrical power	MW	Generation capacity net of auxiliary loads for thermal power plants, installed capacity for wind power, peak capacity for solar PV.
Max. capacity factor	%	Amount of time that a power plant is able to produce electricity. It takes into account, for example, yearly maintenance. It is higher than the actual capacity factor due to the fact that it does not consider, for example, load following, curtailing etc.
Capacity factor	%	Ratio of the actual output of a power plant over a year, to its potential output if it were possible for it to operate at full nameplate capacity indefinitely.
Technical lifetime	Years	Total time period during which an asset/machine can technically perform.
Percentage of CO_2 captured (only for CCS)	%	Percentage of CO_2 captured by a CCS technology.
Thermal power (only for thermal power plants)	MW	Thermal power supplied to a power plant.
Electrical efficiency at peak electrical load	%	Electrical efficiency when a CHP plant maximises electrical output.
Electrical efficiency at peak thermal load	%	Electrical efficiency when a CHP plant maximises heat output.
Thermal efficiency at peak thermal load	%	Thermal efficiency when a CHP plant maximises heat output.
Power capacity	MW	The full capacity to charge an energy storage system.
Roundtrip efficiency	%	Ratio of the total output of an energy storage system (discharge) divided by the total energy input (charge).
Storage capacity	MWh	Total energy which can be stored in a system.

Min time for charging	hours	Minimum time in which an energy storage system can be fully charged.
Min time for discharging	hours	Minimum time in which an energy storage system can be fully discharged.
Financial parameters		**Description**
CAPEX, reference/low/high	EUR/kW	CAPital EXpenditure (CAPEX) is the cost of delivery of a plant as if no interest was incurred during construction. The CAPEX is given as a reference value with a lower and higher bound. See Section 3.2.1 for more information.
FOM	% of CAPEX ref.	Operating and Maintenance costs (O&M costs) that do not vary significantly with a technology's electricity generation/consumption are classified as fixed. FOM costs exclude personnel costs and costs of refurbishment needed to extend lifetime beyond technical lifetime.
VOM	EUR/MWh	Variable Operation and Maintenance expenses are production-related costs which vary with electrical generation/consumption. Here, they exclude personnel, fuel and CO_2 emission costs.
FOM refurbishment cost	% of CAPEX ref.	Additional annual FOM (after operating beyond half of technical lifetime) to extend technical lifetime for a given period of time which is specific for each technology.
Transport and storage cost (only for CCS)	EUR/MWh	Reference cost of CO_2 transport and storage for typical plant location.
Environmental parameters		**Description**
CO_2 emissions total	tCO_2/MWh	Direct and indirect CO_2 emissions. Direct emissions emanate from the installation itself. The indirect emissions are a consequence of the activities at the installation, but they occur at different locations and are normally outside the control of the installation, e.g. mining and transport.
GHG emissions total	tCO_2eq/MWh	Direct and indirect greenhouse gas emissions, measured in equivalent CO_2 emissions.
Water consumed	litres/kWh	Water consumed (i.e. not returned to the water system), e.g. water evaporated in the cooling towers.
Water withdrawn	litres/kWh	Water withdrawn from the water system. This includes both water that is returned to the water system (at higher temperature) and water that is consumed.

2.2 Discussion about selected parameters

2.2.1 Capital costs

A common problem encountered when evaluating cost data from the open literature is that different sources do not contain the same cost components and that the definition of the sub-components of the CAPEX varies. For example, the owner's cost is not included in all estimates. In order to correct for such discrepancies, breakdowns of the capital costs were established. These were then used to correct the CAPEX estimates for each data source. However, in practise it was often difficult to arrive to a precise CAPEX breakdown since the sources did mostly not provide detailed information about their assumptions in this respect.

The capital expenditure (CAPEX) cost estimates are limited to the "fence boundary" of a power plant. As a general rule the capital costs were broken down as given in Table 2.

Table 2. Description of capital cost components.

CAPEX components		Description
Civil and structural costs		Costs for site preparation excluding the costs of infrastructure connections, i.e. electricity, fuel and water connections. These are for example construction of buildings and roads on the site, drainage, construction of buildings on the site.
Mechanical equipment supply and installation costs	Major equipment costs	Supply and installation costs of core-components like for instance boilers, cooling towers, steam turbine generators, condensers, photovoltaic modules, combustion turbines.
	Balance of plant costs	Supply and installation costs not included in the primary system, e.g. compressors, pumps, piping.
Electrical and I&C supply and installation		Costs included here are for instance electrical transformers, switchgear, switchyards, instrumentation.
Project indirect costs		These costs are not directly accountable to a cost object. They can include engineering, construction management, security costs, contractor overhead costs, maintenance, and construction contingency.
Owner's cost	Development costs	Costs that the utility will have to pay in addition to the engineering, procurement and construction, e.g. preliminary feasibility and engineering studies, permits, legal fees, land acquisition, taxes, licensing
	Interconnection costs	Costs for infrastructure connections, i.e. electricity, fuel and water.
	Insurance costs	Insurance costs.

In addition, capital costs were adjusted for:

- inflation based on data from EUROSTAT[a];
- annual averages currency exchange rates for non-EU countries;
- cost escalations of power plants using for example Power Capital Cost Index/European Power Capital Cost Indexing (PCCI/EPCCI).

Costs for financing are not included in the CAPEX estimates of this report.

It should be understood that significant uncertainties are inherent in long term forecasts since numerous factors will influence the evolution of the costs, e. g. learning rates, energy policy support decisions, global and national economic growth, and competition with other technologies. Therefore, a reference value with a range (low/high) is given in this report. In

[a] This correction was not in combination with the PCCI/EPCCI indexing since the latter already includes inflation.

addition, a quality assessment of each CAPEX estimate is made by employing the NUSAP approach, see Section 2.2.2.

The CAPEX projections and their learning rates were aligned with the forecasted energy technology capacity expansion rates of the latest European Commission energy system study (EC, 2013). The Reference scenario of that report includes policies and measures adopted in the Member States by April 2012 and policies, measures and legislative provisions (including binding targets) adopted by or agreed in the first half of 2012 at EU level, in such a way that there is almost no uncertainty with regard to their adoption. This concerns for example the Energy Efficiency Directive, on which political agreement was reached by that time.

2.2.2 Quality of CAPEX data evaluation using NUSAP approach

A systematic approach called NUSAP was used to evaluate the quality of the CAPEX data. Five qualifiers were used for this purpose: Numeral, Unit, Spread, Assessment, and Pedigree (vd Sluijs et al, 2005; Kloprogge et al, 2011). The *Numeral* qualifier is estimated based on expert judgement and incorporation of information from recent studies. The *Unit* qualifier is the unit of the numeral. The numerals are given with *Spreads*, i.e. a high and a low estimate. The *Assessment* qualifier is a judgement made by the technology expert on the quality of the data. The options available are either "high", "medium", or "low". The *Pedigree* matrix is supposed to guide the technology expert in this assessment of the quality of data. A pedigree matrix is used to code qualitative expert judgements for three criteria, i.e. convergence of data, empirical basis, and quality of reports, into a discrete numeral scale from 0 (weak) to 4 (strong), see Table 3. From these three criteria an average was calculated that guided the expert in assessing the uncertainty either as a 'low', 'medium', or 'high' quality estimate. A 'low' means that the uncertainties are large and a 'high' that there is more confidence in the assessment. The experts typically gave a low for a value-ladenness of <2.0, a medium for 2.0-2.5, and a high for >2.5.

Table 3. Pedigree matrix.

Value-ladenness	**Convergence of data**	**Empirical basis**	**Quality of reports**
Criteria Score	*Distribution of data*	*Availability of data sources*	*Type of sources*
4	Very strong agreement (standard deviation / median <5 %)	Ample choice of data (>10 sources)	All excellent reports
3	Strong agreement (standard deviation / median <8 %)	Satisfactory choice of data (5 - 10 sources)	Majority excellent reports
2	OK agreement (standard deviation / median <12 %)	Small sample of data available (2 - 5 sources)	Half excellent reports
1	Weak agreement (standard deviation / median <20 %)	Single source	Minority excellent reports
0	No agreement	Educated guess	No excellent reports

2.2.3 Learning rates

Learning rates are often used to extrapolate past capital cost reductions to provide an indication of future CAPEX costs. The one factor learning rate is evaluated here, which is as a function of the installed capacity of a technology. This is a common simplification, but it has its limitations and should be used with caution. In reality, cost reductions are the result of more complex processes, e.g. learning from research could be another important factor (JRC, 2012). This report determines the learning rates based on the plant technology level, so it does not consider expected cost reduction at component level.

3 Disclaimer

This report contains projections of techno-economic parameters of energy technologies. Such projections contain considerable uncertainties since many factors will influence the development of these technologies both what concerns economic and technical performance.

4 Wind power

Wind power is the conversion of kinetic wind energy into electricity. It is the most successful renewable energy technology over the two last decades with regard to deployment rates. Most of the wind power deployment has been onshore until now, but in the future offshore wind is expected to have the highest growth rate.

The investment costs of wind energy projects can vary widely because they are highly site-related. Factors influencing the investment costs are, for instance, turbine transport distance and conditions, soil or sea bed characteristics, and distance to the grid connection point.

The 2013 Technology Map (JRC, 2014a) can be consulted for more information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives. In addition, the 2013 JRC wind status report (JRC, 2014b) presents a thorough picture of European wind R&D projects.

4.1 Onshore wind

New onshore wind turbines have typically a rated capacity of more than 2 MW. Historically, the size of wind turbines have increased with time and this trend is expected to continue. By 2050 the average size of an onshore wind turbine is expected to be 4.5 MW. Usually, wind turbines are built grouped in wind farms sharing civil works and a substation and grid connection point.

The typical capacity factors for onshore wind are 1800–2200 full-load hours equivalent. Technology progress tends to increase these figures, but the best sites onshore have already been taken, which means that often new wind farms are built at locations with lower wind speeds.

The cost components included in the CAPEX estimate for onshore wind are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☐ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

The estimated CAPEX breakdown for onshore wind can be seen in Figure 1.

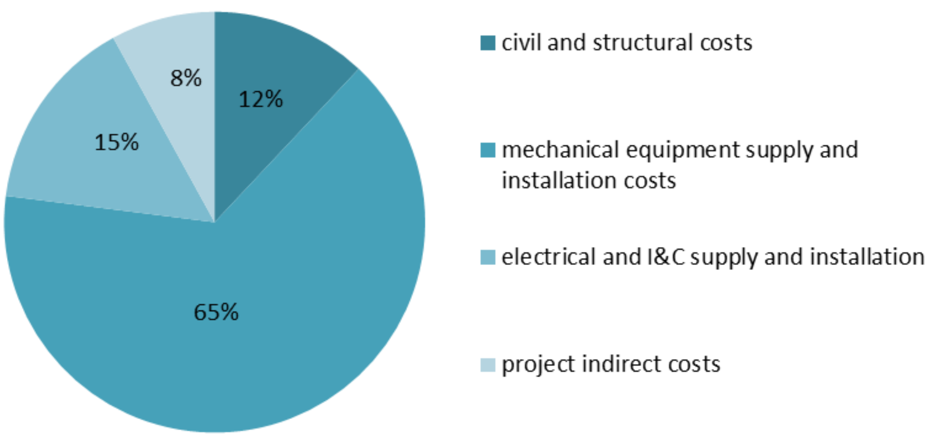

Figure 1. CAPEX breakdown for onshore wind

Current onshore wind energy is a comparably mature technology. It is expected that capital costs will drop further, but at a moderate rate. The drop is partially due to the fact that power ratings of wind farms are scaled up with time. The CAPEX estimate in Table 4 is based on the assumption that the average wind speed is 7-8.5 m/s.

Table 4. Reference indicators for onshore wind.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	2.15	3	3.5	4	4.5
Max. capacity factor	*%*	40	50	60	65	65
Avg. capacity factor	*%*	23	30	35	40	45
Technical lifetime	*years*	20	22	25	25	25
Costs						
CAPEX ref	*€$_{2013}$/kW*	1400	1350	1300	1200	1100
CAPEX low	*€$_{2013}$/kW*	1200	1100	1000	900	800
CAPEX high	*€$_{2013}$/kW*	2300	2000	1800	1700	1700
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	10	10	10	10	10
FOM	*% CAPEX ref.*	2.7	2.4	2.2	1.9	1.7
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	10	9	8	7	6
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	85	230	300	350	400

4.2 Offshore wind

Since offshore wind is a less mature technology than onshore wind, greater technological improvements and CAPEX reductions are expected until 2050. For example, technical lifetime and maximum capacity factors are expected to increase.

The cost components included in the CAPEX estimate for offshore wind are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

The estimated CAPEX breakdown can be seen in Figure 2.

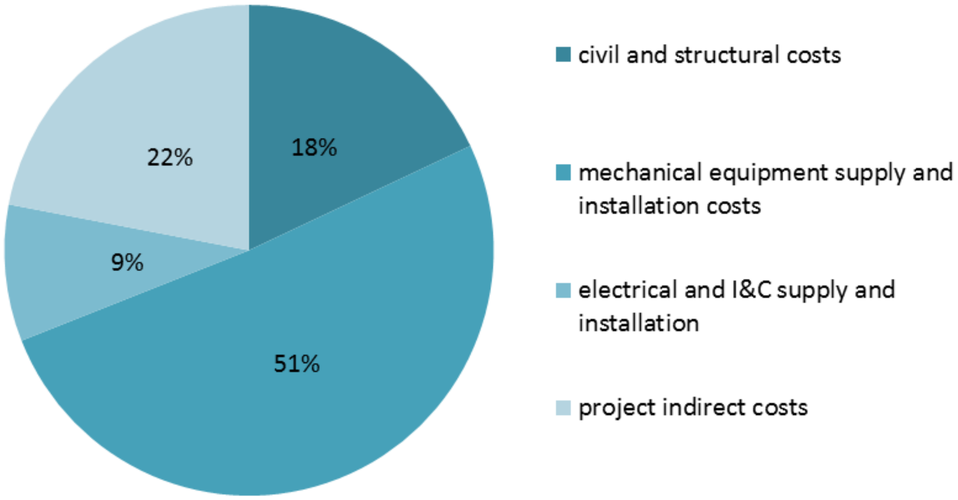

Figure 2. CAPEX breakdown for offshore wind.

The CAPEX estimate provided in assumes a medium yield, i.e. average wind speeds of 7-8.5 m/s.

Table 5. Reference indicators for offshore wind.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	4	6	9	12	15
Max. capacity factor	*%*	50	55	60	65	65
Avg. capacity factor	*%*	34	40	46	48	48
Technical lifetime	*years*	20	25	30	30	30
Costs						
CAPEX ref	*€$_{2013}$/kW*	3470	2880	2580	2380	2280
CAPEX low	*€$_{2013}$/kW*	3080	2580	2280	2080	1790
CAPEX high	*€$_{2013}$/kW*	4760	4270	3970	3470	3270
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	7	7	7	7	7
FOM	*% CAPEX ref.*	3.7	3.2	3	2.8	2.3
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	16	14	13	11	9
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	3	45	300	500	700

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5 Solar energy

The two main technology groups for solar electricity production are solar photovoltaic (PV) and solar thermal electricity power (STEP) plants. The latter is also known as concentrating solar power (CSP) systems. The former exploits the photovoltaic effect, where electron-pairs generated in semiconductors are spatially separated by an internal electrical field. This leads to positive and negative charges, which create a voltage and therefore electricity. The STEP systems produce electricity by concentrating the sunlight for heating a liquid, solid or gas that is then used for electricity production.

Solar PV is expected to grow significantly over the coming decades in Europe, but in the near term the growth rate is anticipated to slow down due to changes in the legal frameworks in several member states. The growth prospect of STEP is more uncertain due to that capital costs are still high and less research budget is allocated to it compared to solar PV.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives. More detailed information about current trends in the solar PV industry can be found in the PV Status report 2013 (JRC, 2013).

In 2013, more than 85 % of new PV systems were based on crystalline Si technology which is highly mature for a wide range of applications. The crystalline Si is expected to remain the dominant PV technology in the short-to-medium term.

Despite the fact, that PV system hardware is a globally traded and priced more or less the same worldwide, PV system prices vary significantly from country to country. The so-called 'soft costs', which mainly consist of financing and permitting costs, as well as labour requirements and installer/system integrator margins, are the main reason for the significant differences which are still observed. Also, the CAPEX will vary significantly from country to country depending on market maturity, i.e. market size and competition between different installer, regulatory framework and permitting rules. The CAPEX range takes these differences into account. The non-technology related costs for solar PV are expected to rise as a share of the total costs of projects. Therefore the cost reductions are expected to be less than the historical reduction rates.

The technical performance of PV modules is guaranteed by manufacturers for up to 25 years, but the actual lifetime of the modules is often significantly longer when proper maintenance is carried out. The increase in average capacity factors is mainly due to the expectations, that sun-rich regions will install more PV in the future as system prices go down.

The cost components included in the CAPEX estimate for solar PV are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☐ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

The estimated CAPEX breakdown can be seen in Figure 3.

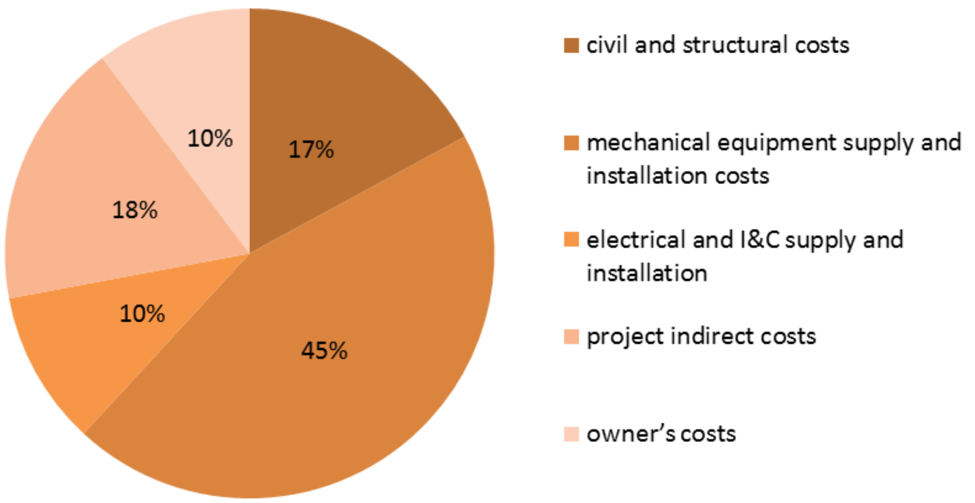

Figure 3. CAPEX breakdown for commercial solar PV.

5.1 Commercial solar PV system 0.1-2 MW

Table 6. Reference indicators for commercial solar PV systems between 100 kW and 2 MW.

	Unit	2014	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	1	-	-	-	-
Max. capacity factor	*%*	17	17	17	17	17
Avg. capacity factor	*%*	13	14	16	17	17
Module Efficiency	*%*	15	17	20	25	30
Technical lifetime	*years*	25	25	25	25	25
Economical						
CAPEX ref	*€$_{2013}$/kW*	1100	900	810	760	720
CAPEX low	*€$_{2013}$/kW*	1000	800	720	680	640
CAPEX high	*€$_{2013}$/kW*	1200	1000	900	850	800
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	16	14	12	11	10
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	45	40	36	32	28
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	-	-	-	-	-

5.2 Commercial solar PV >2 MW without tracking

Table 7. Reference indicators for commercial solar PV systems more than 2 MW without tracking.

	Unit	2014	2020	2030	2040	2050
Technical						
Net electrical power	MW	6	-	-	-	-
Max. capacity factor	%	17	17	17	17	17
Avg. capacity factor	%	13	14	16	17	17
Module efficiency	%	15	17	20	25	30
Technical lifetime	years	25	25	25	25	25
Economical						
CAPEX ref	$€_{2013}$/kW	980	800	640	580	520
CAPEX low	$€_{2013}$/kW	900	650	520	470	420
CAPEX high	$€_{2013}$/kW	1400	900	720	650	580
Quality of CAPEX estimate				low		
CAPEX learning rate	%	16	14	12	11	10
FOM	% CAPEX ref	1.7	1.7	1.7	1.7	1.7
VOM	$€_{2013}$/MWh	0	0	0	0	0
Environmental						
Direct GHG emissions	$tCO_2(eq)$/GWh	0	0	0	0	0
Indirect GHG emissions	$tCO_2(eq)$/GWh	45	40	36	32	28
Water consumed	l/kWh	0	0	0	0	0
Water withdrawn	l/kWh	0	0	0	0	0
Evolution						
Max. potential	GW	-	-	-	-	-

5.3 Commercial solar PV >2 MW with tracking

Table 8. Reference indicators for commercial solar PV systems more than 2 MW with tracking.

	Unit	2014	2020	2030	2040	2050
Technical						
Net electrical power	MW	20	-	-	-	-
Max. capacity factor	%	21	21	21	21	21
Avg. capacity factor	%	18	19	20	21	21
Module efficiency	%	15	17	20	25	30
Technical lifetime	years	25	25	25	25	25
Economical						
CAPEX ref	$€_{2013}$/kW	1450	1100	890	790	710
CAPEX low	$€_{2013}$/kW	1350	850	680	610	550
CAPEX high	$€_{2013}$/kW	1700	1400	1130	1010	900
Quality of CAPEX estimate				low		
CAPEX learning rate	%	16	14	12	11	10
FOM	% CAPEX ref	1.5	1.5	1.5	1.5	1.5
VOM	$€_{2013}$/MWh	0	0	0	0	0
Environmental						
Direct GHG emissions	$tCO_2(eq)$/GWh	0	0	0	0	0
Indirect GHG emissions	$tCO_2(eq)$/GWh	45	40	36	32	28
Water consumed	l/kWh	0	0	0	0	0
Water withdrawn	l/kWh	0	0	0	0	0
Evolution						
Max. potential	GW	-	-	-	-	-

5.4 Residential solar PV <100 kW

Table 9. Reference indicators for residential solar PV systems of less than 100 kW.

	Unit	2014	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	0.1	-	-	-	-
Max. capacity factor	*%*	17	17	17	17	17
Avg. capacity factor	*%*	12	12	13	14	14
Module efficiency	*%*	15	17	20	25	30
Technical lifetime	*years*	25	25	25	25	25
Economical						
CAPEX ref	*€$_{2013}$/kW*	1310	1100	990	930	880
CAPEX low	*€$_{2013}$/kW*	1150	950	850	810	760
CAPEX high	*€$_{2013}$/kW*	1850	1250	1120	1060	1000
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	16	14	12	11	10
FOM	*% CAPEX ref*	2	2	2	2	2
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	45	40	36	32	28
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	-	-	-	-	-

5.5 Solar thermal electricity power plants

The most common form of concentration for large-scale STEP plants is by reflection. Concentration is either to a line or to a point. An important attribute of STEP is the ability to integrate thermal storage, which allows mitigating the impact of thermal transients such as clouds passing above the plant, and electrical transients to the grid. Plants are now being designed for 6-7.5 hours of full-load storage. The economic potential of concentrated solar in Europe is mostly limited to the Mediterranean countries.

The most mature, large-scale technology of concentrated solar power is the parabolic trough/heat-transfer medium system. The capacity factor without thermal storage of a STEP plant is about 1800 to 3000 hours per year. Systems with thermal storage generally achieve capacity factors between 4000 and 5200 hours.

The cost components included in the CAPEX estimate are:

☒ Civil and structural costs
☒ Major equipment costs
☒ Balance of plant costs
☒ Electrical and I&C supply and installation
☒ Project indirect costs
☐ Development costs
☒ Interconnection costs
☐ Insurance costs

The estimated CAPEX breakdown for STEP is given in Figure 4.

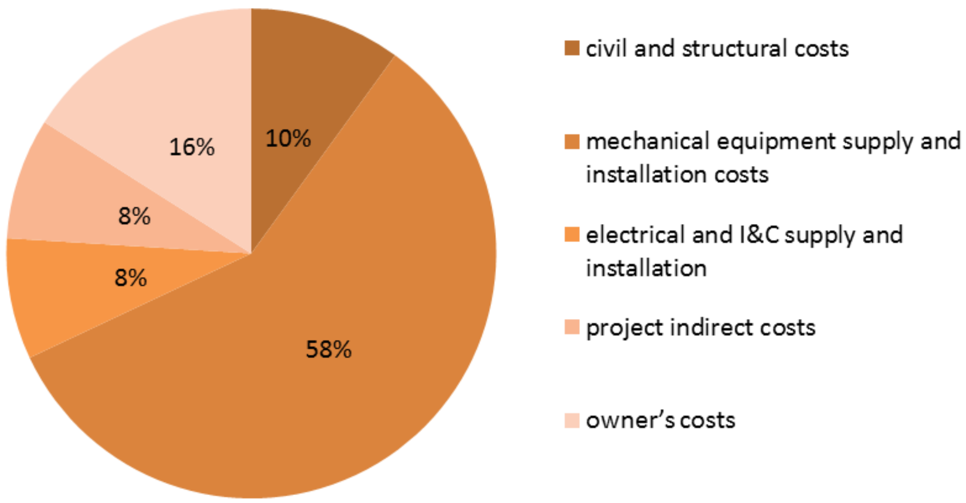

Figure 4. CAPEX breakdown for STEP.

Table 10 presents techno-economic data for a parabolic trough without thermal storage given.

Table 10. Reference indicators for STEP without thermal storage.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	100	-	-	-	-
Thermal power	*MW*	278				
Max. capacity factor	*%*	42	-	-	-	-
Avg. capacity factor	*%*	37	38	40	41	41
Net efficiency	*%*	36	-	-	-	-
Technical lifetime	*years*	30	30	30	30	30
Economical						
CAPEX ref	$€_{2013}$/kW	5600	4500	3800	3500	3400
CAPEX low	$€_{2013}$/kW	4100	3300	3000	2800	2600
CAPEX high	$€_{2013}$/kW	6900	6000	5000	4500	4000
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	10	10	10	10	10
FOM	*% CAPEX ref*	4	4	4	4	4
VOM	$€_{2013}$/MWh	8	8	8	8	8
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	0	0	0	0	0
Indirect GHG emissions	$tCO_2(eq)/GWh$	35	35	35	35	35
Water consumed	*l/kWh*	3	3	3	3	3
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max. potential	*GW*	-	-	-	-	-

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6 Hydropower

Hydropower energy is the result of potential energy stored in water in an elevated reservoir. When released the running water drives a turbine and a generator that produces electricity. The run-of-the-river does not require a dam, or only a very small one. Hydropower is the most widely used form of renewable electricity worldwide. Its potential is already well exploited in Europe and therefore the expected growth is limited (JRC, 2013). The highest potential in Europe lies in low-head plants (<15 m) and in the refurbishment of existing facilities.

The technical and economic performance of hydropower is very dependent on the site specifications and utility operating strategies. The CAPEX range aims at taking into account, at a European level, such differences as well as other uncertainties. Overall, slightly increasing CAPEXs are expected due to the fact that the most attractive sites have been or will be exploited before the less attractive ones. The Fixed Operation and Maintenance (FOM) *refurbishing* cost are introduced after 40 years of operation, which is assumed to add 20 years to the technical lifetime.

The techno-economic data presented here concern three sizes of hydropower with a dam or reservoir as well as the run-of-the-river (RoR) hydropower plant.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

The cost components included in the CAPEX estimates are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

The CAPEX breakdown for a large hydropower plant is given in Figure 5.

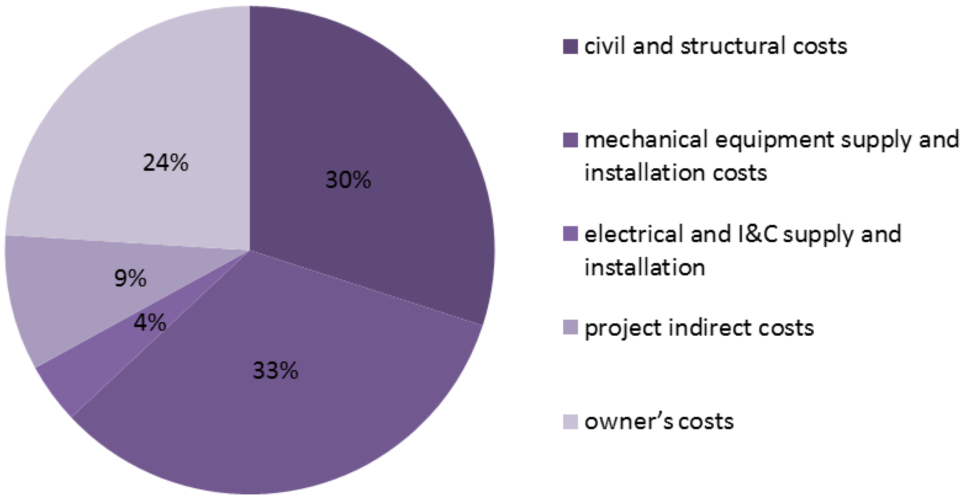

Figure 5. Capex breakdown of hydropower plant.

6.1 Hydropower dam and reservoir, >100 MW

Table 11. Hydropower larger than 100 MW

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	500	500	500	500	500
Avg. capacity factor	*%*	35	35	35	35	35
Technical lifetime	*years*	60	60	60	60	60
Economical						
CAPEX ref	*€$_{2013}$/kW*	2200	2200	2200	2200	2200
CAPEX low	*€$_{2013}$/kW*	1100	1100	1100	1100	1100
CAPEX high	*€$_{2013}$/kW*	3000	3000	3000	3000	3000
Quality CAPEX estimate		medium				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.0	1.0	1.0	1.0	1.0
FOM refurbishment	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	3	3	3	3	3
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	6	6	6	6	6
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	-	-	-	-	-

6.2 Hydropower dam and reservoir, 10-100 MW

Table 12. Hydropower dam and reservoir between 10-100 MW.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	70	70	70	70	70
Avg. capacity factor	*%*	40	40	40	40	40
Technical lifetime	*years*	60	60	60	60	60
Economical						
CAPEX ref	*€$_{2013}$/kW*	3300	3360	3370	3370	3370
CAPEX low	*€$_{2013}$/kW*	1200	1220	1230	1230	1230
CAPEX high	*€$_{2013}$/kW*	4500	4580	4600	4600	4600
Quality CAPEX estimate		medium				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
FOM refurbishment	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	5	5	5	5	5
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	6	6	6	6	6
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	96	102	-	-	-

6.3 Hydropower dam and reservoir, <10 MW

Table 13. Hydropower dam and reservoir less than 10 MW.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	10	10	10	10	10
Avg. capacity factor	*%*	37	37	37	37	37
Technical lifetime	*years*	60	60	60	60	60
Economical						
CAPEX ref	*€$_{2013}$/kW*	4400	4480	4500	4500	4500
CAPEX low	*€$_{2013}$/kW*	2000	2040	2050	2050	2050
CAPEX high	*€$_{2013}$/kW*	6000	6110	6130	6130	6130
Quality CAPEX estimate		medium				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
FOM refurbishment	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	5	5	5	5	5
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	0	0	0	0	0
Indirect GHG emissions	*tCO_2(eq)/GWh*	6	6	6	6	6
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	14	17	-	-	-

6.4 Hydropower run-of-a-river

Table 14. Hydropower run-of-a-river.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	0.7	0.7	0.7	0.7	0.7
Avg. capacity factor	*%*	37	37	37	37	37
Technical lifetime	*years*	60	60	60	60	60
Economical						
CAPEX ref	*€$_{2013}$/kW*	5500	5600	5620	5620	5620
CAPEX low	*€$_{2013}$/kW*	2500	2540	2560	2560	2560
CAPEX high	*€$_{2013}$/kW*	8000	8150	8180	8180	8180
Quality CAPEX estimate		medium				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
FOM refurbishment	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	5	5	5	5	5
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	0	0	0	0	0
Indirect GHG emissions	*tCO_2(eq)/GWh*	0	0	0	0	0
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	14	17	-	-	-

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7 Geothermal

Geothermal energy is derived from the thermal energy generated and stored in the Earth's interior. It is a commercially proven renewable form of energy that can provide both heat and power. Only power production is treated here. Geothermal energy can provide continuous base-load power generation, immune to weather effects and seasonal variation, with high capacity factors of 95 % for the new power plants.

There are two main categories of geothermal energy, i.e. conventional and advanced geothermal systems also termed enhanced geothermal systems or engineered geothermal systems (EGS). Among the conventional systems, there are three main types: dry steam, flash steam, and binary cycle. There are also variations of those.

In geothermal power plants, drilling and reservoir engineering can constitute more than 50 % of the CAPEX. This specific cost is highly dependent on the geology of the reservoir. The CAPEX figures given in this report concern depths of 2.5 km for flash and binary cycle plants extracting fluids from conventional systems, whereas it is 5.5 km for Organic Rankine Cycle (ORC) plants employing EGS. The CAPEX of these plants would have to be adjusted based on the depth of the main feedzones of production and re-injection wells.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

7.1 Flash power plants

Flash steam power plants are the most common type of geothermal power, making up about two thirds of the installed capacity today. The flash technology makes use of liquid-dominated hydrothermal resources with a temperature above 180 °C. The liquid water flashes as the pressure drops and the steam generated is diverted to a turbine.

The cost components included in the CAPEX estimate for Flash power plants are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

The CAPEX breakdown for a flash power plant is given in Figure 6.

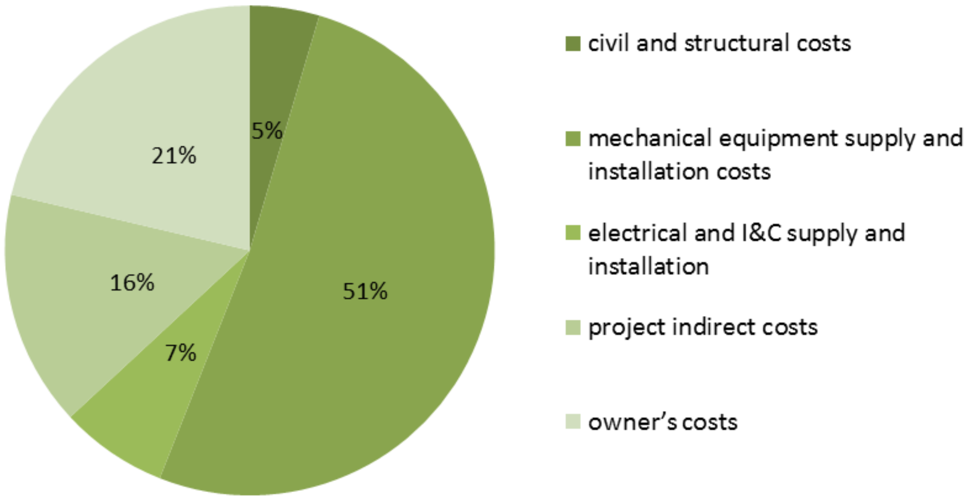

Figure 6. Capex breakdown of a hydrothermal flash power plant.

The upper CAPEX range assumes that the production and injection wells are 3.5 km deep.

Table 15. A Flash power plant extracting fluid from hydrothermal system at 2.5 km depth

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	45	45	45	45	47
Gross electrical power	*MW*	47	47	47	47	47
Thermal power	*MW*	196	191	188	184	180
Net efficiency	*%*	23	23.5	23.9	24.4	24.9
Max. capacity factor	*%*	95	95	95	95	95
Avg. capacity factor	*%*	95	95	95	95	95
Technical lifetime	*years*	30	30	30	30	30
Costs						
CAPEX ref	*€$_{2013}$/kWe*	5530	4970	4470	4020	3610
CAPEX low	*€$_{2013}$/kWe*	2500	2500	2500	2500	2500
CAPEX high	*€$_{2013}$/kWe*	5930	5370	4870	4420	4010
CAPEX floor	*€$_{2013}$/kWe*	2000	2000	2000	2000	2000
Quality of CAPEX estimate				medium		
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	1.4	1.6	1.8	2.0	2.2
Environmental						
Direct CO_2 emissions	*$tCO_2(eq)/GWh$*	122	122	122	122	122
Indirect CO_2 emissions	*$tCO_2(eq)/GWh$*	92	92	92	92	92
Water consumed	*l/kWh*	0.04	0.04	0.04	0.04	0.04
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max. potential	*GWe*	-	-	-	-	-

7.2 Organic Ranking Cycle

Electric power generation units using binary cycles constitute the fastest-growing group of geothermal plants as they are able to use low- to medium-temperature sources. Binary plants employing the ORC uses heat from hot water to boil a working fluid, which is usually an organic compound with low boiling point. The working fluid is vaporised in a heat exchanger and used to rotate a turbine.

The cost components included in the CAPEX estimate for ORC are:

☒ Civil and structural costs

☒ Major equipment costs

☒ Balance of plant costs

☒ Electrical and I&C supply and installation

☒ Project indirect costs

☒ Development costs

☒ Interconnection costs

☒ Insurance costs

Table 16. Organic Rankine Cycle hydrothermal system.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	7.3	7.5	7.7	8.0	8.2
Gross electrical power	*MW*	9.0	-	-	-	-
Thermal power	*MW*	54	54	54	54	54
Net efficiency	*%*	13.3	13.8	14.2	14.7	15.1
Max. capacity factor	*%*	95	95	95	95	95
Avg. capacity factor	*%*	95	95	95	95	95
Technical lifetime	*years*	30	30	30	30	30
Costs						
CAPEX ref	*€$_{2013}$/kWe*	6970	6600	6240	5870	5510
CAPEX low	*€$_{2013}$/kWe*	6470	6100	5740	5370	5010
CAPEX high	*€$_{2013}$/kWe*	7470	7100	6740	6370	6010
CAPEX floor	*€$_{2013}$/kWe*	-	-	-	-	-
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	2.1	2.2	2.3	2.5	2.7
Environmental						
Direct CO2 emissions	*$tCO_2(eq)/GWh$*	4	4	4	4	4
Indirect CO2 emissions	*$tCO_2(eq)/GWh$*	92	92	92	92	92
Water consumed	*l/kWh*	1	1	1	1	1
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max. potential	*GWe*	-	-	-	-	-

7.3 Organic Ranking Cycle Enhanced Geothermal Systems

EGS tap into the Earth's deep geothermal resources that are otherwise not economical due to lack of water and fractures, location or rock type. EGS has the potential to produce large amounts of electricity almost anywhere in the world. The basic concept is to drill two wells into the hot dry rock with limited permeability and fluid content at a depth of 5-10 km. Cold water is pumped into one well and hot water is then extracted from the second well.

The cost components included in the CAPEX estimate for ORC EGS are:

- ☐ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☐ Electrical and I&C supply and installation
- ☐ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

Table 17. Organic Rankine Cycle Enhanced Geothermal System at 5.5 km depth.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	4.4	4.6	4.8	5.1	5.3
Gross electrical power	*MW*	4.9	5.1	5.4	5.6	5.9
Thermal power	*MW*	41	41	41	41	41
Net efficiency	*%*	10.6	11.2	11.8	12.3	12.9
Max. capacity factor	*%*	95	95	95	95	95
Avg. capacity factor	*%*	95	95	95	95	95
Technical lifetime	*years*	30	30	30	30	30
Costs						
CAPEX ref	*€$_{2013}$/kWe*	12600	10300	9000	8600	8200
CAPEX low	*€$_{2013}$/kWe*	11700	9600	8400	8000	7600
CAPEX high	*€$_{2013}$/kWe*	13400	11000	9600	9100	8700
CAPEX floor	*€$_{2013}$/kWe*	-	-	-	-	-
Quality of CAPEX estimate		Medium				
CAPEX learning rate	*%*					
FOM	*% CAPEX ref.*	1.8	1.8	1.9	1.9	1.9
Environmental						
Direct CO_2 emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect CO_2 emissions	*$tCO_2(eq)/GWh$*	55	55	55	55	55
Water consumed	*l/kWh*	18	18	18	18	18
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max. potential	*GWe*	-	-	-	-	-

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8 Ocean

Ocean energy includes wave and tidal energy, ocean thermal energy conversion (OTEC) and osmotic power generation. Other alternatives are being explored as well, but their perspectives are uncertain. Given the advanced status of wave and tidal energy, only these two technologies are presented here. There is currently limited information available on the costs of OTEC and osmotic power generators. These technologies are currently at a low TRL (4/5) (IRENA, 2014), and an accurate and complete breakdown of their cost-components is currently not provided.

The ocean energy resources in the Atlantic Arc are abundant, however, their economic potential is still difficult to assess due to the fact that ocean energy is at an early stage of development. Substantial budgets have to be allocated for RD&D, market pull schemes and infrastructure needs in order for capital costs to become competitive.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

8.1 Wave

Wave power is generated by the capture of energy from surface waves, which is transformed into mechanical energy. The most favourable sites are those with higher waves, however in order to deploy in these sites concerns over reliability of the structures and availability of grid connections need to be overcome. The current status of technologies does not allow to be separated.

The cost components included in the CAPEX estimate for Wave energy are:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☐ Interconnection costs[a]
- ☐ Insurance costs

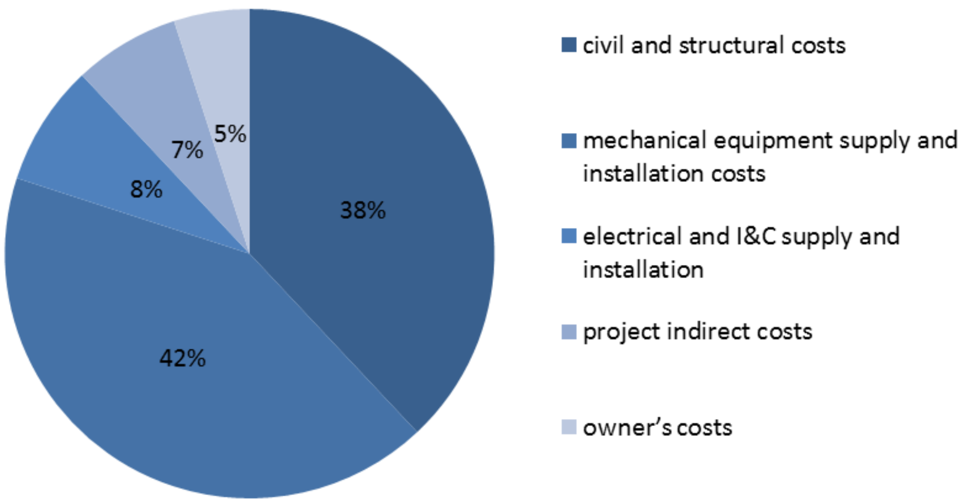

Figure 7. CAPEX breakdown for wave power.

[a] Interconnection estimates are currently included in the electrical and I&C category.

The future power rating of these plants is very uncertain, hence ranges are given up to 2050. Given the current state of the art, the upper limits for current CAPEX estimates are used in the near-term. Long-term estimates however align with the future predictions.

Table 18. Techno-economic data for wave energy.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power[a]	*MW*	1-5	5-20	30-40	40-50	50-400
Max. capacity factor	*%*	36	45	47	47	50
Avg. capacity factor	*%*	20	23	28	32	36
Technical lifetime	*years*	20	20	20	20	20
Costs						
CAPEX ref	*€$_{2013}$/kW*	9080	5790	4480	2650	2300
CAPEX low	*€$_{2013}$/kW*	7590	5060	3890	2560	2050
CAPEX high	*€$_{2013}$/kW*	10700	6390	5490	2700	2560
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	12	12	12	12	12
FOM	*% CAPEX ref.*	3.6	4.1	4.7	5.8	5.8
FOM learning rate	*%*	3	3	3	3	3
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	0	0	0	0	0
Indirect GHG emissions	*tCO_2(eq)/GWh*	8	8	8	8	8
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	0.03	0.19	1.9	2.0	3.2

8.2 Tidal

The tide generates water flow that can be exploited by hydraulic turbines to generate power. Favourable application sites are those with high flow velocities. Potential resources are expected to increase with improvements in system design and turbine technology.

The cost components included in the CAPEX estimate for Tidal energy are as follows:

☒ Civil and structural costs

☒ Major equipment costs

☒ Balance of plant costs

☒ Electrical and I&C supply and installation

☒ Project indirect costs

☒ Development costs

☐ Interconnection costs

☐ Insurance costs

[a] Current estimates for wave energy plants focus on the development of 10MW arrays, projects for up to 40MW have been announced but no clear time-scale is currently available.

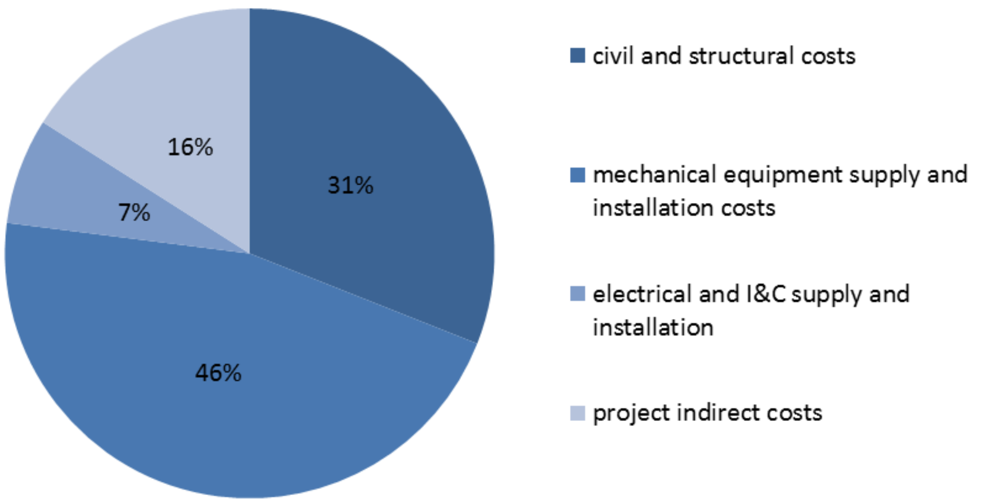

Figure 8. CAPEX breakdown for tidal power.

The future power rating of these plants is very uncertain, hence ranges are given up to 2050. Given the current state of the art, the upper limit for current CAPEX estimates are used in the near-term. Long-term estimate however align with the future predictions.

Table 19. Techno-economic data for tidal energy.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power[a]	*MW*	10	10-20	20-30	30-40	50-400
Max. capacity factor	*%*	36	45	47	47	50
Avg. capacity factor	*%*	34	37	40	42	45
Technical lifetime	*years*	20	20	20	20	20
Costs						
CAPEX ref	*€$_{2013}$/kW*	10700	4400	3100	2100	1900
CAPEX low	*€$_{2013}$/kW*	9300	3600	3000	1800	1700
CAPEX high	*€$_{2013}$/kW*	12300	5500	3400	2800	2500
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	12	12	12	12	12
FOM	*% CAPEX ref.*	3.4	3.6	3.8	4.3	4.9
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	2	2	2	2	2
Water consumed	*l/kWh*	0	0	0	0	0
Water withdrawn	*l/kWh*	0	0	0	0	0
Evolution						
Max. potential	*GW*	0.04	0.4	2.9	3.1	10

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[a] Current estimates for tidal energy plants focus on the development of 10MW arrays, however projects for up to 400+MW have been announced but no clear time-scale is currently available. Two projects receiving NER300 funds have a nominal power of 8 and 10MW respectively and expected operation start date is 2016/2017.

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9 Advanced fossil fuels

Fossil fuels contribute with the largest share to European electricity generation. Although it is a mature sector significant changes are anticipated due to the fact that climate change concerns need to be addressed. In the near to medium term, old plants are expected to be either be retrofitted or replaced with other ones. Other measures foreseen are, for example, to convert plants to cogeneration plants, see Section 8.13, and co-fire with biofuel, see Section 8.10. Also, in the medium to long term fossil plants will increasingly add Carbon Capture and Storage technology, see Section 8.9.

Sources providing higher heating value (HHV) have been converted to lower heating value (LHV). Thermal power refers to the inlet calorific value needed to produce the net power. It is calculated using the net efficiency of each plant. Emissions and water consumption are obtained for 2020 and estimated for the following years according to the increase in efficiency. Different assumptions have been taken in order to complete as much as possible each one of the tables, for instance, extrapolating the ratio between emissions for 2020, to the other years. Or, assuming the same costs decrease in a plant with CCS than its equivalent plant without CCS. The estimation of staff working in the different plants takes into account different ratios calculated with data found for coal power plants, IGCC power plant (ELCOGAS), and oxy-combustion plant (Compostilla).

The 2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

9.1 Open-cycle gas turbine

The open-cycle gas turbine (OCGT) burns fuel in a combustion chamber and uses the combustion gases to drive a turbine. A compressor is mounted on the same shaft that draws in air and thereby increases the intensity of the burning flame. The OCGT is mainly used for peak load electricity production.

In the CAPEX estimate includes the following cost components for both OCGT technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

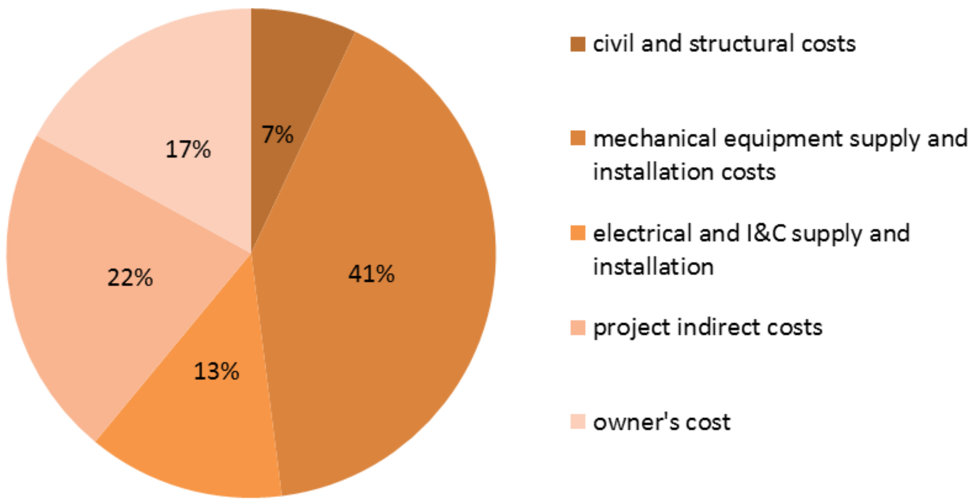

Figure 9. CAPEX breakdown of OCGT.

The Open-Cycle Gas Turbine (OCGT) conventional is obsolete and it will be replaced by OCGT advanced in the future.

Table 20. Open-Cycle Gas Turbine conventional

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	85	n/a	n/a	n/a	n/a
Gross electrical power	*MW*	88	n/a	n/a	n/a	n/a
Thermal power	*MW*	220	n/a	n/a	n/a	n/a
Max. capacity factor	*%*	95	n/a	n/a	n/a	n/a
Avg. capacity factor	*%*	15	n/a	n/a	n/a	n/a
Technical lifetime	*years*	30	n/a	n/a	n/a	n/a
Net efficiency (LHV)	*%*	38	n/a	n/a	n/a	n/a
Costs						
CAPEX ref	$€_{2013}$/kWe	770	n/a	n/a	n/a	n/a
CAPEX low	$€_{2013}$/kWe	630	n/a	n/a	n/a	n/a
CAPEX high	$€_{2013}$/kWe	920	n/a	n/a	n/a	n/a
Quality CAPEX estimate		medium				
CAPEX learning rate	*%*	1	n/a	n/a	n/a	n/a
FOM	*% CAPEX ref.*	1	n/a	n/a	n/a	n/a
VOM	$€_{2013}$/MWh	13	n/a	n/a	n/a	n/a
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	635	n/a	n/a	n/a	n/a
Indirect GHG emissions	$tCO_2(eq)/GWh$	120	n/a	n/a	n/a	n/a
Water consumed	*l/kWh*	-	n/a	n/a	n/a	n/a
Water withdrawn	*l/kWh*	-	n/a	n/a	n/a	n/a
Evolution						
Max potential	*GWe*	-	n/a	n/a	n/a	n/a

Table 21. Open Cycle Gas Turbine advanced

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	250	250	250	250	250
Gross electrical power	*MW*	260	260	260	260	260
Thermal power	*MW*	630	630	580	570	560
Max. capacity factor	*%*	95	95	95	95	95
Avg. capacity factor	*%*	15	15	15	15	15
Technical lifetime	*years*	30	30	30	30	30
Net efficiency (LHV)	*%*	40	40	43	44	45
Costs						
CAPEX ref	*€$_{2013}$/kWe*	550	550	550	550	550
CAPEX low	*€$_{2013}$/kWe*	400	400	400	400	400
CAPEX high	*€$_{2013}$/kWe*	650	650	650	650	650
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	5	5	5	5	-
FOM	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	11	11	11	11	11
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	575	575	535	525	510
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	110	110	100	100	100
Water consumed	*l/kWh*	-	-	-	-	-
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

9.2 Combined cycle gas turbine advanced

Combined Cycle Gas Turbine (CCGT) is the dominant gas-based technology. It uses the exhausts from the gas cycle to heat up water to produce steam. The technology is already mature so capital costs are expected to remain stable. The CCGT is a flexible plant that can be used both for load following and base load power production.

In the CAPEX estimate includes the following cost components for both CCGT technologies:

☒ Civil and structural costs

☒ Major equipment costs

☒ Balance of plant costs

☒ Electrical and I&C supply and installation

☒ Project indirect costs

☒ Development costs

☒ Interconnection costs

☒ Insurance costs

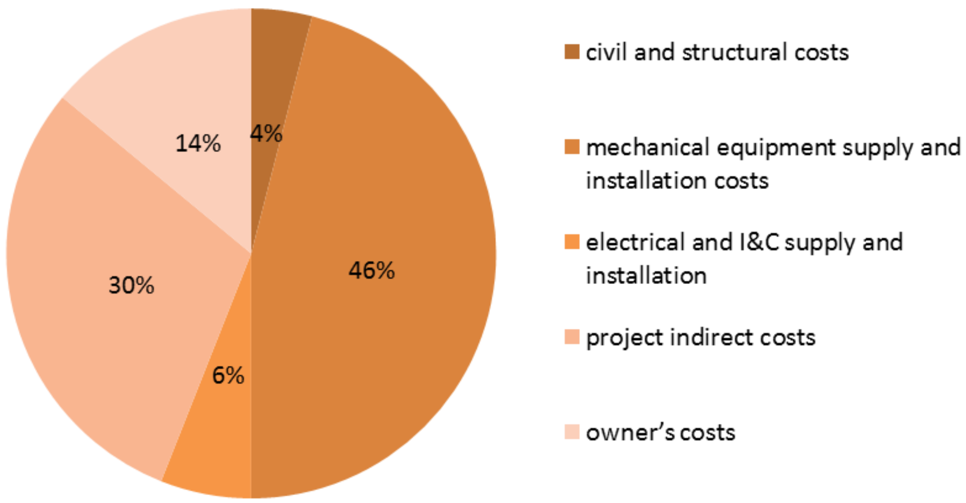

Figure 10. CAPEX breakdown of CCGT.

Table 22. Combined Cycle Gas Turbine advanced.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	580	580	580	580	580
Gross electrical power	*MW*	600	600	600	600	600
Thermal power	*MW*	1000	965	935	935	920
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	30	30	30	30	30
Net efficiency (LHV)	*%*	58	60	62	62	63
Costs						
CAPEX ref	*€$_{2013}$/kWe*	850	850	850	850	850
CAPEX low	*€$_{2013}$/kWe*	700	700	700	700	700
CAPEX high	*€$_{2013}$/kWe*	950	950	950	950	950
Quality of CAPEX estimate				medium		
CAPEX learning rate	*%*	5	5	5	5	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	2	2	2	2	2
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	370	360	350	350	340
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	70	68	65	65	64
Water consumed	*l/kWh*	750	725	700	700	690
Water withdrawn	*l/kWh*	980	945	915	915	900
Evolution						
Max potential	*GWe*	-	-	-	-	-

9.3 Pulverised supercritical coal/lignite plants

Currently, supercritical pulverised coal power is the dominant option for new coal-fired power plants. These new coal-fired power plants have higher efficiency and lower emission of CO_2 per kWh than existing plants. Coal plants have higher investment costs compared to natural gas plants, but this is compensated by lower fuel costs.

The sizes of these power plants range between 200-1300 MW_e. It is expected that higher steam temperatures can be reached in the future, which would allow operating at higher pressures with higher net efficiencies.

Since the 1990's both hard coal and lignite usage were in a declining trend. However, due to the European crisis and its subsequent low price for the tonne of CO_2 emitted, high natural gas prices, increased capacity from coal exporters from Indonesia and Australian, Pacific demand lower than expected (and high coal capacities), and the shale gas boom in the US, the coal market prices have been depressed. Overall, the situation has led to an increase of using of coal in Europe.

In the CAPEX estimate includes the following cost components for both pulverised coal supercritical technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

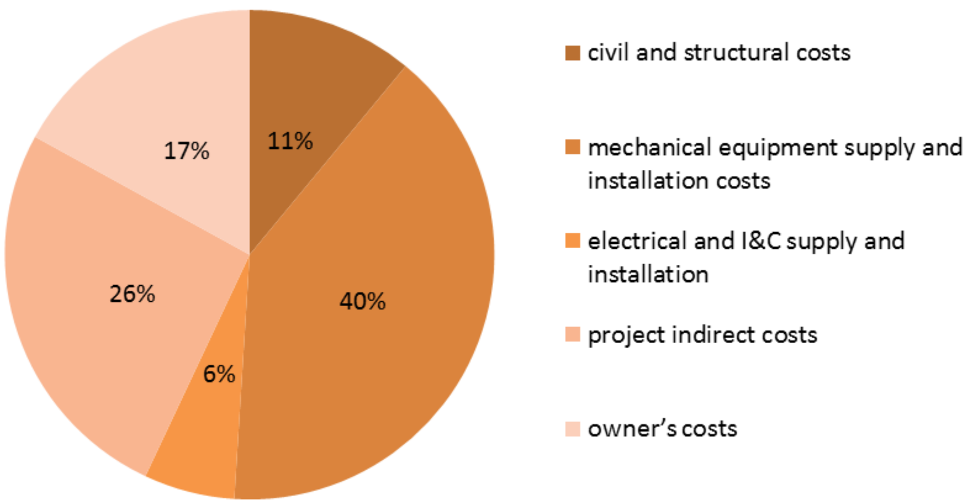

Figure 11. CAPEX breakdown of pulverised coal supercritical.

Table 23. Pulverised coal supercritical.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	750	750	750	750	750
Gross electrical power	*MW*	790	790	790	790	790
Thermal power	*MW*	1670	1630	1560	1560	1560
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	45	46	48	48	48
Costs						
CAPEX ref	$€_{2013}$/kWe	1600	1600	1600	1600	1600
CAPEX low	$€_{2013}$/kWe	1550	1550	1550	1550	1550
CAPEX high	$€_{2013}$/kWe	1700	1700	1700	1700	1700
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	1	1	1	1	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
FOM learning rate	*%*	2	-	-	-	-
VOM	$€_{2013}$/MWh	3.6	3.6	3.6	3.6	3.6
No. staff / year	*1*	135	135	135	135	135
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	890	880	840	840	840
Indirect GHG emissions	$tCO_2(eq)/GWh$	95	93	89	89	89
Water consumed	*l/kWh*	1760	1720	1650	1650	1650
Water withdrawn	*l/kWh*	2210	2160	2070	2070	2070
Evolution						
Max potential	*GWe*	-	-	-	-	-

Table 24. Pulverised lignite supercritical.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	750	750	750	750	750
Gross electrical power	*MW*	795	795	795	795	795
Thermal power	*MW*	1790	1670	1600	1600	1600
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	42	45	47	47	47
Costs						
CAPEX ref	$€_{2013}$/kWe	2000	2000	2000	2000	2000
CAPEX low	$€_{2013}$/kWe	1700	1700	1700	1700	1700
CAPEX high	$€_{2013}$/kWe	2400	2400	2400	2400	2400
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	1	1	1	1	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
FOM learning rate	*%*	2	-	-	-	-
VOM	$€_{2013}$/MWh	4.5	4.5	4.5	4.5	4.5
No. staff	*1*	135	135	135	135	135
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	1010	950	910	910	910
Indirect GHG emissions	$tCO_2(eq)/GWh$	110	100	96	96	96
Water consumed	*l/kWh*	1750	1630	1570	1570	1570
Water withdrawn	*l/kWh*	2210	2060	1970	1970	1970
Evolution						
Max potential	*GWe*	-	-	-	-	-

9.4 Supercritical fluidized bed

Fluidized bed plants are working at lower temperatures than pulverized combustion plants. Lignite is locally produced, and practically not imported or exported.

In the CAPEX estimate includes the following cost components for both Fluidised bed supercritical technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

Table 25. Fluidized bed lignite

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	550	550	550	550	550
Gross electrical power	*MW*	580	580	580	580	580
Thermal power	*MW*	1310	1280	1230	1230	1230
Max. capacity factor	*%*	85	85	85	85	85
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	42	43	45	45	45
Costs						
CAPEX ref	*€$_{2013}$/kWe*	1900	1900	1900	1900	1900
CAPEX low	*€$_{2013}$/kWe*	1615	1615	1615	1615	1615
CAPEX high	*€$_{2013}$/kWe*	2280	2280	2280	2280	2280
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-				
FOM	*% CAPEX ref.*	2	2	2	2	2
VOM	*€$_{2013}$/MWh*	6	6	6	6	6
No. staff / year	*1*	100	100	100	100	100
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	1010	985	940	940	940
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	110	105	100	100	100
Water consumed	*l/kWh*	750	735	700	700	700
Water withdrawn	*l/kWh*	980	960	915	915	915
Evolution						
Max. potential	*GWe*	-	-	-	-	-

9.5 Integrated Gasification Combined Cycle (IGCC)

IGCC plants operate at higher efficiencies and produce fewer emissions of SO_2, NO_x and particulate matter. It produces gas, called syngas, which is usually made from coal, petcoke and residual oils. Syngas is versatile since it can be converted into a wide range of products, e.g. H_2, ammonia or small organic compounds. The syngas is used in a combined cycle to produce electricity.

In the CAPEX estimate includes the following cost components for IGCC technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

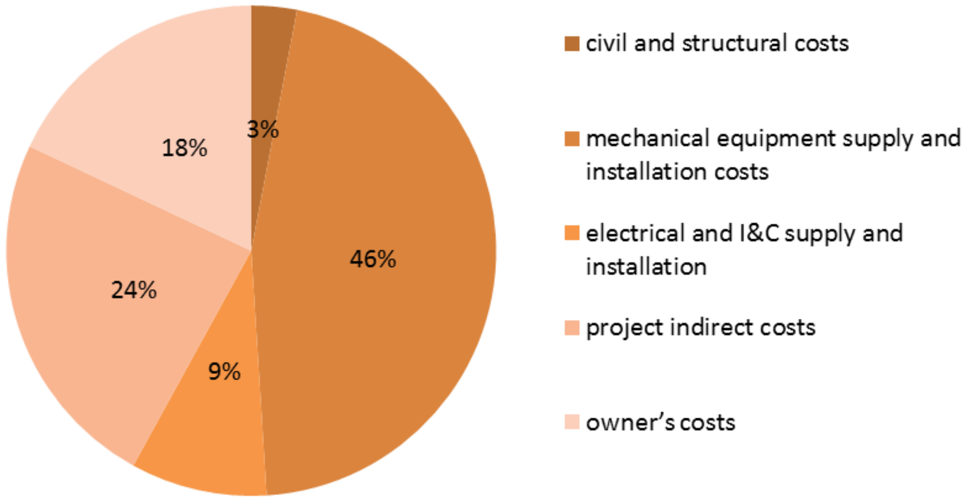

Figure 12. CAPEX breakdown for IGCC coal.

Table 26. Integrated Gasification Combined Cycle coal

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	600	600	600	600	600
Gross electrical power	*MW*	700	700	700	700	700
Thermal power	*MW*	1330	1330	1330	1280	1200
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	35	35	35	35	35
Net efficiency (LHV)	*%*	45	46	46	47	50
Costs						
CAPEX ref	*€$_{2013}$/kWe*	2500	2300	2300	2300	2200
CAPEX low	*€$_{2013}$/kWe*	2450	2255	2255	2055	2150
CAPEX high	*€$_{2013}$/kWe*	3100	2850	2850	2850	2730
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	11	11	11	11	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	5	5	5	5	5
No. staff / year	*1*	300	300	300	300	300
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	900	880	880	860	810
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	100	98	98	96	90
Water consumed	*l/kWh*	1280	1250	1250	1220	1150
Water withdrawn	*l/kWh*	1610	1575	1575	1540	1450
Evolution						
Max potential	*GWe*	-	-	-	-	-

Table 27. Integrated Gasification Combined Cycle lignite

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	600	600	600	600	600
Gross electrical power	*MW*	725	725	725	725	725
Thermal power	*MW*	1400	1330	1300	1280	1280
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	35	35	35	35	35
Net efficiency (LHV)	*%*	43	45	46	47	47
Costs						
CAPEX ref	$€_{2013}$/kWe	3100	3000	3000	3000	3000
CAPEX low	$€_{2013}$/kWe	2650	2600	2600	2600	2600
CAPEX high	$€_{2013}$/kWe	3350	3250	3250	3250	3250
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-				
FOM	*% CAPEX ref.*	3	3	3	3	3
VOM	$€_{2013}$/MWh	7	7	7	7	7
No. staff / year	*1*	300	300	300	300	300
Environmental						
Direct GHG emissions	$tCO_2(eq)$/GWh	1005	960	940	920	920
Indirect GHG emissions	$tCO_2(eq)$/GWh	115	110	105	100	100
Water consumed	*l/kWh*	580	555	545	530	530
Water withdrawn	*l/kWh*	800	765	750	735	735
Evolution						
Max. potential	*GWe*	-	-	-	-	-

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10 Carbon capture and storage

Carbon Capture and Storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related gases. The concept can also include the utilisation of the captured CO_2 as feedstock for industrial applications. CCS is based on well-known technologies, but it has until now not been applied to large-scale plants. So far the problem is that CCS is expensive and energy-consuming compared to conventional power production from fossil fuels. Also, CCS needs to demonstrate safe and permanent storage of CO_2.

In the CAPEX estimate includes the following cost components for CCS technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☒ Insurance costs

A CAPEX breakdown was not possible to establish for CCS. Sources providing HHV has been converted to LHV. Thermal power refers to the inlet calorific value needed to produce the net power. It is calculated using the net efficiency of each plant. Efficiency loss or efficiency penalty is theoretically a "negative efficiency". It is the difference between the efficiency without capture, and the efficiency of the plant with CCS. Emissions and water consumption are obtained for 2020 and estimated for the following years according to the increase in efficiency. Different assumptions have been taken in order to complete as much as possible each one of the tables, for instance, extrapolating the ratio between emissions for 2020, to the other years. Or, assuming the same costs decrease in a plant with CCS than its equivalent plant without CCS. The estimation of staff working in the different plants takes into account different ratios calculated with data found for coal power plants, IGCC power plant (ELCOGAS), and oxy-combustion plant (Compostilla).

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

10.1 CCS post-combustion

Post-combustion capture is the most established CCS technology. It involves CO_2 scrubbing from the flue gas. It is predicted to have the largest deployment among the existing CCS technologies since it can be included in existing fossil fuel combustion plants with little plant modification. Chemical absorption is the most mature technique, but several other alternatives exist as well.

Table 28. CCGT advanced CCS post combustion

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	485	485	485	485	485
Gross electrical power	*MW*	550	550	550	550	550
Thermal power	*MW*	970	930	880	880	880
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	30	30	30	30	30
Net efficiency (LHV)	*%*	50	52	55	55	55
Efficiency loss from CCS	*%*	8	8	7	7	7
CO_2 captured (only CCS)	*%*	86	86	86	86	86
Costs						
CAPEX ref	*€$_{2013}$/kWe*	1500	1500	1500	1500	1500
CAPEX low	*€$_{2013}$/kWe*	1250	1250	1250	1250	1250
CAPEX high	*€$_{2013}$/kWe*	1750	1750	1750	1750	1750
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	4	4	4	4	4
Transport storage cost	*€$_{2013}$/MWh*	4	-	-	-	-
No. staff / year	*1*	-	-	-	-	-
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	53	50	48	48	4
Indirect GHG emissions	*tCO_2(eq)/GWh*	85	85	77	77	75
Water consumed	*l/kWh*	1450	1400	1320	1320	1295
Water withdrawn	*l/kWh*	1900	1840	1740	1740	1700
Evolution						
Max. potential	*GWe*	-	-	-	-	-

Table 29. Pulverised coal supercritical CCS post-combustion

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	630	630	630	630	630
Gross electrical power	*MW*	790	790	790	790	790
Thermal power	*MW*	1855	1800	1800	1660	1660
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	34	35	35	38	38
Efficiency loss from CCS	*%*	11	11	10	10	10
CO_2 captured (only CCS)	*%*	87	87	87	87	87
Costs						
CAPEX ref	*€$_{2013}$/kWe*	3000	2700	2550	2550	2550
CAPEX low	*€$_{2013}$/kWe*	2600	2340	2210	2210	2210
CAPEX high	*€$_{2013}$/kWe*	3350	3020	2850	2850	2850
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	2	-	-	-	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	5.5	5.5	5.5	5.5	5.5
Transport storage cost	*€$_{2013}$/MWh*	7	-	-	-	-
No. staff / year	*1*	270	270	270	270	270
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	110	105	105	95	95
Indirect GHG emissions	*tCO_2(eq)/GWh*	125	120	120	115	115
Water consumed	*l/kWh*	3210	3210	3120	2875	2875
Water withdrawn	*l/kWh*	4170	4050	4050	3750	3750
Evolution						
Max potential	*GWe*	-	-	-	-	-

Table 30. Fluidised bed lignite CCS post combustion

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	480	480	480	480	480
Gross electrical power	*MW*	580	580	580	580	580
Thermal power	*MW*	1550	1500	1410	1410	1410
Max. capacity factor	*%*	85	85	85	85	85
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	31	32	34	34	34
Efficiency loss from CCS	*%*	10	11	11	11	11
CO_2 captured (only CCS)	*%*	87	87	87	87	87
Costs						
CAPEX ref	*€$_{2013}$/kWe*	3500	3500	3500	3500	3500
CAPEX low	*€$_{2013}$/kWe*	2975	2975	2975	2975	2975
CAPEX high	*€$_{2013}$/kWe*	4200	4200	4200	4200	4200
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-				
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
VOM	*€$_{2013}$/MWh*	10	10	10	10	10
Transport storage cost	*€$_{2013}$/MWh*	8.5	-	-	-	-
No. staff / year	*1*	200	200	200	200	200
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	140	135	130	130	130
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	165	160	150	150	150
Water consumed	*l/kWh*	2370	2300	2165	2165	2165
Water withdrawn	*l/kWh*	3300	3200	3010	3010	3010
Evolution						
Max potential	*GWe*	-	-	-	-	-

10.2 CCS oxyfuel

This technology uses an O_2/CO_2 stream instead of air for combustion, which results in higher concentrations of CO_2 in the flue gases. This process suggests high efficiency levels and allows retrofitting existing plants. The main disadvantage is the large quantity of oxygen required, which is expensive both in terms of capital costs and energy consumption.

Table 31. Pulverised coal supercritical CCS oxyfuel.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	580	580	580	580	580
Gross electrical power	*MW*	790	790	790	790	790
Thermal power	*MW*	1615	1570	1490	1450	1450
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	40	40	40	40	40
Net efficiency (LHV)	*%*	36	37	39	40	40
Efficiency loss from CCS	*%*	9	9	9	9	9
CO_2 captured (only CCS)	*%*	90	90	90	90	90
Costs						
CAPEX ref	*€$_{2013}$/kWe*	3000	2700	2550	2550	2550
CAPEX low	*€$_{2013}$/kWe*	2600	2340	2210	2210	2210
CAPEX high	*€$_{2013}$/kWe*	3400	3060	2890	2890	2890
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	2.5	2.5	2.5	2.5	2.5
FOM learning rate	*%*	2	2	-	-	-
VOM	*€$_{2013}$/MWh*	3	3	3	3	3
Transport storage cost	*€$_{2013}$/MWh*	15	-	-	-	-
No. staff / year	*1*	260	260	260	260	260
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	90	87	85	80	80
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	110	105	100	95	95
Water consumed	*l/kWh*	-	-	-	-	-
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

10.3 CCS pre-combustion

Pre-combustion capture involves the capture of CO_2 from a synthesis gas stream produced through gasification of solid fuels or through steam reforming of natural gas. The most common application is for an IGCC plant.

Table 32. IGCC CCS pre-combustion.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	510	510	510	510	510
Gross electrical power	*MW*	675	675	675	675	675
Thermal power	*MW*	1460	1380	1380	1160	1160
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	35	35	35	35	35
Net efficiency (LHV)	*%*	35	37	40	41	44
Efficiency loss from CCS	*%*	10	9	6	6	6
CO_2 captured (only CCS)	*%*	88	88	88	88	88
Costs						
CAPEX ref	*€$_{2013}$/kWe*	3100	2885	2825	2825	2825
CAPEX low	*€$_{2013}$/kWe*	2800	2600	2550	2550	2550
CAPEX high	*€$_{2013}$/kWe*	3550	3300	3230	3230	3230
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	5	5	5	5	-
FOM	*% CAPEX ref.*	3	3	3	3	3
VOM	*€$_{2013}$/MWh*	6	6	6	6	6
Transport storage cost	*€$_{2013}$/MWh*	5.5	-	-	-	-
No. staff / year	*1*	400	400	400	400	400
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	150	140	130	125	118
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	125	120	110	105	100
Water consumed	*l/kWh*	2050	1940	1795	1750	1630
Water withdrawn	*l/kWh*	2510	2375	2195	2150	2000
Evolution						
Max potential	*GWe*	-	-	-	-	-

Table 33. IGCC lignite CCS pre combustion.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	510	510	510	510	510
Gross electrical power	*MW*	700	700	700	700	700
Thermal power	*MW*	1460	1380	1280	1250	1250
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	35	35	35	35	35
Net efficiency (LHV)	*%*	35	37	40	41	41
Efficiency loss from CCS	*%*	8	8	6	6	6
CO_2 captured (only CCS)	*%*	89	89	89	89	89
Costs						
CAPEX ref	*€$_{2013}$/kWe*	4500	4370	4370	4370	4370
CAPEX low	*€$_{2013}$/kWe*	3950	3820	3820	3820	3820
CAPEX high	*€$_{2013}$/kWe*	5000	4850	4850	4850	4850
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	2.3	2.3	2.3	2.3	2.3
VOM	*€$_{2013}$/MWh*	8	8	8	8	8
Transport/storage cost CO_2	*€$_{2013}$/MWh*	8	-	-	-	-
No. staff / year	*1*	400	400	400	400	400
Environmental						
Direct GHG emissions	*tCO_2(eq)/GWh*	123	116	107	105	105
Indirect GHG emissions	*tCO_2(eq)/GWh*	104	98	90	88	88
Water consumed	*l/kWh*	1530	1450	1340	1300	1300
Water withdrawn	*l/kWh*	1900	1800	1665	1620	1620
Evolution						
Max potential	*GWe*	-	-	-	-	-

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11 Nuclear fission

Nuclear power currently generates about two thirds of the low carbon electricity and 30 % of the total electricity in Europe. It is likely to continue to contribute to a significant share of the base-load low-carbon electricity in the coming decades too.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

11.1 Generation II

Most of the currently operating nuclear power plants in Europe are of the second generation. The bulk of them were built in the 1980's with original design lifetimes of up to 40 years. The majority of them are expected to be granted life time extensions of 10-20 years.

The CAPEX estimate includes the following cost components for Gen II nuclear technologies:

☒ Civil and structural costs	☒ Project indirect costs
☒ Major equipment costs	☒ Development costs
☒ Balance of plant costs	☒ Interconnection costs
☒ Electrical and I&C supply and installation	☒ Insurance costs

In order to take into account long time operation (LTO) of nuclear power plants, the 'FOM refurbishment cost' is assumed to be added after 30 years of operation and it is assumed that it will extend the operation by 15 years. The higher FOM refurbishment cost for 2010 and 2020 is due to the safety improvements required after stress tests that followed the accident in Fukushima.

New Generation II reactors are not foreseen to be built again within the EU, and therefore CAPEX projections are not made here.

Table 34. Generation II LWR.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	1075	1075	1075	1075	1075
Gross electrical power	*MW*	1107	1107	1107	1107	1107
Thermal power	*MW*	3260	3260	3260	3260	3260
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	81	81	81	81	81
Technical lifetime	*years*	40	50	60	60	60
Net efficiency	*%*	33	33	33	33	33
Costs						
CAPEX ref	$€_{2013}/kWe$	n/a	n/a	n/a	n/a	n/a
CAPEX low	$€_{2013}/kWe$	n/a	n/a	n/a	n/a	n/a
CAPEX high	$€_{2013}/kWe$	n/a	n/a	n/a	n/a	n/a
Quality of CAPEX estimate		n/a				
FOM	*% CAPEX ref.*	2.1	2.1	2.1	2.1	2.1
FOM refurbishment	*% CAPEX ref.*	2.4	2.4	1.9	1.9	1.9
VOM	$€_{2013}/MWh$	8	8	8	8	8
No. staff / year	*1*	450	450	450	450	450
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	0	0	0	0	0
Indirect GHG emissions	$tCO_2(eq)/GWh$	15	15	15	15	15
Water consumed	*l/kWh*	6	6	6	6	6
Water withdrawn	*l/kWh*	160	159	158	157	156
Evolution						
Max potential	*GWe*	130	130	118	90	25

11.2 Generation III Light Water Reactor

The current state of art of commercial nuclear power plants is the Gen III reactor, which is an evolution of the Gen II reactors with enhanced safety features and reliability. The first Gen III reactors in Europe are expected to be connected to the grids in 2016. The Gen III reactors are expected to replace the Gen II reactors in the coming decades.

The CAPEX estimate includes the following cost components for Gen III nuclear technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

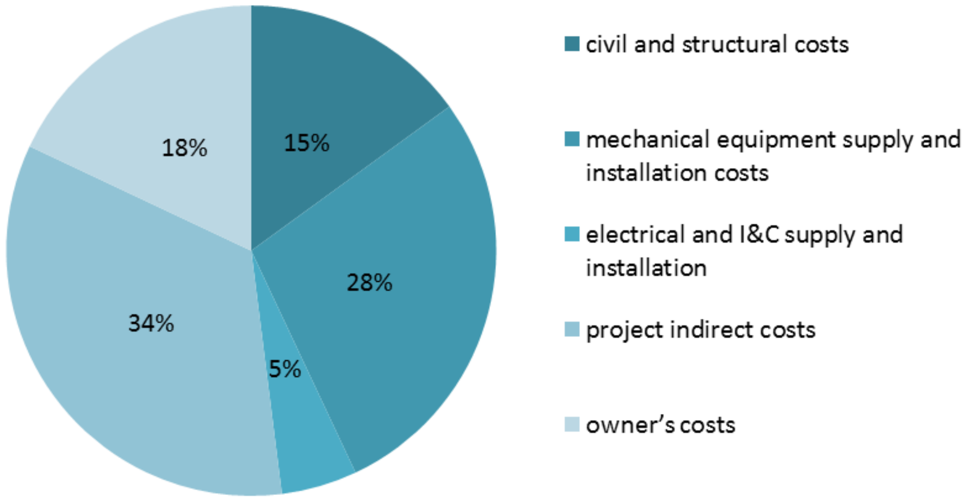

Figure 13. CAPEX breakdown of Gen III LWR.

Table 35. Data for nuclear fission Generation III light water reactor.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	1410	1420	1430	1440	1450
Gross electrical power	*MW*	1450	1460	1480	1510	1550
Thermal power	*MW*	3800	3800	3800	3800	3800
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	81	81	81	81	81
Technical lifetime	*years*	60	60	60	60	60
Net efficiency	*%*	37	37	38	38	38
Costs						
CAPEX ref	*€$_{2013}$/kWe*	4500	4350	4100	3800	3750
CAPEX low	*€$_{2013}$/kWe*	4000	3850	3650	3400	3350
CAPEX high	*€$_{2013}$/kWe*	6000	5800	5450	5050	5000
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	3.5	3.5	3.5	3.5	3.5
FOM	*% CAPEX ref.*	2.1	2.1	1.9	1.7	1.6
FOM refurbishment	*% CAPEX ref.*	n/a	n/a	n/a	2	2
VOM	*€$_{2013}$/MWh*	2.5	2.5	2.5	2.5	2.5
No. staff / year	*1*	450	450	450	450	450
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	0	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	15	15	15	15	15
Water consumed	*l/kWh*	6	6	6	6	6
Water withdrawn	*l/kWh*	160	159	158	157	156
Evolution						
Max potential	*GWe*	0	3.3	40	80	120

11.3 Small and medium sized LWR

Small and medium sized nuclear reactors (SMR) have electrical powers of up to 700 MW, or generally less than 300 MW per reactor module. Design objectives of SMRs can vary significantly, e.g. improved safety and security, offer electricity and heat, or more independent operation. The growth potential for SMRs in Europe is uncertain.

The CAPEX estimate includes the following cost components SMR nuclear technologies:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☐ Interconnection costs
- ☐ Insurance costs

Since SMRs can be in commercial operation by 2020 at earliest, no data is given for 2010.

Table 36. Data for nuclear fission Small and Medium sized light water reactor.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	n/a	225	225	225	225
Gross electrical power	*MW*	n/a	-	-	-	-
Thermal power	*MW*	n/a	800	800	800	800
Max. capacity factor	*%*	n/a	95	95	95	95
Avg. capacity factor	*%*	n/a	-	-	-	-
Technical lifetime	*years*	n/a	60	60	60	60
Net efficiency	*%*	n/a	28	28	28	28
Costs						
CAPEX ref	*€$_{2013}$/kWe*	n/a	6300	5750	5350	5300
CAPEX low	*€$_{2013}$/kWe*	n/a	3850	3650	3400	3350
CAPEX high	*€$_{2013}$/kWe*	n/a	7750	7100	6550	6500
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	n/a	2	2	2	2
FOM refurbishment	*% CAPEX ref.*	n/a	n/a	n/a	n/a	2
VOM	*€$_{2013}$/MWh*	n/a	2.5	2.5	2.5	2.5
No. staff / year	*1*	n/a	450	450	450	450
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	n/a	0	0	0	0
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	n/a	15	15	15	15
Water consumed	*l/kWh*	n/a	2	2	2	2
Water withdrawn	*l/kWh*	n/a	43	43	43	43
Evolution						
Max potential	GWe	n/a	0	1	16	48

11.4 Generation IV Sodium-Cooled Fast Reactor and Lead-cooled Fast Reactor

The fourth generation of nuclear reactors is presently being developed. Some of these are fast neutron reactor concepts, which aim at a more sustainable fuel cycle with about 50 times more efficient fuel usage and ability to transmute nuclear waste. These reactor types are expected to be commercially available in Europe after 2040.

No reliable data concerning CAPEX costs for the Sodium-cooled Fast Reactor (SFR) and the Lead-cooled Fast Reactor (LFR) are available. Instead the assessment here is made in relation to the Gen III reactor design.

The CAPEX estimate includes the following cost components for Gen IV SFR nuclear technology:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☐ Interconnection costs
- ☐ Insurance costs

Table 37. Sodium-cooled fast reactor.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	n/a	n/a	n/a	1500	1500
Gross electrical power	*MW*	n/a	n/a	n/a	-	-
Thermal power	*MW*	n/a	n/a	n/a	3600	3600
Max. capacity factor	*%*	n/a	n/a	n/a	90	90
Avg. capacity factor	*%*	n/a	n/a	n/a	80	80
Technical lifetime	*years*	n/a	n/a	n/a	60	60
Net efficiency	*%*	n/a	n/a	n/a	42	42
Costs						
CAPEX ref	*€$_{2013}$/kWe*	n/a	n/a	n/a	4900	4500
CAPEX low	*€$_{2013}$/kWe*	n/a	n/a	n/a	3900	3900
CAPEX high	*€$_{2013}$/kWe*	n/a	n/a	n/a	6400	5200
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	n/a	n/a	n/a	3.5	3.5
OM	*% CAPEX ref.*	n/a	n/a	n/a	2.1	2.1
FOM refurbishment	*% CAPEX ref.*	n/a	n/a	n/a	n/a	n/a
No. staff / year	*1*	n/a	n/a	n/a	450	450
Environmental						
Direct CO_2 emissions	*CO_2(eq)/GWh*	n/a	n/a	n/a	0	0
Indirect CO_2 emissions	*CO_2(eq)/GWh*	n/a	n/a	n/a	0.8	0.8
Water consumed	*l/kWh*	n/a	n/a	n/a	6	6
Water withdrawn	*l/kWh*	n/a	n/a	n/a	141	141
Evolution						
Max potential	*GWe*	n/a	n/a	n/a	1	10

The CAPEX estimate includes the following cost components for Gen IV LFR nuclear technology:

☒ Civil and structural costs
☒ Major equipment costs
☒ Balance of plant costs
☒ Electrical and I&C supply and installation
☒ Project indirect costs
☒ Development costs
☐ Interconnection costs
☒ Insurance costs

Table 38. Lead-cooled fast reactor.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	n/a	n/a	n/a	600	600
Gross electrical power	*MW*	n/a	n/a	n/a	-	-
Thermal power	*MW*	n/a	n/a	n/a	1430	1430
Max. capacity factor	*%*	n/a	n/a	n/a	85	85
Avg. capacity factor	*%*	n/a	n/a	n/a	-	-
Technical lifetime	*years*	n/a	n/a	n/a	60	60
Net efficiency	*%*	n/a	n/a	n/a	42	42
Costs						
CAPEX ref	*$€_{2013}$/kWe*	n/a	n/a	n/a	4900	4500
CAPEX low	*$€_{2013}$/kWe*	n/a	n/a	n/a	4500	3800
CAPEX high	*$€_{2013}$/kWe*	n/a	n/a	n/a	7100	6500
Quality of CAPEX estimate		Low				
CAPEX learning rate	*%*	n/a	n/a	n/a	3.5	3.5
OM	*% CAPEX ref.*	n/a	n/a	n/a	2.1	2.1
FOM refurbishment	*% CAPEX ref.*	n/a	n/a	n/a	n/a	n/a
No. staff / year	*1*	n/a	n/a	n/a	450	450
Environmental						
Direct CO_2 emissions	*CO_2(eq)/GWh*	n/a	n/a	n/a	0	0
Indirect CO_2 emissions	*CO_2(eq)/GWh*	n/a	n/a	n/a	0.8	0.8
Water consumed	*l/kWh*	n/a	n/a	n/a	6	6
Water withdrawn	*l/kWh*	n/a	n/a	n/a	141	141
Evolution						
Max potential	*GWe*	n/a	n/a	n/a	1	10

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12 Smart grids

The smart grid is the evolvement of the electricity system that can intelligently integrate the actions of all users connected to it. The electricity system is decomposed in the production, transmission and distribution and the consumption. The transmission system is the high voltage long-distance connections when the distribution system is the medium and low voltage which is applied to the residential level. The transmission includes Alternating and Direct Current installations deployed underground, overhead or under the water and is the backbone of the electricity system.

The cost analysis below focuses on the transmission and distribution infrastructure costs and provides the rough estimated values from the references.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

12.1 Transmission

The transmission infrastructure transfers the bulk of electricity over longer distances. Most transmission lines are High Voltage Alternating Current (HVAC) with the installation of High Voltage Direct Current (HVDC) to be increased.

Table 39. Overhead transmission infrastructure cost that apply to 500 MVA installations.

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	60	60	60	60	60
Costs						
CAPEX ref	*€$_{2013}$/km*	800 000	565 000	510 000	480 000	450 000
CAPEX low	*€$_{2013}$/km*	700 000	530 000	460 000	400 000	350 000
CAPEX high	*€$_{2013}$/km*	900 000	590 000	560 000	550 000	540 000
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*% CAPEX ref.*	2	2	2	2	2

12.2 Distribution

The distribution system carries the electricity from the transmission to the consumers.

Table 40. Distribution lines of 20 kV.

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	40	40	40	40	40
Economical						
CAPEX ref	*€$_{2013}$/km*	12000	-	-	-	-
CAPEX low	*€$_{2013}$/km*	7000	-	-	-	-
CAPEX high	*€$_{2013}$/km*	16000	-	-	-	-
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	2	2	2	2	2
VOM	*€$_{2013}$/MWh*	-	-	-	-	-

12.3 Underground and submarine cables

The submarine power cables are components used for transmission of electricity under the sea. Their installation cost is higher compared to underground cables because additional challenges appear on the construction of marine environment resistant equipment and there is the need of sophisticated installation and maintenance tools (cable ships).

Table 41. Submarine cables.

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	40	40	40	40	40
Economical						
CAPEX ref	*€$_{2013}$/km*	3 000 000	2 600 000	2 400 000	2 200 000	2 100 000
CAPEX low	*€$_{2013}$/km*	3 000 000	2 400 000	2 100 000	1 900 000	1 700 000
CAPEX high	*€$_{2013}$/km*	3 000 000	2 800 000	2 600 000	2 500 000	2 500 000
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*% CAPEX ref.*	2	2	2	2	2

12.4 Back to back HVDC

The HVDC back to back technology is applied for the transmission of electricity in long distances, under the water and connecting electricity systems operating under different frequencies. The back to back HVDC includes only the converter stations.

Table 42. Back to back HVDC

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	80	80	80	80	80
Economical						
CAPEX ref	*€$_{2013}$/MW*	100 000	85 000	80 000	75 000	75 000
CAPEX low	*€$_{2013}$/MW*	100 000	90 000	85 000	85 000	90 000
CAPEX high	*€$_{2013}$/MW*	100 000	80 000	70 000	65 000	60 000
Quality of CAPEX estimate		medium				
VOM	*% CAPEX ref.*	3	2.8	2.5	2.2	2

12.5 Static VAR Compensators

The Static VAR compensators (SVC) are part of the Flexible Alternating Current Transmission Systems (FACTS) family. They provide voltage support, harmonic protection, and consequently increase the stability of the system. The installation of SVC delays the need of the transmission system expansion.

Table 43. Static VAR compensators.

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	-	-	-	-	-
Economical						
CAPEX ref	*€$_{2013}$/kVAr*	39	35	32	28	26
CAPEX low	*€$_{2013}$/kVAr*	39	37	35	33	32
CAPEX high	*€$_{2013}$/kVAr*	39	33	29	25	21
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	-	-	-	-	-
VOM	*% CAPEX ref.*	-	-	-	-	-

12.6 Static synchronous compensators

A STAtic synchronous COMpensator (STATCOM) belongs to the FACTS family. It provides the same type of services as the SVCs, but is offers better behaviour due to the use of IGBTs power electronic devices. The installation of STATCOM delays the need of the transmission system expansion.

Table 44. STAtic synchronous COMpensator (STATCOM)

	Unit	2013	2020	2030	2040	2050
Technical						
Technical lifetime	*years*	-	-	-	-	-
Economical						
CAPEX ref	*€$_{2013}$/kVAr*	55	60	53	48	40
CAPEX low	*€$_{2013}$/kVAr*	55	64	58	55	50
CAPEX high	*€$_{2013}$/kVAr*	55	57	48	40	35
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	-	-	-	-	-
VOM	*% CAPEX ref.*	-	-	-	-	-

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13 Bioenergy power generation

The technologies in use for bioenergy power generation are mostly based on mature direct combustion boiler and steam turbine systems. While biomass-only systems exist, the vast majority of biomass is currently co-combusted with coal in existing power plants. This has mostly economic advantages but also technological ones. In fact conversion efficiency is generally higher for co-fired biomass than for biomass-only plants. Economically, most biomass technologies have difficulties in competing with fossil fuels: technologies are less mature and feedstocks are costly. Furthermore, one of the key issues for large-scale bioenergy development is the availability and mobilization of biomass.

Bioenergy is often regarded as a CO_2-neutral technology, under the assumption that the CO_2 emitted at combustion was previously absorbed by the growing plant. However, it is not to be forgotten that the combustion of biomass actually physically generates larger amounts of CO_2 than most fossil fuels. This is due to a lower energy density compared to fossil fuels. For this reason, in the tables below, the "direct GHG emissions" should be interpreted as the CO_2 emissions at the point of combustion. In traditional energy modelling, these emissions will not be included.

The value indicated as "indirect GHG emissions" instead includes the supply chain emissions associated to the production of bioenergy. These values reflect a general average of the default GHG emissions values reported in more details in (JRC, 2014). However, values change largely depending on the biomass feedstock (forest biomass, energy crops and wood industry residues), the transport distance (intra-EU or imported biomass) and production processes (chips, pellets). For disaggregated values and methodological details please refer to that work. These values do not include possible indirect effects or market mediated impacts of bioenergy such as indirect land use change or material displacement from other industries. Also, these values do not include any contribution from eventual land use emissions. For all details please see (JRC, 2014).

All of the technologies described below can be associated with some sort of CCS technology exactly as plants burning fossil fuels. Bio-CCS plants are currently indicated as one of the very few carbon-negative options for power generation. However, this is still in the pilot phase (see section 8.7 or the 2013 Technology Map for details on CCS technology).

The CAPEX estimate includes the following cost components:

☒ Civil and structural costs
☒ Major equipment costs
☒ Balance of plant costs
☒ Electrical and I&C supply and installation
☒ Project indirect costs
☒ Development costs
☐ Interconnection costs
☐ Insurance costs

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

[a] Considering a carbon content of wood = 0.5 kg C/kg dry wood and an energy content equal to 19 MJ/kg dry wood. The result is the emission of 1.83 kg CO_2/kg dry wood. This value needs to be then divided by the final conversion considered.

13.1 Grate furnace steam turbine

This is the standard and simpler technology for stand-alone biomass power plants.

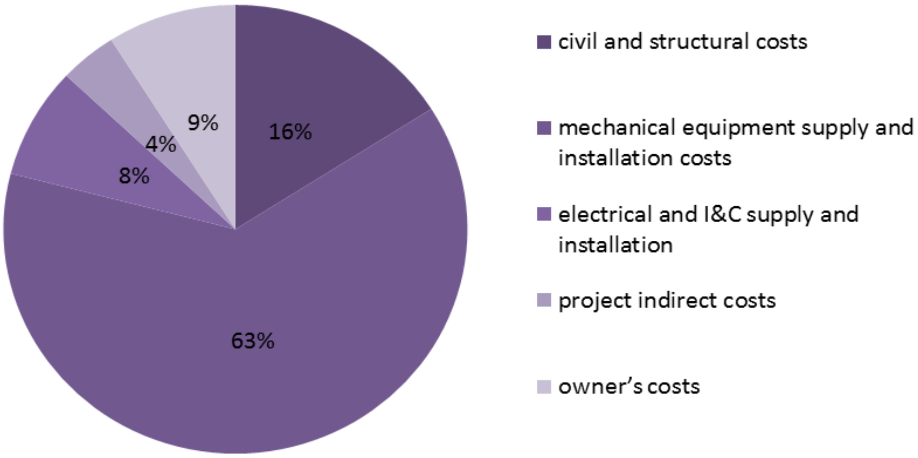

Figure 14. CAPEX breakdown of biomass grate furnace

Table 45. Grate furnace

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	50	50	50	50	50
Gross electrical power	*MW*	55	55	55	55	55
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	70	70	70	70	70
Technical lifetime	*years*	25	25	25	25	25
Net efficiency	*%*	34	35	36	38	38
Economical						
CAPEX ref	*€$_{2013}$/kWe*	2890	2620	2370	2150	1950
CAPEX low	*€$_{2013}$/kWe*	2500	2250	2020	1820	1640
CAPEX high	*€$_{2013}$/kWe*	3900	3500	3140	2810	2520
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*					
FOM	*% CAPEX ref.*	2.2	2.2	2.2	2.2	2.2
FOM refurbishment	*% CAPEX ref.*	1.1	1.1	1.1	1.1	1.1
VOM	*€$_{2013}$/MWh*	3.5	3.5	3.5	3.5	3.5
Labour cost during construction/installation	*% CAPEX ref.*	1.1	1.1	1.1	1.1	1.1
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	1031	1003	954	920	914
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	165[a]	161	153	147	146
Water consumed	*l/kWh*	2.1	2.1	2.1	2.1	2.1
Water withdrawn	*l/kWh*	3.3	3.3	3.3	3.3	3.3
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] For comparison, the Fossil Fuel Comparator for electricity as reported in the SWD(2014) 259 is equal to 670 tCO_2(eq.)/GWh.

[a] Values are calculated based on an average value of 56 tCO2 (eq.)/GWh of biomass at plant gate and then divided by the conversion efficiency reported above and time-dependent.

[a] The "total GHG emissions" value does not include direct emissions since these will be typically excluded from energy systems modelling.

13.2 Fluidised bed boiler

This technology employs a fluidized bed boiler with either a bubbling (BFB) or a circulating bed (CFB). It is generally associated to a Rankine cycle with steam turbine. Compared to grate furnace boilers, larger scales can be achieved, with the same large fuel flexibility and with a higher conversion efficiency of the feedstock to heat.

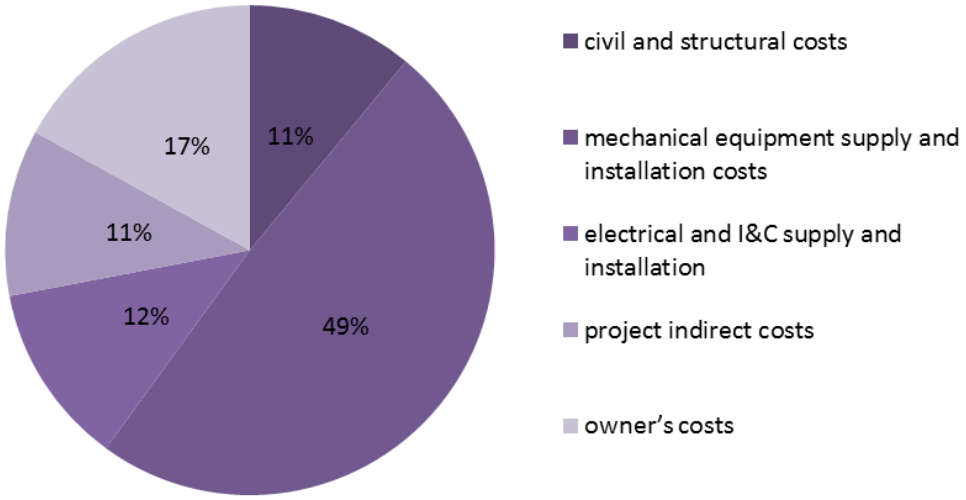

Figure 15. CAPEX breakdown of fluidised bed boiler.

Table 46. Fluidised bed boiler (circulating or bubbling) plus steam turbine

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	50	50	50	50	50
Gross electrical power	*MW*	55	55	55	55	55
Max. capacity factor	*%*	-	-	-	-	-
Avg. capacity factor	*%*	-	-	-	-	-
Technical lifetime	*years*	25	25	25	25	25
Net efficiency	*%*	35	36	37	38	39
Economical						
CAPEX ref	*€$_{2013}$/kWe*	2960	2620	2330	2060	1830
CAPEX low	*€$_{2013}$/kWe*	1760	1540	1350	1190	1040
CAPEX high	*€$_{2013}$/kWe*	3610	3170	2780	2440	2140
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	1.8	1.8	1.8	1.8	1.8
FOM refurbishment	*% CAPEX ref.*	0.9	0.9	0.9	0.9	0.9
VOM	*€$_{2013}$/MWh*	3.8	3.8	3.8	3.8	3.8
Labour cost during construction/installation	*% CAPEX ref.*	0.9	0.9	0.9	0.9	0.9
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	992	965	939	914	891
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	159	154	150	146	143
Water consumed	*l/kWh*	2.1[a]	2.1	2.1	2.1	2.1
Water withdrawn	*l/kWh*	3.3[b]	3.3	3.3	3.3	3.3
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] Cooling tower

[b] Cooling tower

13.3 Biomass IGCC

The biomass IGCC (Integrated Gasification Combined Cycle) is still in the pilot stage. It employs a gasifier to produce syngas. This is then combusted in a gas turbine. The hot flue gases from the gas turbine are passed through a heat recovery boiler where additional steam is produced and additional electricity is generated with a steam turbine.

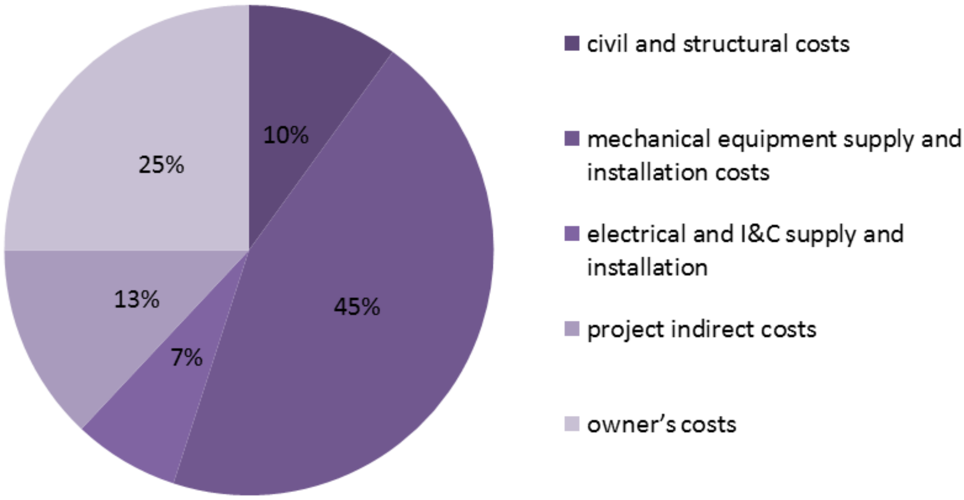

Figure 16. CAPEX breakdown of IGCC with CCS.

Table 47. Biomass IGCC.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	20	20	20	20	20
Gross electrical power	*MW*	24	24	24	24	24
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	70	70	70	70	70
Technical lifetime	*years*	25	25	25	25	25
Net efficiency	*%*	35	37	43	47	48
Economical						
CAPEX ref	*€$_{2013}$/kWe*	4810	3810	3140	2840	2560
CAPEX low	*€$_{2013}$/kWe*	1760	1390	1230	1090	970
CAPEX high	*€$_{2013}$/kWe*	5530	4380	3640	3260	2930
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*					
FOM	*% CAPEX ref.*	2.2	2.2	2.2	2.2	2.2
FOM refurbishment	*% CAPEX ref.*	1.1	1.1	1.1	1.1	1.1
VOM	*€$_{2013}$/MWh*	8.2	8.2	8.2	8.2	8.2
Labour cost during construction/installation	*% CAPEX ref.*	1.1	1.1	1.1	1.1	1.1
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	856	824	769	730	723
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	137	132	123	117	116
Water consumed	*l/kWh*	2.1[a]	2.1	2.1	2.1	2.1
Water withdrawn	*l/kWh*	3.3[b]	3.3	3.3	3.3	3.3
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] Cooling tower

[b] Cooling tower

13.4 Anaerobic digestion (AD)

The anaerobic digestion technology employs bacteria to digest anaerobically the organic fraction of biomass (mostly cellulose and hemi-cellulose). Various feedstocks can be used, from energy crops to manures to food waste. The feedstock has a certain influence on the CAPEX. In this analysis an average cost is presented. The variability of the data can be partially explained with the costs of the plants using different feedstocks rather than with uncertainty of the data available.

The values in this category mainly include on-farm plants; other applications such as biogas production from landfills and from water treatment plants are not included.

Anaerobic digestion is a mature technology and in the last years significant investments and capacity expansion has occurred in some Member States (JRC, 2014). The main technology analysed here is the combustion of biogas in reciprocating gas engines for the generation of power and, potentially, heat. An alternative plant configuration includes a step for biogas upgrading to biomethane and injection into the natural gas grid. This is not covered in this section even though the upstream technology, up to the digester, is basically the same.

The GHG emissions associated to this technology are highly dependent on the substrate mix that is fed into the digester. Energy crops, in fact, carry the burden of the cultivation emissions, while manures can even have negative emissions since digestion is better in terms of GHG emissions than the management of raw manures. For this reason, a general number is not given in the table. Detailed GHG emissions results can be found in (JRC, 2014). Indicatively, emissions from electricity produced from AD of maize vary between 146 tCO_2 (eq.)/GWh and 603 tCO_2 (eq.)/GWh. Emissions from electricity produced from AD of manure on the other hand vary between -922 tCO_2 (eq.)/GWh and 122 tCO_2 (eq.)/GWh.

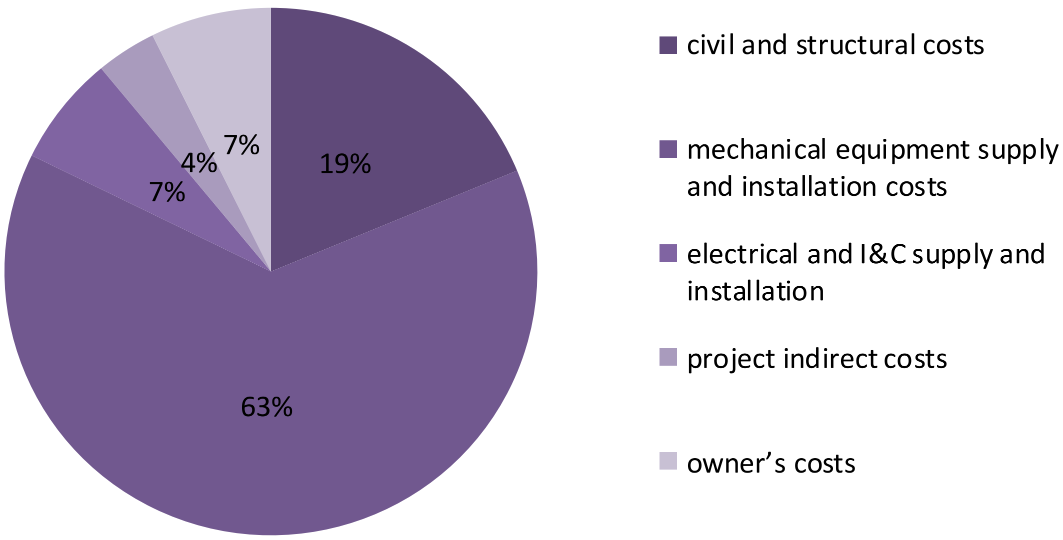

Figure 17. CAPEX breakdown of anaerobic digestion.

Table 48. Anaerobic digestion.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	1	1	1	1	1
Gross electrical power	*MW*	1.1	1.1	1.1	1.1	1.1
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	70	70	70	70	70
Technical lifetime	*years*	20	20	20	20	20
Net efficiency	*%*	36	38	40	42	45
Economical						
CAPEX ref	$€_{2013}$/kWe	3880	3180	2760	2520	2300
CAPEX low	$€_{2013}$/kWe	2540	2080	1700	1530	1380
CAPEX high	$€_{2013}$/kWe	6380	5210	4260	3830	3450
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*					
FOM	*% CAPEX ref.*	4.1	4.1	4.1	4.1	4.1
FOM refurbishment	*% CAPEX ref.*	2.0	2.0	2.0	2.0	2.0
VOM	$€_{2013}$/MWh	3.1	3.1	3.1	3.1	3.1
Labour cost construction/installation	*% CAPEX ref.*	2.0	2.0	2.0	2.0	2.0
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	-	-	-	-	-
Indirect GHG emissions	$tCO_2(eq)/GWh$	79	-	-	-	-
Water consumed	*l/kWh*	0.5[a]	0.5	0.5	0.5	0.5
Water withdrawn	*l/kWh*	-	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] Cooling tower

13.5 Municipal solid waste incinerator

Incineration of Municipal Solid Waste (MSW) generally employs moving grate furnaces. MSW incineration plants have to sustain higher costs because of the advanced flue gas cleaning systems required. Also, high fuel handling costs should be considered.

When the organic fraction of MSW is separated from the rest of the materials, either at the collection plant or source-separated, incineration is an alternative with the anaerobic digestion. However, when MSW is not separated, digestion may not be possible and incineration is left as the sole alternative.

Table 49. MSW incinerator.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	50	50	50	50	50
Gross electrical power	*MW*	60	60	60	60	60
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	80	80	80	80	80
Technical lifetime	*years*	25	25	25	25	25
Net efficiency	*%*	27	31	34	37	42
Economical						
CAPEX ref	€$_{2013}$/kWe	6080	5630	5240	4870	4540
CAPEX low	€$_{2013}$/kWe	4900	4430	4010	3630	3280
CAPEX high	€$_{2013}$/kWe	8870	8020	7260	6560	5940
Quality of CAPEX estimate		high				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	3	3	3	3	3
FOM refurbishment	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	€$_{2013}$/MWh	6.9	6.9	6.9	6.9	6.9
Labour cost construction/installation	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
Environmental						
Direct GHG emissions	$tCO_2(eq)/GWh$	-	-	-	-	-
Indirect GHG emissions	$tCO_2(eq)/GWh$	-	-	-	-	-
Water consumed	*l/kWh*	2.1[a]	2.1	2.1	2.1	2.1
Water withdrawn	*l/kWh*	3.3[b]	3.3	3.3	3.3	3.3
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] It is very difficult to generalize a value of GHG emissions for MSW incineration due to the variability of materials, supply chains composition and other parameters. Conventionally organic fraction of MSW is considered to be carbon-neutral and no CO2 emissions are accounted for its combustion. Furthermore, the upstream processes leading to the supply of of MSW to the incineration plant could be allocated to the waste collection rather than to the bioenergy production pathway. With these assumptions, the GHG emissions actually associated to the combustion of organic municipal waste incineration would be very low.

[a] Cooling tower

[a] Cooling tower

13.6 Co-firing of biomass and coal

Co-firing of biomass with coal can be achieved with various technological configurations, e.g. direct and indirect co-firing. The additional (marginal) investment costs are limited. The costs reported in Table 50 are considered to be marginal costs for the additional equipment required for biomass handling and, eventually, combustion.

GHG emissions should also be considered as marginal, so associated only to the biomass combusted. These are equal to the ones given earlier (see Table 45 for example) but generally with higher conversion efficiencies than biomass-only installations.

Table 50. Retro-fitting co-firing (pulverized coal furnace or fluid bed)

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	-	-	-	-	-
Gross electrical power	*MW*	-	-	-	-	-
Max. capacity factor	*%*	90	90	90	90	90
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	-	-	-	-	-
Net efficiency	*%*	37	39	40	41	43
Economical						
CAPEX ref	*€$_{2013}$/kWe*	500	460	420	390	360
CAPEX low	*€$_{2013}$/kWe*	200	180	160	150	130
CAPEX high	*€$_{2013}$/kWe*	1150	1050	960	890	830
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	5.2	5.2	5.2	5.2	5.2
FOM refurbishment	*% CAPEX ref.*	2.6	2.6	2.6	2.6	2.6
VOM	*€$_{2013}$/MWh*	-	-	-	-	-
Labour cost construction/installation	*% CAPEX ref.*	2.6	2.6	2.6	2.6	2.6
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Water consumed	*l/kWh*	2.1[a]	2.1	2.1	2.1	2.1
Water withdrawn	*l/kWh*	3.3[b]	3.3	3.3	3.3	3.3
Evolution						
Max potential	*GWe*	-	-	-	-	-

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[a] Cooling tower

[b] Cooling tower

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14 Cogeneration

Cogeneration is the simultaneous generation of electric power and useful thermal heat from a single heat source. Cogeneration can be done with conventional fossil fuel sources, nuclear, and renewables like biomass, geothermal, and solar STEP. Cogeneration can assist in balancing variable renewable electricity production.

14.1 Biomass CHP

Biomass CHP incorporates various boiler technologies that make use of the waste heat.

The CAPEX estimate includes the following cost components:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☒ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☐ Interconnection costs
- ☐ Insurance costs

Table 51. Biomass CHP.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	75	-	-	-	-
Gross electrical power	*MW*	83	-	-	-	-
Max. capacity factor	*%*	90	-	-	-	-
Avg. capacity factor	*%*	65	67.5	67.5	72.5	72.5
Technical lifetime	*years*	25	-	-	-	-
Net efficiency	*%*	30	-	-	-	-
Economical						
CAPEX ref	*€$_{2013}$/kWe*	3670	3300	2990	2750	2540
CAPEX low	*€$_{2013}$/kWe*	3800	3130	2750	2450	2180
CAPEX high	*€$_{2013}$/kWe*	5510	4580	4020	3560	3150
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	2.3	2.3	2.3	2.3	2.3
FOM refurbishment	*% CAPEX ref.*	1.1	1.1	1.1	1.1	1.1
VOM	*€$_{2013}$/MWh*	3.3	3.3	3.3	3.3	3.3
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	805	-	-	-	-
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	93	-	-	-	-
Water consumed	*l/kWh*	2.1	-	-	-	-
Water withdrawn	*l/kWh*	3.3	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

14.2 CCGT CHP

Combined Cycle Gas Turbine (CCGT) is the dominant gas-based technology. It uses the exhausts from the gas cycle to heat up water to produce steam. The CCGT conventional CHP is expected to be replaced by the CCGT advanced CHP in the future, hence no projections for CCGT conventional are made after 2010.

The CAPEX estimate includes the following cost components:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☐ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

Table 52. CCGT conventional CHP.

	Unit	2013	2020	2030	2040	2050
Technical						
Gross thermal capacity	*MW*	710	n/a	n/a	n/a	n/a
Efficiency @peak elec. load	*%*	42	n/a	n/a	n/a	n/a
Efficiency @peak thermal Load	*%*	35	n/a	n/a	n/a	n/a
Max. capacity factor	*%*	93	n/a	n/a	n/a	n/a
Avg. capacity factor	*%*	89	n/a	n/a	n/a	n/a
Technical lifetime	*years*	30	n/a	n/a	n/a	n/a
Economical						
CAPEX ref	*€$_{2013}$/kWe*	880	n/a	n/a	n/a	n/a
CAPEX low	*€$_{2013}$/kWe*	700	n/a	n/a	n/a	n/a
CAPEX high	*€$_{2013}$/kWe*	1060	n/a	n/a	n/a	n/a
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	4	n/a	n/a	n/a	n/a
FOM	*% CAPEX ref.*	8.5	n/a	n/a	n/a	n/a
FOM refurbishment	*% CAPEX ref.*	1.3	n/a	n/a	n/a	n/a
VOM	*€$_{2013}$/MWh*	2.4	n/a	n/a	n/a	n/a
No. staff	*1*	31	n/a	n/a	n/a	n/a
Environmental						
Direct GHG emissions	tCO_2(eq)/GWh	269	n/a	n/a	n/a	n/a
Indirect GHG emissions	tCO_2(eq)/GWh	54	n/a	n/a	n/a	n/a
Water consumed	l/kWh	0.01	n/a	n/a	n/a	n/a
Water withdrawn	l/kWh	0.01	n/a	n/a	n/a	n/a
Evolution						
Max potential	GWe	-	n/a	n/a	n/a	n/a

The CAPEX estimate for CCGT advanced CHP includes the following cost components:

- ☒ Civil and structural costs
- ☒ Major equipment costs
- ☐ Balance of plant costs
- ☒ Electrical and I&C supply and installation
- ☒ Project indirect costs
- ☒ Development costs
- ☒ Interconnection costs
- ☐ Insurance costs

Table 53. CCGT advanced CHP.

	Unit	2013	2020	2030	2040	2050
Technical						
Gross thermal capacity	*MW*	480	463	446	435	431
Efficiency @peak elec. Load	*%*	57	59	61	62	63
Efficiency @peak ther. Load	*%*	45	46	47	48	49
Max. capacity factor	*%*	96	96	96	96	96
Avg. capacity factor	*%*	86	86	86	86	86
Technical lifetime	*years*	30	30	30	30	30
Economical						
CAPEX ref	*€$_{2013}$/kWe*	1010	1000	990	980	970
CAPEX low	*€$_{2013}$/kWe*	900	870	850	840	830
CAPEX high	*€$_{2013}$/kWe*	1240	1210	1180	1160	1150
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	4	4	3	3	3
FOM	*% CAPEX ref.*	3.9	3.9	3.9	3.9	3.9
FOM refurbishment	*% CAPEX ref.*	1.3	1.3	1.3	1.3	1.3
VOM	*€$_{2013}$/MWh*	4	4	4	4	4
No. staff	*1*	31	31	31	31	31
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	232	230	227	224	222
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	47	46	46	45	45
Water consumed	*l/kWh*	0.01	0.01	0.01	0.01	0.01
Water withdrawn	*l/kWh*	0.01	0.01	0.01	0.01	0.01
Evolution						
Max potential	*GWe*	-	-	-	-	-

14.3 Steam turbine coal supercritical CHP

The emissions are calculated per unit of useful heat.

The CAPEX estimate for CCGT advanced CHP includes the following cost components:

☒ Civil and structural costs	☒ Project indirect costs
☒ Major equipment costs	☒ Development costs
☐ Balance of plant costs	☒ Interconnection costs
☒ Electrical and I&C supply and installation	☐ Insurance costs

Table 54. Steam turbine coal supercritical CHP

	Unit	2013	2020	2030	2040	2050
Technical						
Gross thermal capacity	*MW*	1250	1200	1170	1150	1120
Efficiency @peak elec. load	*%*	39	41	42	43	43
Efficiency @peak ther. load	*%*	-	-	-	-	-
Max. capacity factor	*%*	95	95	95	95	95
Avg. capacity factor	*%*	85	85	85	85	85
Technical lifetime	*years*	35	35	35	35	35
Economical						
CAPEX ref	*€$_{2013}$/kWe*	2030	2030	2030	2030	2030
CAPEX low	*€$_{2013}$/kWe*	1940	1940	1940	1940	1940
CAPEX high	*€$_{2013}$/kWe*	2210	2210	2210	2210	2210
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	7	6	5	5	5
FOM	*% CAPEX ref.*	-	-	-	-	-
FOM refurbishment	*% CAPEX ref.*	-	-	-	-	-
VOM	*€$_{2013}$/MWh*	5.1	5.1	5.1	5.1	5.1
No. staff	*1*	94	92	90	88	86
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	406	397	392	388	383
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	48	47	47	46	46
Water consumed	*l/kWh*	0.01	0.01	0.01	0.01	0.01
Water withdrawn	*l/kWh*	0.01	0.01	0.01	0.01	0.01
Evolution						
Max potential	*GWe*	-	-	-	-	-

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15 Hydrogen and fuel cells

A fuel cell system can either use pure hydrogen directly or a hydrogen rich gas from a fuel processor to produce electricity and heat through the fuel cell stack. Fuel cells are converting hydrogen rich gases electrochemically and can therefore reach high efficiencies. Fuel cell systems can be used in stationary, automotive and portable applications and can be fabricated from different materials. Proton exchange membrane, solid oxide and molten carbonate fuel cell technologies are presented below for stationary applications that use natural gas.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technical status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

15.1 Proton exchange membrane CHP fuel cells

Proton exchange membrane fuel cell systems are, among other applications, suited to provide residential heat and power.

Table 55. PEM CHP fuel cells.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	0.0008	0.0008	0.0008	0.0008	0.0008
Gross capacity	*MW*	0.0022	0.0022	0.0022	0.0022	0.0022
Electrical efficiency @peak electrical load	*%*	36	37	38	39	39
Electrical efficiency @peak thermal load	*%*	-	-	-	-	-
Thermal efficiency @peak thermal load	*%*	52	52	52	52	52
Heat to power ratio	*1*	1.4	1.4	1.4	1.3	1.3
Max. capacity factor	*%*	98	99.7	99.7	99.7	99.7
Avg. capacity factor	*%*	-	-	-	-	-
Technical lifetime	*years*	3.3	3.3	5	7.5	10
Costs						
CAPEX ref	*€$_{2013}$/kWe*	50000	15000	11500	8500	7800
CAPEX low	*€$_{2013}$/kWe*	47500	14250	10920	8070	7410
CAPEX high	*€$_{2013}$/kWe*	52500	15750	12070	8920	8190
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	0	0	0	0	0
VOM*	*€$_{2013}$/MWh*	200	115	70	50	45
Environmental						
Direct GHG emissions	*$tCO_2(eq)$/GWh*	-	-	-	-	-
Indirect GHG emissions	*$tCO_2(eq)$/GWh*	-	-	-	-	-
Water consumed	*l/kWh*	-	-	-	-	-
Water withdrawn	*l/kWh*	-	-	-	-	-

* Includes, annual O&M as well as fuel cell stack replacements to enable extension of the technical lifetime to the economic lifetime

15.2 Solid oxide fuel cells CHHP

Solid oxide fuel cell systems are suited to provide electricity and heat (at high quality).

Table 56. SOFC CHHP fuel cells.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power	*MW*	0.05	0.05	0.05	0.05	0.05
Gross capacity	*MW*	0.09	0.09	0.09	0.08	0.08
Electrical efficiency @peak electrical load	*%*	53	53	55	59	61
Electrical efficiency @peak thermal load	*%*	-	-	-	-	-
Thermal efficiency @peak thermal load	*%*	32	32	32	34	34
Heat to power ratio	*1*	0.6	0.6	0.58	0.57	0.56
Max. capacity factor	*%*	98	98	98	98	98
Avg. capacity factor	*%*	-	-	-	-	-
Technical lifetime	*years*	3.3	3.3	7.5	7.5	10
Costs						
CAPEX ref	*€$_{2013}$/kWe*	18000	6300	4000	2550	1850
CAPEX low	*€$_{2013}$/kWe*	17100	5980	3800	2420	1760
CAPEX high	*€$_{2013}$/kWe*	18900	6610	4200	2680	1940
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	0	0	0	0	0
VOM*	*€$_{2013}$/MWh*	120	65	25	10	8
Environmental						
Direct GHG emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Water consumed	*l/kWh*	-	-	-	-	-
Water withdrawn	*l/kWh*	-	-	-	-	-

* Includes, annual O&M as well as fuel cell stack replacements to enable extension of the technical lifetime to the economic lifetime

15.3 Molten carbonate fuel cell

Molten carbonate fuel cells are suited to provide electricity and heat (at high quality).

Table 57. MCFC CHHP fuel cells.

	Unit	2013	2020	2030	2040	2050
Technical						
Net electrical power AC	*MW*	1.4	1.4	1.4	1.4	1.4
Gross capacity	*MW*	3.0	2.9	2.8	2.7	2.7
Electrical efficiency @peak electrical load	*%*	47	48	50	51	51
Electrical efficiency @peak thermal load	*%*	-	-	-	-	-
Thermal efficiency @peak thermal load	*%*	37	38	39	41	41
Heat to power ratio	*1*	0.79	0.79	0.79	0.80	0.80
Max. hydrogen production capacity	*kg/h*	-	-	-	-	-
Max. capacity factor	*%*	98	98	98	98	98
Avg. capacity factor	*%*	-	-	-	-	-
Technical lifetime	*years*	5	7	7	10	10
Economic lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€$_{2013}$/kWe*	3570	2680	2080	1870	1740
CAPEX low	*€$_{2013}$/kWe*	3390	2540	1980	1780	1660
CAPEX high	*€$_{2013}$/kWe*	3750	2810	2190	1960	1830
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	-	-	-	-	-
FOM	*% CAPEX ref.*	0	0	0	0	0
VOM[*]	*€$_{2013}$/MWh*	40	25	23	16	16
Environmental						
Direct CO2 emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Indirect GHG emissions	*$tCO_2(eq)/GWh$*	-	-	-	-	-
Water consumed	*l/kWh*	-	-	-	-	-
Water withdrawn	*l/kWh*	-	-	-	-	-

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DOE Hydrogen and Fuel Cells Program: Fuel Cell Power Model Case Study Data, available at: http://www.hydrogen.energy.gov/fc_power_analysis.html

Strategic Analysis Inc. (2012), Manufacturing Cost Analysis of Stationary Fuel Cell Systems

[*] Includes, annual O&M as well as fuel cell stack replacements to enable extension of the technical lifetime to the economic lifetime

16 Electricity storage

Energy storage technologies include a large number of technologies that are or could be used in various applications: in support of the power generation technologies, to provide specific services to the market in order to reduce electricity prices during specific hours of the day, add flexibility to the power system, contribute to the integration of distributed energy systems. The mechanism at the basis of each storage technologies is to allow shift in power production or consumption from one time/place to another, in other to satisfy demand of power and guarantee the equalization of generation and consumption at any time.

The major challenge around the development of energy storage technologies is due to the fact that electricity can only be stored after being converted into other forms of energy, which involves the installation of expensive equipment and energy losses. According to some studies (Römer, Benedikt, et al. 2012, Vytelingum, Perukrishnen, et al 2010) the main drivers of electricity storage technologies have been identified in: Increasing needs of flexibility for the system due to an increase in the share of renewable generation; decrease the costs of peak generation by reducing the use of existing ones or avoiding the building of new ones; add stability and flexibility in smart power system.

Pump-hydro storage is the most deployed and commercially available storage technology, which counts 110 GW installed capacity worldwide. Among PHS installations, 38 GW are located in EU, 25 GW in Japan and 22 GW in United States. Storage needs seams to increase in the future though. IEA ETP 2008 high share wind generation scenario estimates the need of storage capacity in Western Europe to be between 0 and 90 GW in the presence of 5% and 30% wind generation.

The storage technologies can be characterized into two categories: the ones which have the ability to store energy over time (several hours) and the ones which have the ability to deliver power very fast. Storage technologies can be used for either short-term applications, such as for example frequency control, or long-term applications, such as load shifting. In general, storage technologies need to be rated at a higher power capacity (MW) over energy storage capacity (MWh) when they are tailored for short-term applications. In this case the power output to energy storage capacity ratio[a] (OtC) is ≥1 and the storage system belongs to the macro-category of “power systems” (Bloomberg NEF 2014). In case of long term applications, the storage technology has a higher energy storage capacity over the output capacity. In this case the output to capacity ratio (OtC) is <1 and the technology belongs to the “energy storage systems”, see Table 58.

This simple categorization turns out to be useful in case of modelling storage technologies for different applications. The table below contains a simple guide on how technical parameters of storage technologies are typically tailored for each service/applications provided.

[a] The *output to capacity* ratio (OtC) is an indicator for capacity utilization. It identifies the relationship between power capacity and energy storage capacity of a storage technology. When OtC is ≥1 the system is generally identified as a power system, while OtC is <1 the system belongs to the energy system technologies. (Bloomberg NEF 2014).

Table 58. Power/energy ratio and typical storage applications.

OtC	Technical parameters	Application	Example
≥1	MW≥MWh	Power system	Short-term applications, e.g. frequency control
<1	MW<MWh	Energy system	Long-term applications, e.g. load shifting

The energy storage technologies included in this report are:

1. Mechanical storage: CAES, PHS, Flywheels;
2. Chemical and electro-chemical storage: Sodium sulphur battery (NaS), Lead-acid battery (Pb-acid), Lithium-ion battery (Li-ion), Vanadium Redox battery;
3. Thermal energy storage.

16.1 Compressed Air Energy Storage

Compressed air energy storage (CAES) is a power storage technology suitable for large-scale energy storage. This technology is based on storing electricity as the potential energy of compressed air. Air is then expanded to produce electricity. Compressed air is typically stored underground in suitable geological formations (salt, hard rock and porous rock or aquifer). Aboveground CAES – of 3 to 50 MW power capacity - are also possible but investment costs in this case are higher (+38 % EUR/kW and +61 % EUR/kWh, SANDIA 2013). There are three categories of CAES technologies, each of them using a different thermodynamic process:

1. diabatic CAES that pressurises and heat air by combusting fuel (usually natural gas) and expand it though turbo gas turbines to generate electricity;
2. isothermal CAES, that captures the heat from air compression and stores it in water until it is needed again for expansion. This continuous heat exchange of storing heat and reused for expansion, eliminates the need for a gas combustion turbine and improves efficiency by 70-90 % (EASE – EERA, 2013; BNEF 2011);
3. adiabatic CAES that uses the thermal energy generated during the compression of air is captured and stored in a thermal storage centre (which increases capital costs), thus eliminating fuel costs and increasing efficiency by 70 % (BNEF, 2011). The only project in the world is the German ADELE, undertaken jointly by RWE, General electric, Ed Zueblin and the German Aerospace Center.

Compared to other storage options, diabatic (underground) CAES has lower investment costs, larger storage capacity, and longer discharge durations. However building times are longer, the geological formation potential is not clear and efficiency is still low at around 40 %.

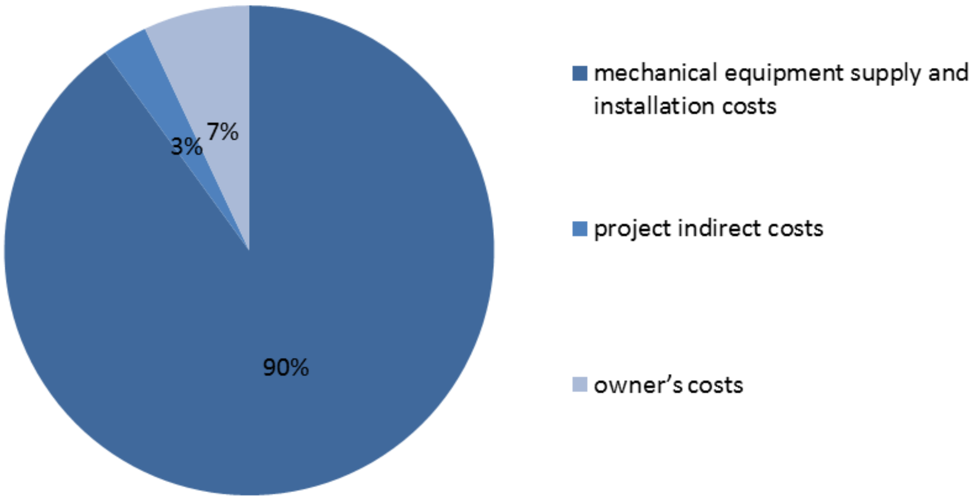

Figure 18. CAPEX breakdown of CAES for large scale energy storage.

Estimations of investment costs for the period 2020 – 2050 do not show real improvement (Black & Veatch for NREL, 2011). Investment cost projections for underground diabatic CAES reported in Table 59 have been estimated on the basis of the cost trend simulations made for Combined Cycle Gas Turbine (CCGT) in (NREL, 2010). This technology seams to well represent possible future cost improvement for diabatic CAES. According to (NREL, 2010), CCGT costs will decrease by 11 % in 2030, 4 % in 2040 and 11.7 % in 2050. This CCGT cost development trend has been applied to the CAES capital costs in each time period and reported in the table below.

Table 59. Diabatic underground compressed air storage (CAES) for large scale energy storage.

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	200	200	200	200	200
Charge efficiency	*%*	40	40	40	40	40
Storage capacity	*MWh*	3000	3000	3000	3000	3000
Min time for charging	*hours*	0.13	0.13	0.13	0.13	0.13
Technical lifetime	*years*	40	55[a]	55	55	55
Economical						
$CAPEX_{ref}$ (storage related)	*$€_{2013}$/kWe*	600	600	530	510	450
$CAPEX_{low}$ (storage related)	*$€_{2013}$/kWe*	350	350	310	300	260
$CAPEX_{high}$ (storage related)	*$€_{2013}$/kWe*	900	900	800	760	670
CAPEX (energy related)	*$€_{2013}$/MWh*	35000	35000	31060	29750	26250
Quality of CAPEX estimate				medium		
FOM	*% CAPEX ref.*	1.3	-	-	-	-
VOM	*$€_{2013}$/MWh*	1.2	-	-	-	-
Evolution						
Max potential	*GWe*	0.4	0.4-0.7	-	-	-

16.2 Flywheel Energy Storage

Flywheels are mechanical devices, where energy is stored as kinetic energy generated by a disk spinning on its axis. During discharging, the flywheel rotation drives the generator to produce electricity. Stored energy depends on flywheel diameter and the square of its rotational speed. This type of storage systems can sustain a large number of life cycles and be installed in any location. They usually have high power but lower energy capacity compared with other energy storage devices.

[a] EASE – EERA 2013

Typical single flywheel module size ranges between 100 kW and 250 kW with 5 kWh to 25 kWh storage capacity. Roundtrip efficiency varies between 80-90 %, with some devices providing up to 97 % roundtrip efficiency (SANDIA, 2003). Life cycle is generally of 100000 cycles or about ca 20 years. Flywheel energy storage systems can be of any size from 100 kW to multi-MW power plants for large scale grid support services. Depending on the specific site, more than 10 MW can be installed per hectare (Beacon Power[a]).

Flywheel systems are suitable for specific applications in different areas: transportation; in renewable energy generation, where MW size flywheel systems are used to stabilize power output, ensure grid stability, frequency regulation and voltage support; in industry, to provide back-up power to uninterruptible power systems (UPS), e.g. data centres, medical devices. Recent research studies have demonstrated that the use of flywheels complementing the operation of conventional technologies, such as batteries, can increase the life-cycle of the latter (EASE EERA, 2013).

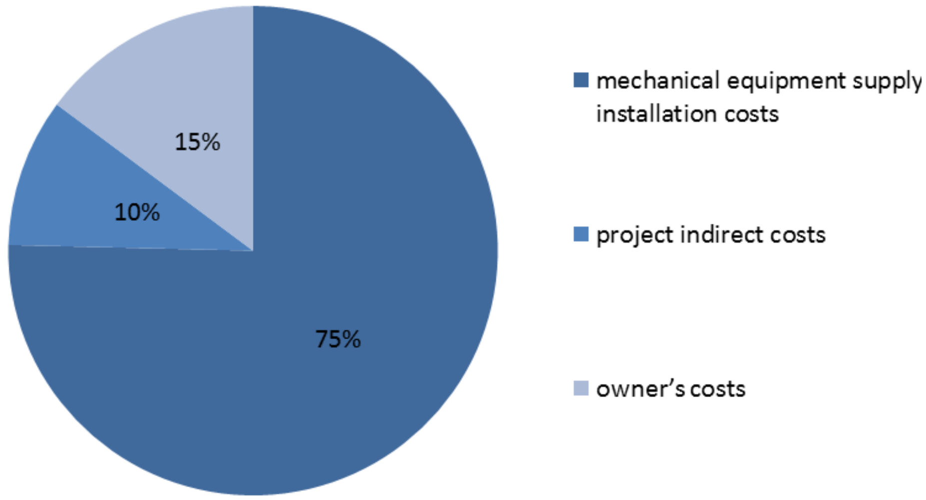

Figure 19. CAPEX breakdown of flywheel energy storage for frequency regulation.

[a] http://beaconpower.com/modular-design/

Table 60. Flywheel energy storage for frequency regulation (one module flywheel device)

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	20 (0.1 –0.25)[a]	-	-	-	-
Roundtrip efficiency	*%*	80 - 90	-	-	-	-
Storage capacity	*MWh*	5 (0.005-0.025) [b]	-	-	-	-
Min time for charging	*hours*	0.25 (from instantaneous to 0.08–0.12)	-	-	-	-
Technical lifetime	*years*	20	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*$€_{2013}$/kWe*	600	-	-	-	-
$CAPEX_{low}$ (storage related)	*$€_{2013}$/kWe*	250	-	-	-	-
$CAPEX_{high}$ (storage related)	*$€_{2013}$/kWe*	1000	-	-	-	-
CAPEX (energy related)	*$€_{2013}$/MWh*	3500000[c]	-	-	-	200000 - 500000[d]
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	1.4	-	-	-	-
VOM	*$€_{2013}$/MWh*	2	-	-	-	-
Evolution						
Max potential	GWe	0.025	-	-	-	-

16.3 Lithium-ion battery

Lithium-ion battery (li-ion) is a relatively new technology, compared for example to sodium sulphur batteries. They belong to the electro-chemical storage technologies and use lithium, which is the most electropositive and lightest metal. Li-ion batteries offer better performance with respect to efficiency rate, energy density and durability, along with the lowest self-discharge rates, compared to other electrical batteries. They are widely used for portable devices at relatively low prices and it is foreseen as the primary candidate also for electric vehicles and residential renewable systems application. Li-ion batteries for power grid applications frequency control as well as voltage support (T&D investment deferral is not an application: if the batteries provide voltage, then they will avoid T&D investment) are less deployed and still at demonstration stage of technological development, with a current world grid-connected installed capacity of 100 MW (IEA, 2014). At present their costs are around EUR 380/kW, as they cannot simply be scaled-up and need enhanced safety and reliability, although high learning rates (30 %) and large research efforts promise a rapid costs reduction.

Li-ion batteries installations can vary in size according to their application. Systems can range between 5 kW to 10 kW of power capacity generally used for distributed systems and up to 1-2 MW for frequency regulation. Storage capacity in large systems can be up to 4 MWh which are currently used in system trail demonstration in USA.

Capital costs projections reported in Table 61 have been estimated by applying the same cost improvement trend presented by Element energy 2012[e], based on the current costs of a generic Li-ion battery for power grid applications. According to the cited source, capital costs decrease of 66 % between 2010 and 2020 and of 14 % between 2020 and

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[a] Typical module size in paranethesis.

[b] Typical module size in paranethesis.

[c] Refers to high speed flywheels. For low speed flywheels the CAPEX is around EUR 250 000/MWh

[d] SET-Plan targets for flywheel technology towards 2030 and beyond, http//setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

[e] Element energy, Cost and performance of EV batteries, 2012 page 91.

2030. According to the cited source, costs between 2020 and 2030 decrease at a decreasing rate (79 %, which derives from (66 %-14 %)/66 %)). This means that some cost improvement is foreseen in these decades, but the improvement will be smaller and smaller. The same trend has been applied to estimate costs improvement in the period 2030-2040 and 2040-2050. According to this methodology, costs would decrease of 3 % between 2030 and 2040 and of 1 % in the following decade.

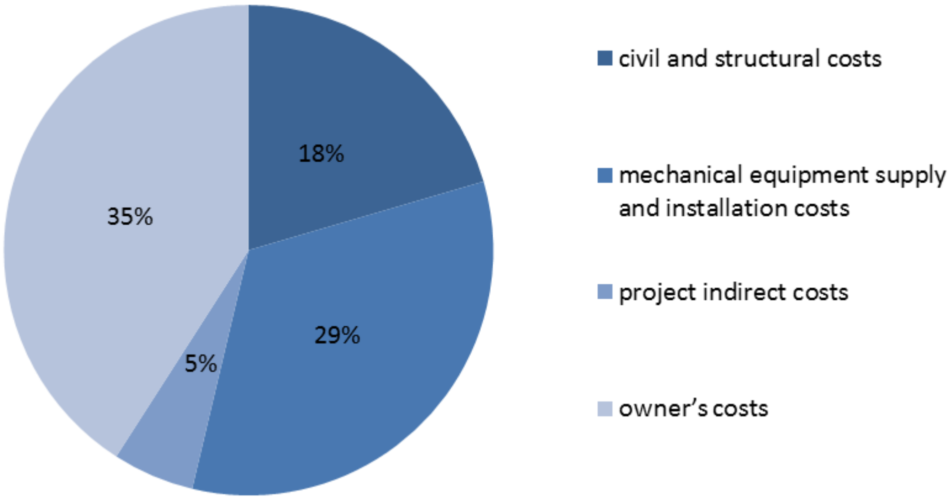

Figure 20. CAPEX breakdown for Li-ion battery for power grid applications.

Table 61. Li-ion storage battery for power grid applications

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	1-3	-	-	-	-
Roundtrip efficiency	*%*	90	-	-	-	-
Storage capacity	*MWh*	0.5–1.2	-	-	-	-
Min time for charging	*hours*	0.1	-	-	-	-
Min time for discharging	*hours*	0.25	-	-	-	-
Technical lifetime	*years*	10	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	490	170	140	140	140
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	390	130	110	110	110
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	590	200	170	165	160
CAPEX (energy related)	*€$_{2013}$/MWh*	752000	255000	205000	248700	245500
Quality of CAPEX estimate		medium				
CAPEX learning rate	*%*	30				
FOM	*% CAPEX ref.*	1.4	1.4	1.4	1.4	1.4
VOM	*€$_{2013}$/MWh*	2.6	2.6	2.6	2.6	2.6
Evolution						
Max potential	*GWe*	0.1	-	-	-	-

16.4 Sodium – sulphur battery

Sodium–sulphur (NaS) batteries are a commercial energy storage technology suitable for "energy" applications such as arbitrage. This technology is based on the sodium-sulphur reaction and requires high operation temperatures (between 300 and 360 °C). This type of electrochemical batteries is generally installed in large size of the orders of MW and has long energy storage duration. Most common NaS storage batteries are provided in multiple of 1 MW / 7 MWh.

NaS are used to provide a number of services, like frequency control, time shifting (or arbitrage), or are installed in hybrid generation systems for renewable integration (making these better dispatchable). The total installed capacity of NaS batteries is currently of 365 MW, located in more than 170 sites globally (SANDIA, 2013; EASE-EERA, 2013).

CAPEX costs and roundtrip efficiency projections for 2020-50 in Table 62 come from the estimation reported in (Black&Veatch for NREL, 2012) and refer to a generic sodium sulphide battery of 7.2 MW.

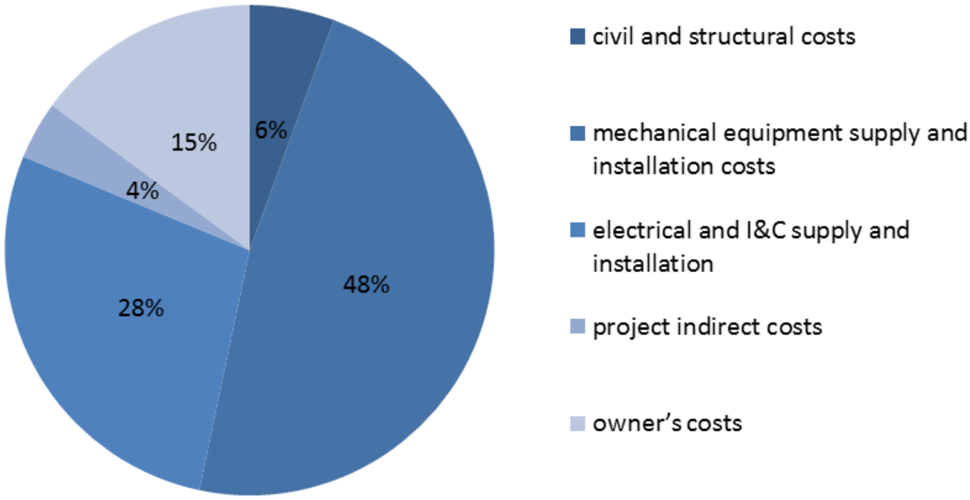

Figure 21. CAPEX breakdown for Na-S energy storage for energy system applications.

Table 62. Na-S energy storage for energy system applications

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	2 - 10	-	-	-	-
Roundtrip efficiency	*%*	80	80	80	80	80
Storage capacity	*MWh*	100	-	-	-	-
Min time for charging	*hours*		-	-	-	-
Min time for discharging	*hours*	5	-	-	-	-
Technical lifetime	*years*	10	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	1000	950	930	890	840
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	500	480	470	450	420
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	1600	1520	1515	1430	1350
CAPEX (energy related)	*€$_{2013}$/MWh*	350000	332500	331500	313000	294600
CAPEX learning rate	*%*	6	-	-	-	-
Quality of CAPEX estimate				medium		
FOM	*% CAPEX ref.*	1.5	-	-	-	-
VOM	*€$_{2013}$/MWh*	2	-	-	-	-
Evolution						
Max potential	*GWe*	0.365	-	-	-	-

16.5 Lead-acid batteries battery

Lead-acid batteries (Pb-acid) are among the first forms of rechargeable battery technology, invented in the mid-1800. They are widely used to power engine starters in the automobile, naval and aeronautical sectors. They are also employed in uninterruptable power supply (UPS) systems to reduce energy losses and in grid installations to provide stability, voltage regulation, and frequency control (SANDIA, 2003). The global Pb-acid battery storage installed capacity is of 192 MW /197 MWh, (BNEF, 2014), of which 70 MW is connected to the grid (IEA, 2014).

Typical size of a grid-connected Pb-acid battery is between 1 and 20 MW for small installation. Bigger projects could reach 100 MW in case of big systems (SANDIA, 2013).

Storage capacity generally varies between 250 kWh (small installations) to 750 MWh (big installations). The biggest advanced Lead-acid battery existing is in Goldsmith, Texas and had a rated Power of 36 MW.

Pb-acid batteries can be used for both short-term applications (seconds of electricity storage) and long-term applications (up to 8 hours of storage capacity). The technical lifetime ranges between 5 to 10 years depending on the number of charge-discharge cycles per year and depth of discharge.

Estimations of capital cost for lead acid battery for 2020-2050 reported in Tables 63 and 64 are based on the costs projections by (Black&Veatch for NREL, 2012) for a generic sodium-sulphide battery[a]. Both technologies are at the commercial status of technological development (EPRI, 2010). In this report investment costs of grid-connected applications of lead acid batteries are assumed to develop with the same trend as the sodium sulphur batteries.

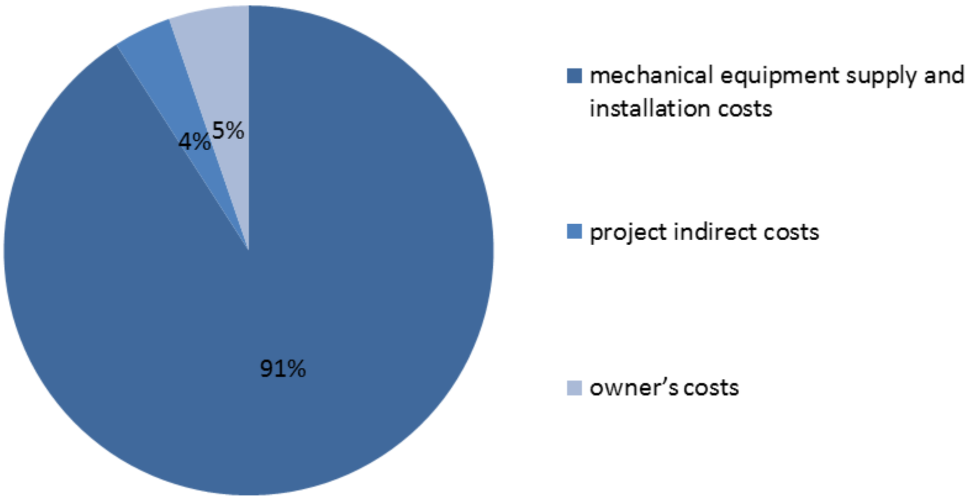

Figure 22. CAPEX breakdown for bulk storage applications.

Table 63. Pb-acid battery for bulk storage applications.

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	50-100	-	-	-	-
Roundtrip efficiency	*%*	80 - 90	-	-	-	-
Storage capacity	*MWh*	250-480	-	-	-	-
Min time for charging	*hours*	0.016	-	-	-	-
Min time for discharging	*hours*	-	-	-	-	-
Technical lifetime	*years*	5 - 10	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*$€_{2013}$/kWe*	410	390	370	350	330
$CAPEX_{low}$ (storage related)	*$€_{2013}$/kWe*	370	350	335	320	300
$CAPEX_{high}$ (storage related)	*$€_{2013}$/kWe*	500	470	450	425	400
CAPEX (energy related)	*$€_{2013}$/MWh*	50000 - 301000	42000 - 286000	38000 - 270000	31000 - 256000	29000 - 241000
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	1.4	-	-	-	-
VOM	*$€_{2013}$/MWh*	0.8	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

[a] See previous paragraph for details on costs improvements over time, up to 2050.

Table 64. Pb-acid battery for frequency regulation.

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	1-12	-	-	-	-
Roundtrip efficiency	*%*	90	-	-	-	-
Storage capacity	*MWh*	0.25-4	-	-	-	-
Min time for charging	*hours*	0.016	-	-	-	-
Min time for discharging	*hours*	-	-	-	-	-
Technical lifetime	*years*	5-10	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	565	540	510	480	450
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	330	320	300	280	266
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	640	610	570	540	510
CAPEX (energy related)	*€$_{2013}$/MWh*	1420000	1350000	1280000	1208000	1140000
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	1.4	-	-	-	-
VOM	*€$_{2013}$/MWh*	0.8	-	-	-	-
Evolution						
Max potential	*GWe*	0.192	-	-	-	-

16.6 Vanadium Redox Flow battery

Vanadium reduction and oxidation (redox) batteries are a type of flow batteries that store chemical energy in external electrolyte tanks. The active material (an aqueous liquid electrolyte) is pumped from the storage tanks into the AC/CD converter (called reaction stacks) where the chemical energy is converted into electrical energy (discharge) or electrical energy is converted into chemical energy (charge). Under specific technical conditions, vanadium redox systems are capable of stepping from zero output to full output within a few milliseconds. Vanadium redox batteries enjoy high efficiency levels, short term response times and little maintenance needs during their life time. Their technical complexity and relatively low energy density are some of the main disadvantages of this technology which make it less competitive compared to other types of batteries. VRB are well suited for some energy applications, in support of PV and wind power integration, spinning reserve and load levelling.

Most common VRB installations range between 50 kW and 1 MW. Commercial units vary typically between 5 kW and 250 kW in size. Several VRB projects are currently in operation at pre-commercial phase in wind farms in Australia, Japan, United States and Ireland. The Minami Hayakita Substation Vanadium Redox Flow Battery is currently operating in Japan with a rated power of 15 MW and 4 hours of storage capacity while an additional battery of 15 MW / 4 hours is under development by Sumitomo to help integrate the large amount of solar PV systems being installed (DOE, Global Energy Storage Database (http://www.energystorageexchange.org/).

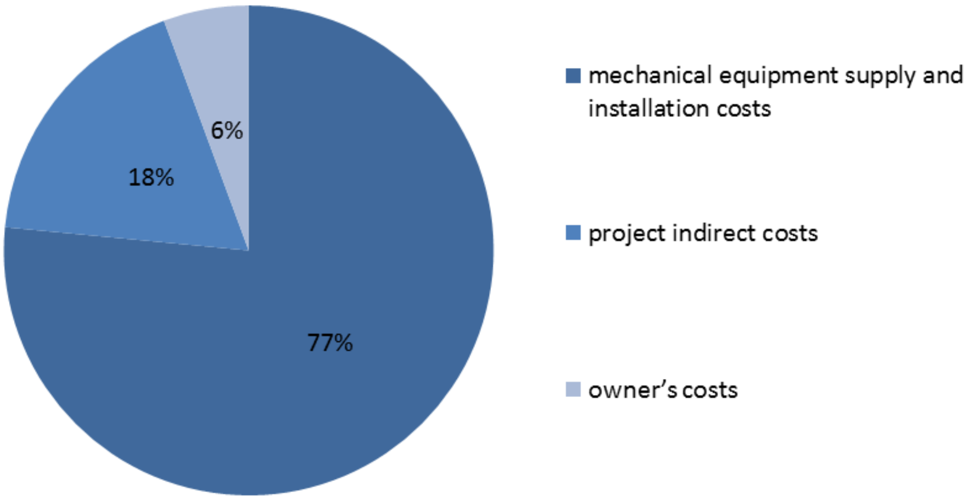

Figure 23. CAPEX breakdown of redox flow energy storage for power system applications.

Table 65. Redox flow energy storage for power system applications

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	0.05–10	-	-	-	-
Roundtrip efficiency	*%*	75	-	-	-	-
Storage capacity	*MWh*	0.02–3.6	-	-	-	-
Min time for charging	*hours*	0.0027	-	-	-	-
Min time for discharging	*hours*	-	-	-	-	-
Technical lifetime	*years*	10	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	1240	810	730	310	310
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	780	290	210	180	180
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	1700	710	510	440	440
CAPEX (energy related)	*€$_{2013}$/MWh*	405850	109700	86180	104020	104020
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	2	-	-	-	-
VOM	*€$_{2013}$/MWh*	2	-	-	-	-
Evolution						
Max potential	*GWe*	-	-	-	-	-

16.7 Thermal energy storage

Thermal energy storage is a commercially available option for both large and small-scale deployment. Thermal energy can be stored by adding energy to a material (generally water, but it can be also a solid) to increase its temperature without changing its phase (sensible heat thermal energy storage). This technology is often used in a number of residential and industrial applications. Another form of thermal energy storage uses the heat relies (discharging) or absorption (charging) during phase changes of a material from solid to liquid or from liquid to gas and vice versa. The most common materials used in phase change thermal energy storage are ice, Na-acetate, trihydrate, paraffin, erytritol. This technology offers higher storage capacity, lower temperature change and higher energy density compared to sensible heat storage system. Pilot and demonstration projects have shown some difficulties in the implementation of this technology though (Mahlia et al., 2014). Alternatively, heat and cold can be stored through thermo-chemical storage that uses reactions, in the form of adsorption, or adhesion of a substance to the surface of a solid of a liquid. Reaction materials currently under investigation are microporous or composite materials (IEA-ETSAP-IRENA, 2013).

Thermal energy storage can be used to store waste heat form large industrial process (centralised thermal storage, typically from hundreds of kW to several MW) or to accumulate solar heat (distributed thermal storage, generally in the range of few tens of kW), generally used in residential or commercial buildings. It is increasing the interest in the application of thermal energy storage for concentrating solar power plants as a way to improve the dispatchability of solar generation (Kuravi et al., 2013).

Table 66. Thermal energy storage for concentrating solar power applications.

	Unit	2013	2020	2030	2040	2050
Technical						
Charge capacity	*MW*	50	-	-	-	-
Charge efficiency	*%*	65	-	-	-	-
Thermal power	*MW*	10	-	-	-	-
Storage capacity	*MWh*	350	-	-	-	-
Min time for charging	*hours*	0.5	-	-	-	-
Min time for discharging	*hours*	-	-	-	-	-
Technical lifetime	*years*	20	-	-	-	-
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	1200	-	-	-	-
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	800	-	-	-	-
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	3000	-	-	-	-
CAPEX (energy related)	*€$_{2013}$/MWh*	24000	-	-	-	-
Quality of CAPEX estimate				low		
FOM	*% CAPEX ref.*	0.2	-	-	-	-
VOM	*€$_{2013}$/MWh*	-	-	-	-	-
Evolution						
Max potential	*GWe*	0.01	-	-	-	-

16.8 Pumped Hydro Storage

Pumped hydro storages (PHSs) have capacities up to 1800 MW[a]. PHS is a well-developed technology, which has been generating electricity in Europe for many years. Despite this, the technology is subject to uncertainties and fluctuating costs. This is largely because the capital costs are highly influenced by the varying civil work requirements in the different locations of the site. Those differences are reflected in the high, reference and low capital cost levels.

The tables below present different cases: (1) two new reservoirs are constructed, (2) one reservoir already exists and a new is constructed, (3) two existing reservoirs need to be prepared for PHS, and finally for a power uprate of an existing PHS.

[a] http://www.cedren.no/Portals/Cedren/Pdf/HydroBalance/3_RioualD_Pumped%20storage%20hydropower%20status.pdf

Table 67. New PHS including both reservoirs.

	Unit	2013	2020	2030	2040	2050
Technical						
Charge capacity	*MW*	500	500	500	500	500
Round-trip efficiency	*%*	80[a]	82	85	88	90
Min time for charging	*hours*	from hours to days				
Technical lifetime	*years*	60	60	60	60	60
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	3000	3000	3000	3000	3000
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	1500	1500	1500	1500	1500
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	4500	4500	4500	4500	4500
CAPEX (energy related)	*€$_{2013}$/MWh*	-	-	-	-	-
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Evolution						
Max. potential expansion	*GWe*	42	61	-	-	-

Table 68. Pumped hydro storage based on one existing reservoir and including one new reservoir, penstock and electrical equipment, assuming grids already exists.

	Unit	2013	2020	2030	2040	2050
Technical						
Charge capacity	*MW*	250	250	250	250	250
Round-trip efficiency	*%*	80[b]	82	85	88	90
Min time for charging	*hours*	-				
Technical lifetime	*years*	60	60	60	60	60
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	1500	1500	1500	1500	1500
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	700	700	700	700	700
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	2000	2000	2000	2000	2000
CAPEX (energy related)	*€$_{2013}$/MWh*	-	-	-	-	-
Quality of CAPEX estimate		low				
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Evolution						
Max. potential expansion	*GWe*	-	-	-	-	3300[c]

[a] Does not take geographical location into account, but also electrical equiptments etc.

[b] Does not take geographical location into account, but also electrical equiptments etc.

[c] At 10 h discharge.

Table 69. Pumped hydro storage including new penstock, new electrical equipment in existing PHS system or for two nearby reservoirs.

	Unit	2013	2020	2030	2040	2050
Technical						
Charge capacity	*MW*	250	250	250	250	250
Round-trip efficiency	*%*	80[a]	82	85	88	90
Min time for charging	*hours*			-		
Technical lifetime	*years*	60	60	60	60	60
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	650	650	650	650	650
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	400	400	400	400	400
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	800	800	800	800	800
CAPEX (energy related)	*€$_{2013}$/MWh*	-	-	-	-	-
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Evolution						
Max. potential expansion	*GWe*	-	-	-	-	400[b]

Table 70. Upgrade existing PHS facility to increase electrical capacity.

	Unit	2013	2020	2030	2040	2050
Technical						
Power capacity	*MW*	50	50	50	50	50
Round-trip efficiency	*%*	80[c]	82	85	88	90
Min time for charging	*hours*			-		
Technical lifetime	*years*	60	60	60	60	60
Economical						
$CAPEX_{ref}$ (storage related)	*€$_{2013}$/kWe*	275	275	275	275	275
$CAPEX_{low}$ (storage related)	*€$_{2013}$/kWe*	200	200	200	200	200
$CAPEX_{high}$ (storage related)	*€$_{2013}$/kWe*	350	350	350	350	350
CAPEX (energy related)	*€$_{2013}$/MWh*	-	-	-	-	-
Quality of CAPEX estimate				low		
CAPEX learning rate	*%*	0	0	0	0	0
FOM	*% CAPEX ref.*	1.5	1.5	1.5	1.5	1.5
VOM	*€$_{2013}$/MWh*	0	0	0	0	0
Evolution						
Max. potential expansion	*GWe*	-	-	-	-	-

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[a] Does not take geographical location into account, but also electrical equiptments etc.

[b] At 10 h discharge.

[c] Does not take geographical location into account, but also electrical equiptments etc.

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17 Heat pumps

The estimates of this section concern electrically-driven HPs (based on the vapour-compression refrigeration cycle) since they represent the larger segment of the HP-market. For this reason, thermally-driven HPs (i.e. absorption and adsorption HPs) and gas engine-driven HPs are not considered.

The data for heat pumps are differentiated between residential and commercial sectors. It has been assumed that heat pumps with thermal capacities greater than 40 kWth are installed in large commercial buildings, e.g. in the service sector. However, it is to be noticed that several sources provide data in an aggregated form, making use of ranges for taking into account of cost differences.

The coefficient of performance (COP) is the ratio of the useful heating or cooling energy provided and the electrical energy consumed by the heat pump. Due to difficulties in the data quest, seasonal performance factors are not included in the estimates even though they are important for characterizing the real operating performances of heat pump systems.

The CAPEX estimate only takes into account the heat source/sink system and the heat pump costs without considering the cost of the distribution system.

2013 Technology Map (JRC, 2014) can be consulted for complementary information about technological status, anticipated developments, market and industry status and potentials, barriers, and R&D priorities and current initiatives.

17.1 Residential heat pumps

Heat pump performance (i.e. COPs and seasonal performance factors) is directly affected by the nature of the heat source/sink; air-, water- and ground- source HPs. Water and ground configurations give, in general, higher operating performance compared to air since water and ground temperatures are less fluctuating then air ones over the year. However air-source heat pumps have lower initial costs than water- and ground- source heat pumps due to a less expensive heat source/sink system and to the fact that air source HPs consist, mainly, of factory-built units which are easy to install. Water-source heat pumps are in general cheaper than ground-source heat pumps since no or less drilling is needed.

Table 71. Water source electrically driven heat pumps - residential

	Unit	2013	2020	2030	2040	2050
Technical						
Thermal capacity	*kWth*	<70	<70	<70	<70	<70
COP	*1*	4	4.2	4.3	4.4	4.5
Technical lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€$_{2013}$/kWth*	1100	1070	1000	950	890
CAPEX low	*€$_{2013}$/kWth*	800	780	730	690	650
CAPEX high	*€$_{2013}$/kWth*	1800	1750	1640	1550	1450
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	4	4	3	3	3

Ground sources heat pumps extracts heat from the underground.

Table 72. Ground source electrically driven heat pumps - residential

	Unit	2013	2020	2030	2040	2050
Technical						
Thermal capacity	*kWth*	<70	<70	<70	<70	<70
COP	*1*	3.5	3.7	3.8	3.9	4
Technical lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€$_{2013}$/kWth*	1700	1650	1550	1460	1370
CAPEX low	*€$_{2013}$/kWth*	1300	1260	1190	1120	1050
CAPEX high	*€$_{2013}$/kWth*	2000	1940	1830	1720	1620
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	2	2	1	1	1

Table 73. Air source electrically driven heat pumps - residential

	Unit	2013	2020	2030	2040	2050
Technical						
Thermal capacity	*kWth*	<70	<70	<70	<70	<70
COP	*1*	3	3.2	3.3	3.4	3.5
Technical lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€$_{2013}$/kWth*	800	780	730	690	650
CAPEX low	*€$_{2013}$/kWth*	500	490	460	430	400
CAPEX high	*€$_{2013}$/kWth*	1100	1070	1000	940	890
Quality of CAPEX estimate		medium				
FOM	*% CAPEX ref.*	2	2	1	1	1

17.2 Commercial heat pumps

Table 74. Ground source electrically driven heat pumps - commercial

	Unit	2013	2020	2030	2040	2050
Technical						
Thermal capacity	*kWth*	>40	>40	>40	>40	>40
COP	*1*	3.4	3.6	3.7	3.8	3.9
Technical lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€$_{2013}$/kWth*	3500	3400	3200	3010	2830
CAPEX low	*€$_{2013}$/kWth*	3000	2910	2740	2580	2420
CAPEX high	*€$_{2013}$/kWth*	4000	3890	3650	3440	3230
Quality of CAPEX estimate		low				
FOM	*% CAPEX ref.*	2	2	1	1	1

Table 75. Air source electrically driven heat pumps - commercial

	Unit	2013	2020	2030	2040	2050
Technical						
Thermal capacity	*kWth*	>40	>40	>40	>40	>40
COP	*1*	2.9	3.1	3.2	3.3	3.4
Technical lifetime	*years*	20	20	20	20	20
Economical						
CAPEX ref	*€2013/kWth*	2000	1930	1780	1650	1520
CAPEX low	*€2013/kWth*	1500	1440	1330	1220	1120
CAPEX high	*€2013/kWth*	2500	2410	2240	2080	1920
Quality of CAPEX estimate				low		
FOM	*% CAPEX ref.*	2	2	1	1	1

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18 List of abbreviations

AD	Anaerobic Combustion
BFB	Bubbling Fluidized Bed
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COP	Coefficient Of Performance
CSP	Concentrated Solar Power
CCS	Carbon Capture and Storage
EGS	Engineered Geothermal Systems
EPCCI	European Power Capital Cost Index
ETRI	Energy Technology Reference Indicator
EU	European Union
FACTS	Flexible Alternating Current Transmission Systems
FOM	Fixed Operation and Maintenance
HHV	Higher Heating Value
HP	Heat Pump
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGCC	Integrated Gasification Combined Cycle
LHV	Lower Heating Value
LFR	Lead-cooled Fast Reactor
LTO	Long Term Operation
MSW	Municipal Solid Waste
NaS	Sodium Sulphur
NUSAP	Numerical Unit Spread Assessment Pedigree
OCGT	Open Cycle Gas Turbine
ORC	Organic Rankine Cycle
OtC	Output To Capacity ratio
OTEC	Ocean Thermal Energy Conversion
PCCI	Power Capital Cost Index
PHS	Pumped Hydro Storage

PV	Photo voltaic
Redox	REDuction and OXidation
RoR	Run of the river
SET-Plan	Strategic Energy Technology Plan
SFR	Sodium-cooled Fast Reactor
Si	Silicon
SMR	Small and Medium sized Reactors
STATCOM	STAtic synchronous COMpensator
STEP	Solar thermal electricity power
SVC	Static VAR Compensators
TRL	Technology Readiness Level
UPS	Uninterruptable Power Supply
VOM	Variable Operation and Maintenance

European Commission

EUR 26950 EN – Joint Research Centre – Institute for Energy and Transport

Title: **Energy Technology Reference Indicator (ETRI) projections for 2010-2050**

Authors: J. Carlsson, M. del Mar Perez Fortes, G. de Marco, J. Giuntoli, M. Jakubcionis, A. Jäger-Waldau, R. Lacal-Arantegui, S. Lazarou, D. Magagna, C. Moles, B. Sigfusson, A. Spisto, M. Vallei, , E. Weidner

Luxembourg: Publications Office of the European Union

2014 – 108 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series –ISSN 1831-9424

ISBN 978-92-79-44403-6

doi: 10.2790/057687

Abstract

The Strategic Energy Technology Plan (SET-Plan) is the technology pillar of the EU's energy and climate policy. This report contains assessments of energy technology reference indicators (ETRI) and it is aimed at providing independent and up-to-date cost and performance characteristics of the present and future European energy technology portfolio. It is meant to complement the Technology Map of SETIS. Combined these two reports provide:

- **techno-economic data projections for the modelling community and policy makers, e.g.:**
  - **capital and operating costs;**
  - **thermal efficiencies and technical lifetimes;**
- **greenhouse gas emissions, and water consumptions;**
- **an overview of the technology, markets, barriers and techno-economic performance;**
- **a useful tool for policymakers for helping to identify future priorities for research, development and demonstration (RD&D);**

The ETRI report covers the time frame 2010 to 2050. This first version of the report focuses on electricity generation technologies, but it also includes electrical transmission grids, energy storage systems, and heat pumps.

LD-NA-26950-EN-N

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Publications Office

doi: 10.2790/057687

ISBN 978-92-79-44403-6