FINDING YOUR CHEAPEST WAY TO A LOW CARBON FUTURE

The Danish Levelized Cost of Energy Calculator

Danish Energy Agency

Contents

1 Foreword

Low carbon transition is a multifaceted challenge involving political, technical and economic elements. Denmark has developed economic models to optimize decision-making in our energy system, in order to secure continued competitiveness for Danish society. Low carbon transition does not impede prosperity and wealth formation: Since 1990, Denmark has reduced energy consumption by 7% and CO2 emissions by over 30%, while the economy grew more than 55%.

Investments in new power generation and energy efficiency are important long-term decisions, locking in both public spending and climate impacts for decades. Low initial investments do not necessarily mean a cheap energy supply for society. Quality, security and externalities are of great importance. As a part of Denmark's international cooperation, the Danish Energy Agency (DEA) has developed a Levelized Cost of Energy Calculator - LCoE Calculator - to assess the average lifetime costs of providing one MWh for a range of power production technologies or power savings. This tool will help compare and select the optimal technologies in the future national energy supply.

In order to facilitate sound long-term decisions in our partner countries, we are proud to present the LCoE Calculator that enables country specific comparisons of the average costs of conventional and new energy solutions. Focusing on not only project specific costs (investment, O&M, fuels, etc.), but also system and society costs, the model gives a holistic assessment of future costs for countries across the globe.

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2 Introduction and summary

The LCoE Calculator is a tool to estimate and compare the socio-economic costs of electricity production in a simplified manner using localized data and estimates. Based on an internationally widely used methodology, the LCoE Calculator permits comparison of different electricity generation technologies based on fossil, nuclear or renewable energy.

The LCoE Calculator is freely available to everyone interested in investigating the costs of electricity production.

The Levelized Cost of Energy (LCoE) Calculator estimates the average lifetime cost of power production per MWh. The cost elements comprising the LCoE include investment costs, fuel costs, operation and maintenance costs, environmental externalities, system costs, and heat revenue for combined heat and power plants.

The LCoE Calculator also includes a separate energy efficiency module allowing the user to compare the levelized costs of electricity generation with the cost of various electricity saving measures.

Easy to use and adapt

The LCoE Calculator is an MS Excel based tool where all data are visible, making it easy to understand and use. It can be modified to reflect the local conditions in a specific electricity system or a specific country. User instructions are provided for all input parameters to assist the users in adding their own data correctly.

It is an ‘open source tool’, without restrictions of use.

All data can be modified

If the user wishes to explore the unit cost of electricity, the LCoE Calculator has a number of predefined settings to choose from. This feature makes it easy for the user to explore the consequences of e.g. higher fuel prices, a longer period for discounting, or a lower discount rate.
It is possible for the user to modify the default data and to add additional technologies, new fuel types, different price scenarios, etc.

The calculations are presented in the Excel sheet and the results are shown in a diagram with stacked values. Using the standard functionality available in Excel, the user can choose which technologies should be displayed in the graph.

Default production data

Eight different power generation technologies based on international technical and financial data have been incorporated in the Calculator. The data represents typical values for generic power production plants and are primarily based on the IEA publication “Projected cost of generating electricity 2015”. In addition, more than ten technologies based on the data from the Danish Energy Agency’s technology catalogue have been included.
In chapter 6 notes are given regarding methods for finding country specific technology data.

The default fuel and CO_2 prices are based on the projections from the IEA World Energy Outlook 2015, including the three main scenarios “Current Policy”, “New Policy” and “450 ppm”. The default costs for local environmental externalities are primarily based on the European calculations and estimates, and the system integration costs reflect the experience from Denmark and Germany. All these inputs and parameters can be modified by the user, though.

The possibility for adjusting parameters is important to be able to mirror country-specific circumstances as closely as possible. Fuel costs and access to natural resources are some of the parameters that will often differ between countries or regions.

Results using default data

The LCoE Calculator provides the following results for the eight key generation technologies using the default settings for the year 2020.

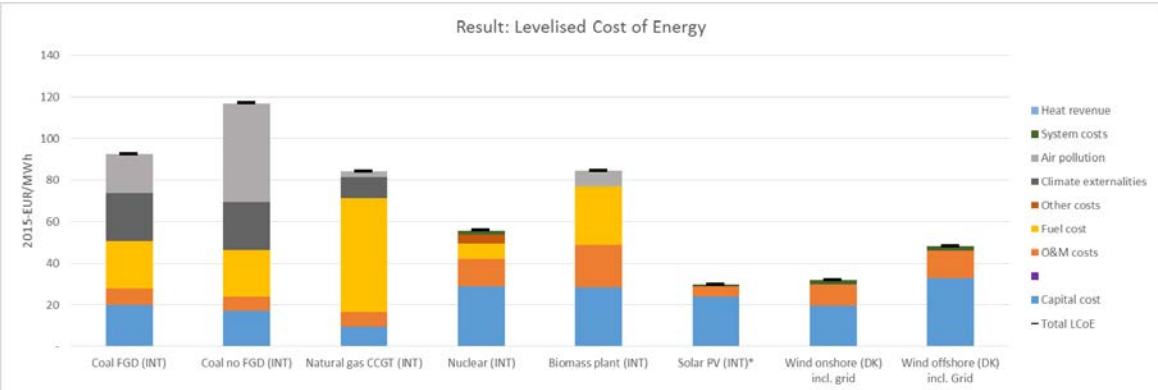


Figure 1: LCoE Results for eight key technologies.

Key Assumptions: Technology data primarily from “Projected cost of generating electricity 2015” (IEA, 2015). However financial (CAPEX and OPEX) data for PV and wind are from the Danish Technology Catalogue. Annual full-load hours for coal, gas and biomass technologies: 5,000, nuclear power: 7,000, onshore wind power: 3,150, Offshore wind power 4,500, solar PV: 1,700. Discount rate: 4% real. Projection prices for fuel and CO_2 *are from the IEA New Policy Scenario 2015, World Energy Outlook, 2015. FGD: flue gas desulphurisation.*

Photovoltaic (PV) and onshore wind demonstrate the lowest LCoE, when all cost elements, including environmental costs and system costs, are considered. The LCoE of off shore wind and nuclear power are at same level and considerable lower than LCoE for the fossil and biomass technologies. It is important to mention that the costs of wind and solar power are site-specific as they depend on the available wind and solar resources. Moreover, the costs of system integration are dependent on the penetration level and the flexibility of the surrounding electricity system. Denmark has a high share of wind power (48 % in 2014), but it also has a very flexible electricity system.In the example, no profile or balancing costs are included.
The LCoE of nuclear power is particularly sensitive to the level of capital costs and the choice of discount rate. The default lifetime is set to 60 years. Furthermore, each country can value the environmental externalities differently.

The cost of the biomass feedstock is an important factor for the cost of generating electricity from biomass. If biomass residues are available at very low or no cost, biomass is close to being competitive with off shore wind power.
With regard to coal-based power production, the cost assigned to the local air pollution may turn out to be a determining factor for the LCoE. The example presented investigates the LCoE of coal power with and without desulphurization equipment. The results show that the costs of increased air pollution by far exceed the additional capital costs of the environmental installations.

Climate abatement costs may be significant depending on the local regulation. The LCoE of natural gas-fired power plants is particularly sensitive to the price of fuel. Both capital costs and environmental costs are moderate.
Renewables such as onshore wind and, especially, PV and off shore wind are considered to be at an earlier stage of cost development than to traditional fossil fuel technologies. The recent years the costs for these technologies have decreased even more than anticipated. Technological progress and economies of scale are expected to keep driving their cost reductions faster than for the other more mature technologies.

In order to account for the influence of the expected future development in terms of investment costs, efficiencies, etc. of the different power production technologies, the user can generate results with current, 2015, and future technical data expected for the years 2020, 2030, and 2050. The projected data for the future years are estimates based on the Danish Energy Agency's Technology Catalogue.

Limitations of the method

The LCoE method is a simple way to compare production technology choices, yet it is associated with certain limitations.

Firstly, it mainly deals with base load technologies, i.e. power generation technologies with a relatively high number of full load hours, which is considered constant over the lifetime. It is not intended to be used for modelling and simulation of the electricity dispatch in a system with many concurrent sources. Similarly, the rate and price of co-generated heat is considered fixed over the year and the technology lifetime.

Secondly, the model only considers the costs and not the revenues (except value of heat produced) of the technologies. The costs are considered evenly distributed over the lifetime, as opposed to a cash flow model approach. Taken together this means that the LCoE Calculator cannot be used for assessing NPVs or return rates of projects. The intention is rather to compare the socio-economic costs of different technologies at a relatively high level and without considering taxes, subsidies and project specific financial costs.

Finally, it should be noted that the validity of any result will depend on the input provided to the model. It is obvious that many values are inherent to the specific country or region, or even a project, in terms of investment and fuel costs, wind and solar resources, environmental costs, etc. It is therefore at the user's discretion to find and verify data in each specific application of the model.

Energy efficiency module

The energy efficiency module (EE module) allows the user to assess the economy of specific or generic energy efficiency measures.

Energy efficiency measures provide an alternative to investments in new energy production capacity and reinforcements of the electricity distribution and transmission grid. By saving an amount of energy, society can avoid the costs of producing and delivering the same amount of energy. If the price of saving energy, i.e. the levelized cost of energy efficiency (LCoEE), is lower than the production costs (LCoE), including cost of delivery, it should represent a better alternative from a socio-economic point of view.

In practice, the cost savings of an energy efficiency measures will depend on the specific electricity system under consideration. Savings are usually highest in systems where there is a growing demand for electricity that requires new investments in the generation and grid capacity.

Figure 2 show the LCoEE for selected efficiency cases compared with the LCoE of power produced by wind turbines and coal power plants. The spans for each EE technology represent different options. In the selected cases, optimization of office ventilation is cheaper than energy from onshore wind farms. The same may, or may not be the case for savings in lighting in commercial buildings depending on the specific efficiency options considered.

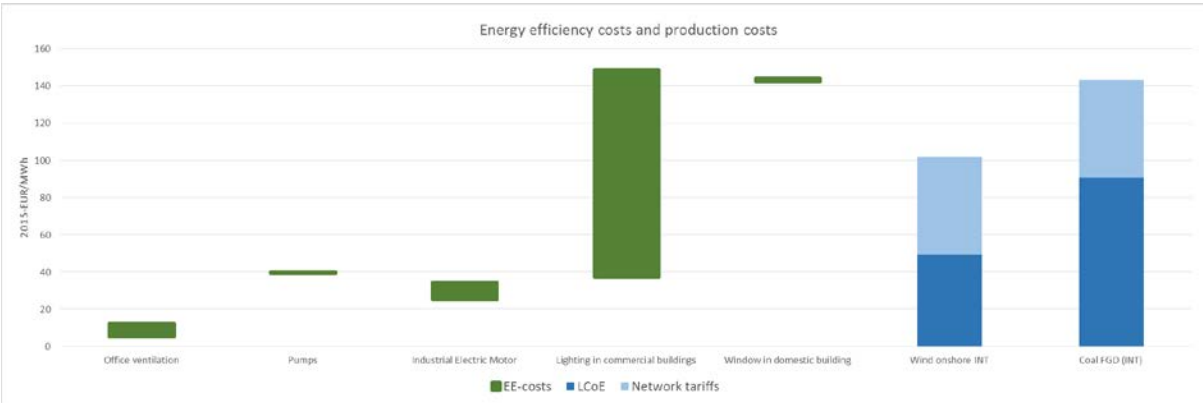


Figure 2:LCoEE Results for various measures compared with LCoE of power produced by wind turbines and coal power plant. The spans for each EE technology represent different options.

It should be noted, that the comparison does not consider when energy is saved. For example, measures curbing electricity demand in peak load hours would have higher value than electricity saved in off-peak hours. In the first case, it would be relevant to compare the cost of saving electricity with the cost of providing peak power.

The purpose of this report

This report describes the methodology applied in the LCoE Calculator including a discussion of key assumptions and parameters. The report also works as a guideline to the LCoE Calculator spread sheet. References to the spreadsheet are made through the document in **bold blue**.

3 Methodology and assumptions

The levelized cost of energy methodology discounts the time series of expenditures and incomes to their present values in a specific base year. It provides the costs per unit of electricity generated which are the ratios of total lifetime expenses (net present value) versus total expected electricity generation, the latter also expressed in terms of net present value. These costs are equivalent to the average price that would have to be paid by consumers to repay all costs with a rate of return equal to the discount rate (Ea Energy Analyses, 2007).

The methodology is relevant for comparing alternative generation options, and assessing their relative competitiveness within a comprehensive harmonised framework. However, it is also important to stress that it does not replace a full electricity system cost analysis that would be carried out in support of expansion planning and decision-making.

With enhanced understanding of the socio-economic costs and benefits, governments and international institutions can develop recommendations for policies to ensure framework conditions, so that market actors would make optimal investment decisions from a societal point of view.

The purpose of the LCoE Calculator is to assess the cost of different electricity sources from a societal perspective. In many aspects the societal perspective differs from the financial perspective or the developer’s perspective. For example it has a long-term perspective, it reflects a socio-economic discount rate, and it takes into consideration as many external impacts as possible.

Cost elements in the calculation of the levelized cost of energy		
	Economic analysis (public sector)	**Financial analysis (private sector)**
Viewpoint	Overall society	Investor / Developer
Decision criteria	Positive net present value	Payback or internal rate of return
Timeframe	Life cycle (technical life)	Often shorter term
Discount rate	Reflects social preferences and other factors	Reflects costs of borrowing, desired returns (normally higher than the economic discount rate)
Energy prices (benefits)	Social values reflect willingness to pay; alternative uses	Prevailing market prices
Costs	Overall costs to society	Private, prevailing market prices
Taxes and subsidies	Ignored	Considered
Social infrastructure (e.g. roads)	Considered	Ignored, if not part of investment
External impacts	Analysed as much as possible	Ignored

Table 1: Differences between economic and financial analyses, adopted from (Ea Energy Analyses, 2007).

The LCoE Calculator provides a framework to include the most important cost elements in a socio-economic evaluation of power generation technologies. The standard LCoE calculation focuses merely on the direct costs of the power plant owner. The LCoE Calculator also includes climate costs, the cost of air pollution (and other environmental externalities) as well as system integration costs. As we show in Chapter 4, inclusion of these external costs may have significant influence on the relative competitiveness between the technologies.

The valuation of many cost elements – environmental and system integration costs in particular – are highly context-specific. Therefore, the LCoE Calculator is designed to allow users enter country- or region-specific data.

Cost elements in the LCoE-calculator
Capital cost – Investment cost of the plant and new or upgraded infrastructure if needed
Fixed operation and maintenance – Yearly costs which are independent of the production
Variable operation and maintenance – Dependent on the produced amount of electricity
Fuel cost – Projected costs of fuels according to IEA World Energy Outlook 2015
Heat revenue – The earnings from heat sale (only applies to combined heat and power plants)
System costs - Balancing costs – Costs of handling deviations from planned production - Profile costs – The value of electricity generation compared to a common benchmark, such as the average electricity market price.
Climate CO_2 emission valued according to projected costs in IEA World Energy Outlook or a custom figure. - CH_4 emissions converted to CO_2 equivalents and valued as such. - N_2O emissions converted to CO_2 equivalents and valued as such.
Air pollution - SO_2 – Socio-economic costs of SO_2 emissions - NO_X – Socio-economic costs of NO_X emissions - $PM_{2.5}$ – Socio-economic costs of $PM_{2,5}$ emissions
Other costs - Radioactivity – Socio-economic cost of radioactivity - Further external costs, can be defined by the user. Could e.g. include costs for reinforcing the electricity infrastructure (defined by variable costs pr. MWh electricity generated)

Table 2: Cost elements included in the LCoE Calculator.

In the following sections the methodology of the LCoE Calculator is described, an overview of the default data included in the model is provided, and guidance to the user on the possibilities for alternative data entry is given.

3.1 Technology data

The electricity generation technologies included in the LCoE Calculator are generic examples that can be used directly in calculations, or used with user-modified properties and settings. The technologies are defined by their:

- Investment costs
- Operation and maintenance costs (fixed and variable)
- Other cost (user defined option)
- Energy efficiencies
- Cogeneration efficiencies (power and heat)
- Lifetime
- Construction time
- Emission factors
- Full load hours (utilization rate)
- System costs

Technical and economic data are described in this section. Operational data for utilization rate are described in section 3.3 and data related to system costs are described in section 3.7. Emission factors are discussed under Environmental externalities, though they are also part of the technology-specific data. The technology data is located in the sheet **TechData** in the LCoE spreadsheet.

International technology data

Eight different power production technologies based on international technical and financial data have been incorporated in the LCoE Calculator. The data represents typical values for generic power production plants and is primarily based on the IEA publication "Projected cost of generating electricity 2015" (IEA, 2015a) and data from the Danish Technology Catalogue.

These data applied from the IEA publication represent the median values of specific reported plant data from 19 OECD countries and 3 non-OECD countries reported to IEA in 2014. The IEA technology data are thus based on a sample, which is not statistically representative and contains large variations due to different cost levels in the different countries. Therefore, the values cannot be presumed as an "OECD average", but merely as examples of realistic values.

The IEA report does not contain emission values, and therefore such values have been obtained from other sources. Further, a variant of a coal-fired power plant without flue gas desulphurization (FGD) has been included by a combination of the IEA data and other sources.

In addition to the IEA data, representative data for a medium-size biomass plant (approx. 50 MW) has been derived from (IRENA, 2015).

Cost data for PV and wind are from the Danish Technology Catalogue (version update March 2018). The recent years the cost for these technologies have decreased more than anticipated and therefore it has been assessed that using data updated in 2016 and 2017 would give more fair results for these technologies. For the wind turbines all technology data are from the Danish Technology Catalogue to make sure that the consistence between the cost data and the technology data.

International Technology Data		
Technology	**Type**	**Technology source (chapter)**
Coal FGD INT	Condensing	Table 6.2 IEA [1)]
Coal no FGD INT	Condensing	Table 6.2 IEA [1) 2)]
Natural gas CCGT INT	Condensing	Table 6.1 IEA [1)]
Nuclear INT	Condensing	Table 6.3 IEA [1)]
Biomass Plant INT	Condensing	IRENA [3)]
Solar PV INT(/DK)*	Solar	Table 6.6 IEA and data sheet 22 DEA [1,4)]
Onshore wind DK	Wind	Data sheet 20 DEA [4)]
Offshore wind DK	Wind	Data sheet 21 DEA [4)]

Table 3: List of international technologies

[1)] Technologies based on IEA Projected costs of generating energy 2015 (Median values), (IEA, 2015a)

[2)] A plant without desulphurisation is estimated to a 15% lower investment cost and a 15% lower variable and fixed O&M cost, (Danish Energy Agency and Energinet.dk, 2014)

[3)] Based on IRENA Renewable Power Generation Costs in 2014 (IRENA, 2015)

[4)] Technologies based on Technology Data for Energy Plants for Electricity and District heating generation(Danish Energy Agency and Energinet, 2018)

In addition, more technologies based on the data from the Danish Energy Agency's technology catalogue have been included.

Danish Energy Technology Catalogue

Another set of technology data is based on the Energy technology catalogue published by the Danish Energy Agency and the Danish TSO, Energinet.dk (Danish Energy Agency and Energinet, 2018). The data provided corresponds to 'best available technology' commissioned in 2020 in Denmark.

The Danish technologies in the LCoE Calculator include wind power, solar photovoltaic cells (PV), three CHPs with different fuels in backpressure mode, and four CHPs with different fuels in extraction mode. One of the extraction CHPs is a coal-fired plant rebuilt to biomass. Extraction turbines are able to combine heat and power production but also to switch between only power or only heat productions, whereas backpressure turbines always produce both heat and power.

Technologies based on the Danish Energy Technology Catalogue, 2014

Technology	Type	Technology source (chapter)
Wind onshore	Wind power	Wind Turbines Onshore - Large (20)
Wind offshore	Wind power	Wind Turbines Offshore (21)
Solar power	Solar PV	Solar Photovoltaic Cells, Grid-connected Systems (22)
Wind nearshore	Wind power	Wind Turbines Offshore (21)
Large CHP - wood pellets	CHP – Extraction	Biomass CHP, Steam Turbine - wood pellets Large (09)
Large CHP - wood chips	CHP – Extraction	Biomass CHP, Steam Turbine - wood chips Large (09)
Large CHP - natural gas CC	CHP – Extraction	Gas Turbine Combined Cycle - Steam Extraction (05)
Large CHP – coal	CHP – Extraction	Advanced Pulverized Fuel Power Plant - Coal CHP (01)
Medium CHP - Wood chips	CHP – Backpressure	Biomass CHP, Steam Turbine - Woodchips Medium (09)
Medium CHP – straw	CHP – Backpressure	Biomass CHP, Steam Turbine - Straw Medium (09)

Table 4: List examples of technologies based on Danish Energy Technology Catalogue, 2014

Custom Technologies

In the LCoE Calculator the default setting for technology data is provided in a data set called TechBase. The user can also choose a sensitivity scenario with higher (TechHigh) or lower (TechLow) investment and operation costs than in TechBase. The default difference for the sensitivity is +/- 25 %, but can be modified in **TechData.**

Moreover, the user can design his/her own technology data independently of the TechBase data. This is done by setting up data in the **TestTech**-sheet. The user can fill in all relevant data and characteristics of a technology, or copy parts of an existing data set from **TechData**.

Definition of technology costs and efficiencies in the Danish Energy Agency Technology Catalogue

Investment costs

The investment costs or initial costs are given as the total investment cost (also called the overnight costs) divided by the net generating capacity, i.e. the capacity as seen from the grid, whether electricity or district heat. Investment cost includes all physical equipment, typically called the engineering, procurement and construction (EPC) price. Infrastructure or connection costs, i.e. electricity, fuel and water connections, are also included. Connection costs can be specified separately, and if done so, should not be a part of the main investment cost. The basic user settings provide an option on whether defined connection costs are shown explicitly on the graph, or included in the general capital cost.

The cost of land, the owners' predevelopment costs (administration, consultancy, project management, site preparation and approvals by authorities) are not included. The cost to dismantle decommissioned plants is also not included, assuming that the decommissioning costs are offset by the residual value of the assets.

Operation and maintenance (O&M) costs

The operation and maintenance costs are either divided in fixed and variable or given as a total of the two. The fixed share of O&M includes all costs, which are independent of how the plant is operated, e.g. administration, operational staff, planned and unplanned maintenance, payments for O&M service agreements, network use of system charges, property tax, and insurance. Re-investments within the scheduled lifetime are also included, whereas re-investments to extend the life are excluded. The variable O&M costs include consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, output related repair and maintenance, and spare parts (however not costs covered by guarantees and insurance).

Energy efficiencies

The LCoE Calculator operates with four different energy efficiencies: Total efficiency, electric efficiency in condensing mode, electric efficiency in CHP mode and heat efficiency. The efficiencies are stated in per cent at ambient conditions; air 15°C and water 10°C and are determined at full load (100 %), continuous operation, on an annual basis, taking into account a typical number of start-up's and shut-down's. (Danish Energy Agency and Energinet.dk, 2014)

The total efficiency equals the total delivery of electricity plus heat at the fence divided by the fuel's energy content. The electricity efficiency equals the total delivery of electricity to the grid divided by the fuel's energy content consumption. Thus, for a plant without heat

If the existing fuel options are not applicable for a new user-defined technology, the user can define a new fuel type. Prices for the new fuel should subsequently be entered in the sheet **FuelPrices** and emission data for the new fuel should be included in the sheet **EmissionFactors**.

For both the international data and the Danish data, four different years of technology data are given (2015, 2020, 2030, and 2050) for each technology. However, only the source of the Danish data contains this information and, therefore, the international data have been extrapolated with same factors as similar technologies from the technology catalogue.

Compared to traditional fossil fuel technologies, renewables are still at a relatively early stage of development. In a longer perspective, through technological progress and economies of scale, renewables may develop and become more competitive to mature energy technologies. For example, the investment costs of solar PV in the Danish data set is expected to decrease from 1.2 million EUR/MW today to EUR 0.82 million MW in 2030. Similarly, offshore wind power investment costs are expected to decrease from app. EUR 3.4 million MW today to EUR 2.4 million MW in 2030. The investment costs of the included combined heat and power plants have only very little or none development until 2050.

Cogeneration values

For thermal plants with cogeneration of heat and power, the C_b coefficient (back-pressure coefficient) is defined as the maximum power generating capacity in back-pressure mode divided by the maximum heat capacity. The C_v-value for an extraction steam turbine is defined as the loss of electricity production, when the heat production is increased one unit at constant fuel input. (Danish Energy Agency and Energinet.dk, 2014)

Technical construction time

A so-called technical construction time is given for each type of plant in the Technology data catalogue (Danish Energy Agency and Energinet.dk, 2014). This indicates the time that will pass from financial closure of building the respective plant until the plant is ready to operate.

Construction time is relevant in the LCoE Calculator since interest payments during the construction period are included in the LCoE calculation, when default settings are applied.

Data reference name	Data source
Basic settings	
TechBase	Technology data for energy plants 2016 updated late as 2018 (Danish Energy Agency and Energinet, 2018) International technologies based on (IEA, 2015a) etc.
User options	
TechLow	25 % lower investment and O&M cost than TechBase
TechHigh	25 % higher investment and O&M cost than TechBase
CostumTech	Designed by user. By default set to Techbase

Table 5: Settings for technology scenarios in the LCoE Calculator

3.2 Technical or economic lifetime

Technical or economic lifetime

One needs to decide whether to use the technical lifetimes of the technologies (which are different) or a common financial lifetime (e.g. the maturity period of the debt finance) of the technologies considered. Usually, the debt of a power plant is fully repaid before the end of its technical life, and hence one needs to assign a scrap value at the end of the financial lifetime (Ea Energy Analyses, 2007). To avoid calculating the scrap values, the LCoE Calculator uses the technical lifetime as depreciation period for all technologies as a standard. However, the user can investigate the impact of different economic lifetimes by setting 'Depreciation period' to a chosen number of years.

Impact of lifetime adjustment on individual technologies can be investigated by defining new technologies in the **TestData** sheet with different assumptions for technical lifetime.

Discount period for fuel and emission costs

By default, the future fuel and emission costs are also discounted over the expected technical lifetime of the technologies. The user may also choose a fixed discount period by changing the setting 'Lookout period' to for example 20 years, which is then used for all technologies.

3.3 Full load hours (utilization rate)

The number of annual full load hours is used to express the utilization rate of the power plant. The assumptions regarding full load hours have a high influence on the LCoE due to contributions from fixed costs such as capital cost and fixed operation and maintenance cost.

Renewables like wind power and solar power have very low marginal costs. Therefore, their annual full load hours are almost exclusively dependent on the available renewable energy resource and the choice of technology. For thermal power plants the number of full load hours depends on their function in the electricity market, i.e. if they operate as base load, mid-load or peak load.

Nuclear power plants also have low marginal cost and would therefore normally operate as base load with a high number of full load hours.

Renewables

For wind and solar PV the Danish Technology Catalogue (Danish Energy Agency and Energinet.dk, 2014) assumes that these technologies will produce and deliver to the market as many hours as possible without any interferences or restrictions from e.g. the market. Large onshore wind turbines are stated to have a capacity factor of 34%, which is equivalent to 3,000 full load hours. Large offshore wind turbines are stated to have a capacity factor of 46-48%, which is equivalent to ca. 4,200 full load hours. In Denmark large new solar PV systems are expected have 1,130 full load hours per year (updated data in the catalogue from March 2015).

Full load hours for both wind power and solar PV production are very site-specific. The full load hours stated in the Technology Catalogue assume a typical location in Denmark, where the wind conditions are relatively good and the sun conditions are relatively poor. For comparison, in India, Africa and South America the typical annual full load hours for solar PV is around 1,800 and can be as high as 2,350 (IRENA, 2015).

The following default values are used for the international technologies in the model.

Default values	Annual full load hours
Coal	5,000
Natural gas	5,000
Nuclear	7,000
Solar PV	1,700
Biomass plant	5,000

Table 6: Default full load hours for international technologies in the LCoE-calculator

It is assumed that coal, natural gas and biomass power plants operate somewhere between base load and mid-load. In the sheet **TechData** the user can change the annual full load hour assumptions for the individual technologies, so as to more accurately reflect the national specifics.

It is important to mention that there is a correlation between the assumptions on full load hours and the profile cost (see section 3.7) of a technology. A dispatchable power plant will normally gain a profile credit because it is able to run when power prices are highest. If the number of full load hours is increased this benefit will drop since the power plant will settle at power prices closer to the average power price.

3.4 Fuel and CO_2-prices

Fuel costs constitute a large share of the total levelized cost of electricity production for thermal plants, and therefore the forecasts of fuel prices have a major influence on the outcome when the LCoE of different technologies are compared. Wind, solar and to some extent nuclear power are not exposed to this factor of uncertainty in the calculation of the LCoE. In the same way, the LCoE of power plants using fossil fuels may be highly influenced by the CO_2-price.

Another thing to bear in mind is that prices of some fuels, like natural gas, vary considerably across regions, and other fuels like biomass are very dependent on the local availability and other local conditions. For this reason, the user may enter his or her own fuel price projections. This is done by setting up a CustomFuel-scenario in the sheet **FuelPrices**.

Oil, gas, and coal prices

In the short term, from 2016 and until 2020, the Calculator uses European forward prices. For year 2020 and onwards the forecasted prices for Europe from IEA's World Energy Outlook 2015 (IEA, 2015b) are applied. Prior to 2016 historical data are applied, with 2015 being a preliminary estimate.

Forward prices and the IEA price forecasts represent only the market value of the fuels and do not take into account transport costs to the place of consumption. Transport costs are included in the total fuel cost in order to reflect the actual fuel cost that a power plant will face. Transport costs are based on the Danish experience.

Prices are provided for both large (centralized) and small-scale power plants (decentralized) because they are usually subject to different transport costs. For example, large-scale natural gas-fired power plants only pay for transmission of gas whereas small-scale power plants would also pay a distribution fee.

For large-scale coal and natural gas-fired power plants transport costs are rather small.

Three fuel price scenarios

Three different price scenarios are included in the LCoE Calculator. Each follows one of the three IEA scenarios from 2020 and onwards: The New Policies Scenario, the Current Policies Scenario, and the 450 ppm Scenario, and are name-given according to these.

The New Policies Scenario takes into account the incorporated policies as of mid-2015 and other relevant political intentions that have been announced, even when the precise implementing measures have not yet been fully defined. This includes the energy-related components of the Intended Nationally Determined Contributions (INDCs), submitted by national governments to the COP21.

The Current Policies Scenario takes into consideration only those policies for which implementing measures have been formally adopted as of mid-2015 and makes the assumption that these policies persist unchanged. This is the so-called 'frozen policy' scenario.

The 450 Scenario adopts the international goal of a maximum temperature rise of 2°C. The scenario assumes a set of policies that bring about a trajectory of greenhouse-gas (GHG) emissions from the energy sector that is consistent with this goal.

Biomass prices

The LCoE Calculator contains several technologies applying different kinds of biomass. Wood pellets and wood chips are traded internationally while straw and 'local biomass' such as low-cost agricultural and forestry waste are primarily traded locally. Therefore, prices for wood pellets and wood chips are generally more representative across regions than prices for straw and local biomass.

Prices for wood pellets, straw, and wood chips are generated by a Biomass Price Model (Ea Energianalyse, 2014) adopting a central, high and low scenario, which are coupled with the three scenarios for fossil fuels (The New Policy Scenario, The 450 Scenario, and The Current Policy Scenario, respectively). Transport costs according to the Danish Energy Agency have been applied to the market prices. As for the fossil fuel prices, both prices for central plant and de-central plants are given. The price for local biomass is an average of a number of different biomass types reported by The International Renewable Energy Agency, and assumed to be constant over time. (IRENA, 2015).

Nuclear fuel

The fuel costs of nuclear power include both front-end and waste management costs. It is based on the median value of the reporting to the *IEA Projected Costs of Generating Electricity* (IEA, 2015a), and it is connected with considerable uncertainty due to, among other things, the different requirements to radioactive waste handling and storage in different countries. The price is expected to be constant over time.

CO_2-price

In the LCoE Calculator the CO_2-price is represented by the European CO_2 quota price, though it is still meant to represent the cost of externalities caused by greenhouse gas emissions. The European CO_2 quota price is market-determined by demand and supply. This means that the CO_2-price incorporated in the LCoE represents the actual cost of emitting CO_2 faced by European electricity producers.

Just as with the fossil fuel prices, the CO_2-price series are comprised of forward prices from 2016 to 2020 and IEA scenario prices onwards, respectively. Prices prior to 2016 are historical prices.

The CO_2-prices are located in the sheet **EmissionPrices**. Here the user can also define a custom CO_2-price scenario.

3.5 Discount rate

The discount rate is used to determine the present value of future costs and revenues.

The LCoE Calculator returns a unit cost for electricity production based on discounted future electricity generation, and is, therefore, heavily influenced by the chosen level of discount rate. The LCoE Calculator applies an annual rate of 4% real as a default value, which is the recommended rate by the Danish Finance Ministry for socio-economic analysis. The user can set the discount rate to any other rate preferred. For comparison, the IEA applies 3 %, 7 % and 10 % in the latest *Projected Costs of Generating Electricity* (IEA, 2015a).

Discount rate adjustment is done in the sheet **UserSettings&Results** in the section ‘Basic user settings’.

When changing the discount rate, both the annualisation of capital costs and the discounting of fuel and CO_2-prices etc. are influenced. The discount rate influences technologies with high investment costs the most, for example solar PV, wind power and nuclear power. For example, if the discount rate is increased from 4 to 10 %, the LCoE of nuclear power is doubled.

Value	Data source
Basic settings	
4%	Guide in socioeconomic analysis from the Danish Energy Agency. (Danish Energy Agency, December 2014)
User options	
The user can set any other values instead of the basic setting	

Table 7: Settings for discount rate in the LCoE Calculator

Interest during construction

Interest during construction in the LCoE Calculator defined as the interest rate paid during the construction of the plant, assuming that loans are needed when construction starts. Interest during construction is a cost both from the investor's point of view, and from a socio-economic perspective.

The LCoE Calculator assumes a linear construction process and applies the discount rate (basic setting of 4 %), which is also used for annualisation of investments and discounting of future fuel and CO_2 prices. Interest during construction is included in the capital costs in the LCoE Calculator. The user can choose not to include interest during construction in the sheet **UserSettings&Results** in the section 'Basic user settings'.

Interest during construction increases the price of technologies with longer construction times relative to those with shorter construction times. Also interests during construction are most important to technologies with high investment costs. To offshore wind power the interest during construction will constitute 6 % of the total investment assuming a discount rate of 4 %. To a coal combined heat and power plant the share will be 9 %. However, the relative difference between the levelized cost of energy from wind power and coal combined heat and power that arises by excluding interest during construction falls as the investment costs are of highest importance to offshore wind power.

Value	Data source
Basic settings	
TRUE, interest rates during construction are included	The discount rate is applied to the construction time
User options	
FALSE, interest rates during construction are not included	

Table 8: Settings for interests during construction in the LCoE-calculator

3.6 Value of heat production

The LCoE calculator includes technologies producing combined heat and power (CHP). In order to calculate the cost of electricity, the value of the heat needs to be subtracted from the power plant's operational costs.

There are several methods to allocate the expended primary fuel between the electricity and heat production from CHP, and as IEA states *`There is no "correct" rule for this allocation; it is dependent on the point of view taken.´*

The LCoE Calculator gives the option of two different methods to calculate the heat value. One is an allocation of fuel and CO_2-costs between electricity and heat and the other is a fixed heat price.

Cost allocation method

Using the cost allocation method, the expended primary fuel (and emission costs) is allocated between heat and the electricity production according to a defined heat efficiency value. The heat efficiency value applied in the Danish context is often 125 % or 200 %.

125 % is set as the default value in the LCoE Calculator but the user can freely determine any other value.

Example:
A combined heat and power plant has a primary fuel consumption of 100 GWh per annum and produces 35 GWh of electricity and 50 GWh of heat. Using a heat efficiency value of 125 % the share of primary fuel allocated for the heat production is 40 GWh (50 GWh/125 %). An equivalent share of emission costs is then allocated for heat production.

Fixed heat price

Using the fixed heat price methodology, the user simply sets the price of heat. The price of heat is multiplied by the heat produced, and this positive revenue stream is then subtracted from the costs of electricity generation. When the fixed heat price is used, the same heat price applies to all combined heat and power plants in the Calculator.

The default socio-economic value of the fixed price in the LCoE Calculator is set to EUR 6.7 per GJ of heat (DKK 50/GJ). For comparison the alternative cost of supplying heat from a wood chip-fired plant or a heat pump is ca. EUR 10-12 per GJ whereas the direct cost of a CHP extraction plant is in the order of EUR 3 per GJ of heat. Both values have been calculated on the basis of technology data from the Danish Energy Agency. Hence, the heat value of EUR 6.7 per GJ of heat assumes that the benefit of combined heat and power production is shared by the electricity and heat side.

The heat value is context-specific as it depends on the alternative sources of heat generation. In the latest *Projected Costs of Generating Electricity* (2015 edition) from IEA a heat credit of EUR 12 per GJ heat has been set as the default value. The LCoE Calculator gives the user the opportunity to apply any heat value.

The user can choose between the two different methods for the valuation of heat in the sheet **UserSettings&Results** in the section ‘Basic user settings’.

User choice	Value	Data source
Cost allocation method	**Basic settings**	
	125 % heat value efficiency	Used by Danish Energy Agency for LCoE calculations
	User options	
	Any other factor	
Fixed price-method	**Basic settings**	
	EUR 6.7 per GJ heat	Assumes that the benefit of CHP is split between electricity and heat.
	User options	
	Any other heat price.	

Table 9: Settings for heat value in the LCoE Calculator

3.7 System integration

Besides the direct costs of investment, fuel, operation and maintenance as well as environmental costs, the various technologies also have costs related to the integration of the generated electricity into the surrounding energy system. This is especially true for technologies with variable output like wind power and solar PV, but also nuclear power has an impact on system costs because of its large and rather inflexible nature. Dispatchable technologies, in turn, may be credited with a system benefit (i.e. a negative system cost).

The system costs can be divided into the following elements, in accordance with (IEA, 2015a):

- **Balancing costs**: This covers the cost of handling deviations from the planned production and the possible extra cost for investments in reserves for handling outages of power plants or transmission facilities.
- **Profile costs:** The value of the electricity generated to the electricity system or electricity market. The value is compared to a common benchmark, such as the average electricity market price. If the technology earns less than the average electricity market price, the difference can be considered a profile cost (and if the technology earns more than the average electricity price we consider this a profile benefit).
- **Grid costs:** Extra costs for expanding and adjusting the electricity infrastructure in order to feed in the electricity production from the technology in question.

System costs are highly dependent on the configuration of each individual electricity system.

Balancing costs

In most electricity markets, electricity production is planned one day ahead in the spot market. If deviations from the planned operation occur during the day of operation, purchase or sale of electricity in the electricity market is necessary and will generate balancing costs. For this reason, balancing costs are particularly relevant for wind and solar power, but might also be so be applicable for other technologies. Compared to a coal-fired power plant, waste-fired power plants and nuclear power plants usually have poorer regulating capacities, while gas turbines have good regulating capacities.

Balancing costs encompass both the costs of holding sufficient reserves to deal with the deviations, and the costs of activating these reserves.

Wind and solar power

The experience from Denmark shows that the balancing cost of wind power is around 2 EUR/MWh in spite of a very high share of wind power. In fact, the balancing costs have decreased from around 3 EUR/MWh in 2005 when the share of wind power was ca. 25% compared to 39 % in 2014.

The cost of balancing is highly dependent on the flexibility of the surrounding electricity system, for example the availability of technologies with good regulation abilities such as hydro power with storage capacity and gas engines. The regulatory framework and the market setup may also have a significant impact on the balancing costs. Balancing markets, which have a high level of competition and allow all types of electricity generators and flexible consumers to participate, are likely to yield low balancing costs.

A survey by (Holttinen, 2013) has shown that at 20 % wind power penetration balancing costs amount to approx. EUR 2-4 per MWh in thermal-based power systems and less than EUR 1 per MWh in power systems dominated by hydro power.

Regarding solar PV, the experience from Germany shows that balancing costs have been in the order of EUR 2-3 per MWh during 2011-2013 (Hirth, 2015).

Thermal power

For thermal power production, balancing costs might also occur if for example a plant fails to deliver. On the other hand, thermal power plants also have the opportunity to make earnings on delivering balancing services for the system. Flexible thermal power plants are likely to have an income from the provision of balancing services.

Nuclear power

Nuclear power plants are often large units in the order of 1,000 – 2,500 MW. Depending on the specific electricity system an expansion with nuclear power may therefore increase the demand for disturbance reserves. Based on (Ea Energy Analyses, 2007) study, we estimate the typical costs of disturbance reserves to ca. 0.7 EUR/MWh.

Balancing costs are included in the sheet **TechData**. Balancing costs are expressed as EUR per MWh and they are assumed to be constant over the technology lifetime.

Profile cost

The profile cost is used to express the relative value of generation to the electricity system or the electricity market. Basically, this is a question of timing: plants which are able to adjust their production according to the system demand have a higher value, whereas intermittent technologies such as wind power would usually have a lower value (Ea Energy Analyses, 2007).

The value of the electricity generation in the electricity market is compared to a common benchmark, such as the average electricity market price. If the technology earns less than the average electricity market price, the difference can be considered a profile cost. If the technology earns more than the average electricity price, this can be considered a profile benefit.

As the share of wind and solar power increases, the value of the generated electricity from these technologies will fall. The first installed capacity may replace expensive generation (e.g. oil-fired) and in some countries, the first MW's yield electricity prices above the average market price, because for instance solar generation coincides well with the electricity peak load. With additionally increased wind and solar generation, cheaper generation is thereafter replaced.

In Denmark, wind power has generated electricity 5-15% below average electricity market price (2002-2014). Strong interconnectors and close location to the large hydro capacities in Sweden and Norway is a major reason for the relatively low profile cost (price gap). Also Danish coal and biomass power plants that were originally designed as base load units have been transformed into some of the most flexible power plants in Europe. For example, the minimum load may be decreased down to 10% of the nominal capacity. Moreover, a number of flexibility measures have been introduced in the same period, including incentives to operate combined heat and power plants more flexibly.

Based on the German power system, the following relation for the value of wind and solar relative to the average electricity market price has been found (Mueller, 2015):

- Wind: 1.1 – 2.2 x W
- Solar: 1.2 – 4.8 x S

Where W = Market share for wind power, S = Market share for Solar.

Assuming an average electricity market price of EUR 40 per MWh we obtain the following profile costs at 5 % and 10 % penetration.

	5 % share	10 % share
Wind	0 EUR/MWh	5 EUR/MWh
Solar	2 EUR/MWh	11 EUR/MWh

Table 10: Estimated profile costs for wind and solar power in the German electricity system

Solar starts out better because its generation coincides well with peak loads, but with increasing penetration, the reduction is steeper than that for wind. This may be due to the fact that the smoothing of the variation is higher for wind. Moreover, wind turbines usually have higher capacity factors than solar PV, which becomes increasingly important at high penetration rates.

By default, the LCOE-calculator does not include system integration cost, as they are difficult to assess and highly dependent on the system in question. By setting the option 'Profile cost' to YES and defining the profile cost for the individual technologies in **TechData,** the impact of profile cost on LCoE can be included. Profile costs are expressed as EUR per MWh and they are assumed to be constant over the technology lifetime.

Grid costs

This cost element covers the necessary costs of expanding or strengthening the distribution and transmission grids when integrating a new technology. Furthermore, it includes increased or avoided line losses in the distribution and transmission grids.

It should be noted that in some cases the direct costs of grid connection (but not reinforcements) are included in the investment cost of the technology, for example in the Danish Energy Technology catalogue, (Danish Energy Agency and Energinet, 2018).

Grid-related costs are very site-specific as they depend highly on the location of the energy sources compared to the existing grid and the load centres. The IEA's publication "Projected Costs of Generating Electricity" (IEA, 2015a) includes a review of wind integration costs in the US and the EU. Usually grid costs of solar and PV projects lie in the range of 2-10 USD per MWh. In some cases, grid costs may even be negative if the location of new generation close to consumers may contribute to deferring investments. This is particularly the case in networks where upgrades are required due to anticipated load growth.

Solar PV is often placed at or near the point of power consumption. At low penetration levels this can also reduce losses in the distribution and transmission networks.

Grid costs are not included in the LCoE Calculator for the current technologies. The user may input his/her own values in the sheet **TechData** as part of 'Other cost', in EUR/MWh, or as part of the investment cost, if the total investment in EUR/MW is known.

3.8 Environmental externalities

When generating electricity, costs to the society (socio-economic costs) are incurred that are not reflected by the markets since they have no direct financial impact on the owner of the generating plant. This is the case for many environmental impacts. Such environmental externalities must therefore be estimated and accounted for separately when calculating the LCoE.

In some cases, the externalities are internalised through national or regional frameworks. This is for instance the case with the EU's emission trading scheme for CO_2 quotas even though prices have been very low in recent years. Many countries also impose taxes on the emissions of SO_2 and NO_x.

In other cases, the costs and benefits must be estimated based on the assessments of local, regional and global effects, i.e. the social costs of producing energy with each specific technology.

It is not easy to quantify such costs and benefits, and many of them will depend on the local or regional settings.

Environmental impacts

Studies based on life cycle assessment approach, e.g. the European ExternE project, (www.externe.info) have established that the most important environmental impacts of energy production are:

- Climate change due to emissions of greenhouse gasses
- Health impacts due to air pollution, including gasses and particles
- For nuclear power: Radioactive pollution during mining, and the risks associated with waste storage and decommissioning of plants.

There are many other relevant impacts associated with energy production, for example caused by emissions of toxic metals, dioxin, water use, degradation of land etc. However, these have been shown to be considerably less important than the three above-mentioned, and have been excluded in the LCoE Calculator for reasons of simplicity. Also, upstream environmental impacts (for example due to mining and transportation of fuels and manufacturing of equipment) are not considered, except for nuclear power for which radioactivity from mine tailings is considered.

Cost assessment

The environmental social costs per unit of energy produced for a technology is not a fixed parameter for all countries and circumstances. The costs depend on the emission factors (i.e. the amount of a polluting substance sent out per MWh produced with a technology) multiplied by the unit emission cost. The emission factors depend on the fuel types and on the technology configuration (for instance the filtering equipment installed in a plant). The unit cost of emissions depends on the location of the plant (for instance the health effects of particles emissions will depend on the population density in the area), and how the damage is valued in a particular country.

Health impacts can be measured as statistically increased mortality and morbidity, which can be converted to monetary terms by using for instance a Willingness to Pay (WTP) approach, i.e. what an average person in a certain country is willing to pay to reduce the risk of death and to obtain improved health. Further reference is made to (ExternE methodology 2005 Update, 2005) and (China National Renewable Energy Centre - Danish Energy Agency, 2014).

It should also be noted that the relation between health impacts and emissions is often not linear, so it is relevant to use a marginal view.
For these reasons the default values of the costs of the environmental externalities given in the LCoE Calculator should always be reviewed in a national and local context.
The sections below introduce the background for the Calculator's default values and mentions possible ranges and relevant sources of information.

Climate change

The emissions of the so-called greenhouse gasses, CO_2, CH_4 and N_2O have no direct local effects, but are a main cause for global warming and climate change, and the impacts thereof are projected to be long-term and irreversible.

Carbon dioxide - CO_2

Carbon dioxide is emitted in all combustion processes in connection with energy production. The emission is directly proportional to the amount of fuel used. The following emission factors have been included in the LCoE Calculator:

CO_2 Emission factors

Fuel	Coal	Natural gas	Fuel oil	Gas oil
CO_2 (kg/GJ fuel)	94	57	79	74

Table 11: CO_2 Emission factors by fuel (Danish Energy Agency, December 2014)

The combustion of biomass also emits CO_2. However, biomass fuels are by default considered CO_2 neutral because it is assumed that the same amount of CO_2 will be removed from the atmosphere when growing the plant material again after harvesting. The sustainability of using biofuels is subject to discussion and depends on many factors.

It is possible to enter CO_2 emission factors for new fuels and change the factors for existing fuels. This is done in the sheet **EmissionFactors.**

Methane - CH_4

Release of methane gas to the atmosphere is an undesirable effect of combustion processes, in particular technologies using natural gas or bio methane, there is a risk of high methane emissions.

Methane released into the atmosphere acts as a concentrated greenhouse gas, with approximately 25 times the global warming potential of CO_2. The emissions of methane are converted to CO_2 equivalents and priced accordingly.

The emission factors presented in Table 13 are based on the central values used by the Danish Energy Agency, but the exact emission factors can vary depending on the technology.

Nitrous oxide N_2O

Nitrous oxide is emitted from combustion processes and also works as a greenhouse gas in the atmosphere with a global warming potential of approximately 298 times that of CO_2.

The emissions of nitrous oxide are converted to CO_2 equivalents and priced accordingly.

The default emission factors used in the LCoE Calculator are presented in Table 13.

Technology	Nitrous oxide, N_2O (g/GJ fuel)	Methane, CH_4 (g/GJ fuel)
Medium CHP - Wood chips	0.6	2.2
Medium CHP - straw	1.1	0.5
Medium CHP - natural gas SC	1.0	1.5
Large CHP - wood pellets	1	-
Large CHP - coal	0.8	1.5
Large CHP - refurb. Wood pellets	0.8	0
Large CHP - natural gas CC	1.0	1.5
Coal FGD INT	0.8	1.5
Coal no FGD INT	1	2
Natural gas CCGT INT	1	2
Biomass plant INT	0.8	3.1

Table 12: Emission factors for greenhouse gasses CH_4 and N_2O by technology. Technologies without emissions not shown. (Danish Energy Agency, December 2014).

CO_2 cost assessment

The economic consequences of climate change are a major issue of research and are associated with considerable uncertainty.

One method to determine the costs is to try to assess the damages, also known as the ’social costs of carbon’. The IPCC 2012 report on Renewable Energy Sources and Climate Change Mitigation mention values 17, 35, and 90 USD/ton CO_2 (2005) for lower value, best guess, and high value. (IPCC, 2012).

Another method is to assess the costs necessary to limit the CO_2 emissions to a certain politically acceptable level, i.e. the cost of reducing the emissions. In countries where the emissions of CO_2 are regulated by a quota market, which aims at fulfilling certain reduction targets (such as the EU Emission trading system), the marginal abatement costs can - with some precaution - be interpreted as the quota price.

In line with the values proposed by the Danish Energy Agency for socio-economic calculations, the LCoE-Calculator contains CO_2 cost values in accordance with the IEA Worlds Energy Outlook scenarios (IEA, 2015a).

In ‘Basic user settings’ in **UserSettings&Results** , the user can choose between the following fuel price scenarios, which also contain CO_2 prices until year 2050:

Fuel price Scenario	Explanation
New Policy (default)	Based on New Policies Scenario, IEA 2015
450 ppm	High - Based on the 450 ppm Scenario, IEA 2015
Current Policies	Low – Based on the Current Policies Scenario, IEA 2015
CustomFuel	Allows the user to define a CO2 price scenario

Table 13: The LCoE Calculator's scenarios for CO_2 prices

The starting values for all scenarios reflect the current, low, European value of the CO_2 quota, which gradually increases to the 2020 value.
The following values for the European Union are used in the Calculator:

Year	New Policy 2015 (default)	450ppm 2015	Current Policies 2015	CustomFuel
	EUR/ton	EUR/ton	EUR/ton	EUR/ton
2015	7	7	7	7
2020	17	17	15	7
2030	28	75	23	11
2040	38	106	30	20

Table 14: CO2 price assumptions for the European Union as per the IEA WEO 2015 scenarios (EURO 2014 per tonne) (IEA, 2015)

Values listed by the IEA for other regions are provided in Table 16 for information.

	Region	Sectors	2020	2030	2040
Current Policies Scenario	European Union	Power, Industry and aviation	20	30	40
	Korea	Power and industry	20	30	40
New Policies Scenario	European Union	Power, Industry and aviation	22	37	50
	Chile	Power	6	12	20
	Korea	Power and industry	22	37	50
	China	Power and industry	10	23	35
	South Africa	Power and industry	7	15	24
450 Scenario	United States and Canada	Power and industry	20	100	140
	European Union	Power, Industry and aviation	22	100	140
	Japan	Power and industry	20	100	140
	Korea	Power and industry	22	100	140
	Australia and New Zealand	Power and industry	20	100	140
	China, Russia, Brazil, and South Africa	Power and industry	10	75	125

Table 15: CO2 price assumptions in selected countries by scenario (USD 2014 per tonne) (IEA, 2015)

Health impacts of air pollution

The health effects of air pollution from electricity generation are mainly local and regional. The most important emissions are SO_2, NO_x and particles.

<u>Sulphur dioxide - SO_2</u>

Combustion processes emit sulphur dioxide corresponding to the fuel's sulphur content, reduced by the measures taken to remove it from the flue gasses, i.e. the desulphurisation share. Thus, the emission factors depend both on the fuel and on the technology.

SO_2 emission factors

Fuel	Coal	Natural gas	Straw	Wood chips	Wood pellets
SO_2 (kg/GJ fuel)	0,270	-	0,200	0,004	0,004

Table 16: Sulphur content by fuel. (Danish Energy Agency, December 2014).

Coal is a major source of sulphur dioxide emissions but the content can vary largely, from 0.5% up to 10 % depending on the origin. Especially lignite ("brown coal") can have very high content of sulphur. The values presented in Table 17 correspond to black coal with low sulphur content.
Natural gas from many sources contains sulphur, but most of it is normally removed when processing the gas.

The default values for desulphurisation efficiency in percent, presented in Table 18, correspond to the current Danish standards.

Technology 2020	Desulphurisation (% of sulphur removed)
Medium CHP - Wood chips	98%
Medium CHP - straw	96%
Medium CHP - natural gas SC	0%
Large CHP - wood pellets	0%
Large CHP - coal	97%
Large CHP - refurb. Wood pellets	97%
Large CHP - natural gas CC	0%
Large CHP - natural gas	0%
Coal FGD INT	95%
Coal no FGD INT	0%
Natural gas CCGT INT	0%
Biomass plant INT	0%

Table 17: Desulphurization share by fuel. (Danish Energy Agency and Energinet, 2018)

The user may enter different values in the LCoE Calculator to represent technologies with different properties.

Health effects

Air pollution with sulphur dioxide affects the local and regional environment, making it is toxic to humans and causing heart and lung diseases, thereby leading to increased mortality and morbidity rates. The damage caused by this can be assessed in different ways. The value used by the Danish Energy Agency of EUR (2011) 12.7 per kilogram of SO_2 is used as the default in the Calculator (Danish Energy Agency, December 2014).
In a study focusing on China (China National Renewable Energy Centre - Danish Energy Agency, 2014) a marginal benefit value of SO_2 reductions with respect to human health of 4.76 RMB (2010) / kg SO_2 is used, equal to ca. 0.5 EUR.

A European study carried out by the European Environment Agency in 2014 indicated values in the range of 9.8 – 28.6 EUR (2005)/kg SO_2 pollution. (European Environment Agency, 2014).

Besides human health effects SO_2 causes acidification that affects forests and lakes, and is corrosive to building materials.

Nitrogen oxides - NO_X

Nitrogen oxides, NO and NO_2, etc., are formed in combustion processes due to a combination of reaction of the components in the air and the nitrogen in the fuel. The concentration increases with the combustion temperature. NO_X emissions can be reduced by various means, for instance by controlling combustion temperatures resulting in lower concentrations to be created, or by catalytic and chemical reduction that removes the NO_x before it leaves the stack. Thus, the emission levels depend both on the fuel and on the technology.

Table 19 indicates the default values that reflect the typical Danish values in accordance with the current emission limits in Denmark, and also international values, obtained from (EPRI, 2012).

Technology 2020	Nitrogen oxides, (g/GJ fuel)
Medium CHP - Wood chips	72
Medium CHP – straw	70
Medium CHP - natural gas SC	15
Large CHP - wood pellets	21
Large CHP – coal	35
Large CHP - refurb. Wood pellets	21
Large CHP - natural gas CC	15
Coal FGD INT	196
Coal no FGD INT	196
Natural gas CCGT INT	39
Biomass plant INT	43

Table 18: Nitrogen oxides emission factors by technology. (Danish Energy Agency, December 2014) *and* (EPRI, 2012).

Health effects of NO_x

NO_x released in the atmosphere contributes to the oxidation of VOC (volatile organic compounds) in a photochemical process which creates ozone. This takes place both on a local and regional scale and results in formation of micro particles that creates smog. Also NO_x plays a role in nutrient enrichment and acidification of the environment, which has effects on the natural environment.

Both the ozone, photosmog, and products of other chemical reactions involving NO_x, give rise to human respiratory problems and other diseases, which lead to increased mortality and morbidity. Furthermore, the smog reduces sunlight intensity and thereby agricultural yields.

The cost of damages can be assessed in different ways. The values used by the Danish Energy Agency of 6.6 EUR (2011)/kg NO_x are the default values set in the LCoE Calculator.

For comparison, a study focusing on China (China National Renewable Energy Centre - Danish Energy Agency, 2014) uses a marginal benefit value of SO_2 reductions with respect to human health of 21.4 RMB (2010) per kilogram NO_x , equal to ca. 2.38 EUR/kg (2010).

A European study carried out by the European Environment Agency in 2014 indicated values in the range of 4.4 – 12.0 EUR (2005)/kg NO_x (2005). (European Environment Agency, 2014).

Particles - $PM_{2,5}$

$PM_{2,5}$ are small particles with a size of 25 microns and below. These are both emitted directly from combustion processes and formed in the atmosphere under influence of SO_2 and NO_x. The intensity of the emissions depends on the fuel, and on the technology, especially on the filters applied following the combustion processes.

Table 20 present the default values that reflect typical Danish values that respect the current emission limits and international values, taken from (EPRI, 2012).

Technology	Particles $PM_{2.5}$ (g/GJ fuel)
Medium CHP - Wood chips	0.3
Medium CHP – straw	1.1
Medium CHP - natural gas SC	0.1
Large CHP - wood pellets	0.3
Large CHP – coal	2.1
Large CHP - refurb. Wood pellets	0.3
Large CHP - natural gas CC	0.1
Coal FGD INT	13.4
Coal no FGD INT	13.0
Natural gas CCGT INT	-
Biomass plant INT	13.25

Table 19: Particles $PM_{2.5}$ emission factors by technology. (Danish Energy Agency, December 2014) *and* (EPRI, 2012).

Health effect of particles

The health effects of particles are heart and lung diseases, thereby leading to increased mortality. Furthermore the smog reduces sunlight intensity and thereby agricultural yields.

The health effects of particles will vary from one region to another depending on the population density, the pollution dispersion patterns, and the atmospheric chemistry.

In the LCoE Calculator, a default cost of 3.2 EUR/kg particles is used, in accordance with the Danish Energy Agency.
A European study carried out by the European Environment Agency in 2014 indicated values of 23-66.7 EUR (2005)/kg particles pollution PM_{10} (2005). The cost of PM_{10} particle impact is converted to $PM_{2.5}$ by multiplying the former with a generic factor of 1.54 based on (European Environment Agency, 2014).

This accounts for the effects of the emitted particles. The effects of the particles formed in the atmosphere due to the NO_x and SO_2 are accounted as a part of these emissions.

Radioactvity

The external costs of radioactivity are only connected with the use of nuclear power. Four types of externalities are often discussed in relation to nuclear power:

- Possible nuclear accidents (dissemination of radioactive substances)
- Radioactive emissions from mine-tailings
- Long-term storage of radioactive waste
- Decommissioning of nuclear power plants

The fuel costs of nuclear energy used in the LCoE Calculator, derived from the IEA Projected Costs of Generating Energy 2015 study, are reported to include both front-end and waste management costs, as well as decommissioning costs of plants. Thus, the two last externalities listed have in fact already been internalized in the context of the default fuel costs of nuclear energy used in the Calculator.

Assessment of the costs of radioactivity in connection with nuclear power is a complex and challenging issue, and different studies on the topic arrive at very different values. The damage is largely connected with the risks of accidents and unwanted events and therefore based on assumptions or statistics regarding the probabilities for such incidents. Further, the consequences may be very extensive and difficult to quantify since they may have vast long-term consequences. There are some examples of major reactor faults and following emissions of radioactivity, and in principle a top-down approach can be used to assess the costs based on such past experience.

However, it may be argued, that plants built in the future will be safer and involve less risk than the already operating plants. A bottom-up approach based on risk assessments of specific new plants will therefore lead to quite different and lower damage values.

According to ExternE radioactive emissions from abandoned mine tailings is another important externality of nuclear power. The emission of Radon 222 will continue for at least 10,000 years. It is uncertain to what degree humans will become exposed to this and, as for the accidents, there is no commonly-agreed methodology for valuation of very long-term damages.

With reference to the ExternE and the Recabs project carried out for IEA-RETD in 2007, the calculator uses the following default values:

Nuclear accidents:	2.5 EUR/MWh (2005)
Radioactive emissions:	1.5 EUR/MWh (2005)
Total damage cost:	4.0 EUR/MWh (2005)

It shall be noted that these values are associated with very high level of uncertainty.

Other externalities

Depending on the individual case explored using the LCoE Calculator, additional externalities, environmental or other might become relevant. This could for instance relate to the use of land, water or other resources, damages to natural environment, etc. In principle, such costs could also be negative values, which would correspond to a benefit obtained. This could be for instance the value of job creation, or other socio-economic benefits.
It is possible for the user to add other costs specifically for each technology. This can, however, only be done by entering the data in EUR/MWh units in the sheet **TechData** in the column M.

3.9 The EE-module

The Levelized Cost of Energy Efficiency (EE module) aims at calculating the costs of saving electricity by implementing different energy conservation and efficiency measures. As for the generation cost calculation the energy efficiency costs are levelled over the expected life time of the investment.

The calculated EE cost does not include the benefit from saved electricity demand. Rather, the result of the EE calculations is the minimum cost of electricity required for the efficiency measure to break even. The idea is that the EE costs for a certain initiative can be compared with the socio economic costs of delivering electricity to the consumer. If the costs for a certain energy efficiency measure are lower than the expected generation cost - including the costs of distribution to the consumer – it will, in general, be beneficial to implement.

The EE module can be used for both very specific measures, e.g. replacing the ventilator drive in a specific building, or for generalized and grouped measures to assess the overall potential and economy of a group of measures, e.g. all street lamps in a city, or replacing all pumps in sewage water treatment systems of a country.

The EE module of the LCoE calculator illustrates this for a number of examples of typical energy efficiency measures within different application areas. However, the EE module is only a way to illustrate and compare the cost of saved energy for different measures on the basis of a few already computed inputs. It does not itself calculate the energy savings and associated costs.

Technology data

The EE module's examples of applying different energy efficiency technologies are founded in realistic cases. However, since they depend on specific conditions and assumptions, the values shall only be taken as examples and it is up to the user to apply data for relevant measures in a local context.
The data for the case examples are explained in annex. 1.

The examples comprise the following:

LCoEE calculator examples			
Application	**Technology**	**Example 1**	**Example 2**
Office ventilation	Electric motors, and variable speed drives	Adding a VSD to existing ventilator system	Replacing the ventilator unit of existing ventilator system
Pumps	Pumps for water supply	Replacing old pumps with new efficient pumps and VSD controller	(none)
Motors	Electric motors for industrial use	Replacing an old motor with a "high efficiency motor"	Replacing an old motor with a "Premium efficiency" motor
Lighting in commercial buildings	LED lighting	Replacing fluorescent lamps with LED	Replacing halogen lamps with LED
Window in domestic building	Window insulation	A window is replaced by a new window with double layer pane. Electricity consumption for electric heating is saved.	A window is replaced by a new window with triple layer pane. Electricity consumption for electric heating is saved.

The main purpose of the calculator is to provide a framework, which allows the user to add own technologies and cases of energy efficiency applications.

Inputs to the EE calculator are given in the sheet **EETechData&Calculation**.

Scope of the energy saving measure to be defined

The user is required to first define the scope of the measure considered (capacity and yearly load profile, or yearly energy consumption). This scope could vary depending on what the user wishes to illustrate, and could be e.g. 'ventilator system in a 1.000 m^2 office building' or 'all street lamps in Shanghai'.

'Before' and 'after' situation

Thereafter the user must specify the relevant technology and economic data corresponding to the defined scope in a situation before and after the measure being taken. This could be either a situation of replacing or rebuilding of equipment, or a choice between two possible design solutions.

Electricity consumption

The user needs to state the yearly energy consumption before and after the energy saving measure. (kWh/year). This will also imply assumptions about the pattern of use, e.g. the load duration curve of the ventilation systems or the number of hours with street lighting.

Investment costs

The corresponding investment for the before and after situation also has to be provided. If the measure is a replacement of an already functioning solution one may choose to omit the investment in the before situation. In case of comparing two alternative solutions, the investment costs are defined for both of these.

Operation and maintenance (O&M) costs

If the measure leads to changes in O&M costs these shall be entered separately for the before and after situation.

The calculator has the possibility to segregate between fixed O&M costs, i.e. yearly costs disregarding the use time (EUR/year), and variable O&M costs, which depend on the energy consumption (EUR/MWh). Depending on the relevance both of these values, one or none can be entered. For many applications the O&M costs will be negligible in comparison with capital costs and the energy costs. For instance, an electric motor requires very little maintenance during its lifetime and a light bulb none at all.

Expected lifetime

The expected lifetime for the energy saving measure shall be entered for the 'before' and 'after' situation as well.

If the solutions have different lifetimes the calculation will take this into account. The lifetime shall correspond to the time during which the solution is expected to be in operation. In some cases, this will be equal to the technical lifetime and in some cases it may be shorter. For instance, the economical life time may be limited by commercial conditions, which is often the case for industrial investments.

Forced replacement or choice between alternative investments

The calculator can be used to compare EE measures in two ways.

Forced replacement

In case of comparing a measure with an already functioning appliance with a remaining lifetime, one speaks about a 'forced replacement'. In this case the investment in the 'before' situation is omitted, since the equipment is assumed to be scrapped. However, since the lifetime of the new solution (the 'after' situation) is most likely longer that the remaining lifetime of the old equipment, the LCoEE is actually only valid for a time corresponding to the remaining lifetime of the old equipment. After that time, the investment should have been made in any case and the situation would therefore correspond to a choice between alternative investments.

The LCoEE is calculated on the basis of the expected lifetime of the new measure and does not take the expected lifetime of the old equipment into account.

Choice between alternative investments

In the other case, it is assumed that the old equipment is worn out and therefore has to be replaced. Here the calculator can be used to compare the LCoEE's of two (or more) alternative solutions. This is done by entering two alternative data sets in the calculator's input table for '-example 1' and '-example 2'. The alternatives may have different values for one or more of the input values, e.g. different lifetimes, investment costs, energy consumptions, etc. When comparing different solutions it is important to ensure that they provide the same energy service to the user.

Discount rate

The discount rate is used to determine the annualised present value of the energy efficiency investment. As for the generation cost calculations, an annual rate of 4% real is applied as a default value. This is the rate, which the Danish Finance Ministry recommends for socio-economic analysis. The user can set the discount rate to any other rate preferred. For comparison, the IEA applies 3 %, 7 % and 10 % in the latest *Projected Costs of Generating Electricity* (IEA, 2015a).

When changing the discount rate, the annualisation of capital costs is influenced. Therefore, the discount rate will influence measures with high investment costs the most.

Discount rate adjustments are made in the sheet **EEUserSettings&Results** in the section 'Basic user settings'.

Value	Data source
Basic settings	
4%	Guide in socioeconomic analysis from the Danish Energy Agency. (Danish Energy Agency, December 2014)
User options	
The user can set any other values instead of the basic setting	

Table 20: Settings for discount rate in the LCoEE calculations

Network tariffs

The cost of supplying electricity to consumers comprises both production and network tariffs (transportation costs). Therefore, network tariffs have to be added to the levelized costs of electricity generation in order to make a fair comparison with electricity saving measures.

Ideally, the network tariffs should express the marginal costs associated with a change in electricity demand, i.e. the grid losses associated with a marginal change in electricity demand, the change in investments in the grid associated with a marginal change in electricity demand and the change in operation and maintenance costs associated with a marginal change in electricity demand. In practice, such information is difficult to derive.

Alternatively, the prevailing distribution and transmission tariffs, can be used as an estimate of the network tariffs. Still, in some countries, it can be difficult to make the breakdown of costs between generation and transport cost. This is particularly the case when the one company is responsible for both production and transportation of electricity.

Typically, the grid tariffs diverge between consumers according to the size of consumption. Large electricity consumers like industries pay a lower cost per unit than households and small enterprises.

In the 2015 transmission tariff overview from Entso-E the average transmission tariff in Europa is found to be 7.98 Euro per MWh for both households and industries (Entso-E, June 2015). A survey done for the European commission in 2015 finds that average distribution tariffs in Europe were 49 Euro per MWh for households, 35 Euro per MWh for small industries, and 10,5 Euro per MWh for large industries, 2013 prices. (AF-Mercados, REF-E and Indra, 2015). Fig. 11-13.

Based on this information a total grid cost of 50 Euro per MWh for households and small enterprises and 20 Euro per MWh for larger industries is applied as default data in the LCoEE-calculations in the **EEUserSettings&Results** sheet. The user has the option to change these values in the basic user settings. As default the grid cost for households and small enterprises is applied in the calculations but this can be changed by the user to the industry grid tariff in the basic user settings.

User choice	Value	Data source
Household/small enterprise	**Basic settings**	
	EUR 50 per MWh electricity	Based on data from ENTSO-E and report for the European commission
	User options	
	Any other grid price	
Industry	**Basic settings**	
	EUR 20 per MWh electricity	Based on data from ENTSO-E and report for the European commission
	User options	
	Any other grid price.	

Table 21: Settings for network tariffs in the LCoEE calculation.

4 Illustration of results

This chapter presents an overview of the results obtained using the LCoE-Calculator. First for the eight key electricity generation technologies, and secondly for the energy efficiency investments.

The inputs used in the electricity generation calculations include the default technology data, the fuel prices, and the assumptions on system and environmental costs presented in Chapter 3. The results also highlight the different cost elements of the technologies, their relative cost competitiveness, as well as the factors that are of particular importance to their respective LCoE.

The results should be considered as solely illustrative, however, as many of the cost elements will differ from country to country depending on e.g. the investment cost levels, the flexibility of the power system, the estimated cost of air pollution, regional differences in fuel prices etc. Hence, in order to carry out an assessment of electricity generation costs in a specific country using the LCoE-Calculator, it is important to apply the relevant local and national data. Nonetheless, the results do provide a good indication of the cost relationships in general, as well as highlight the factors that have the most significant influence on the LCoE for the technologies in question.

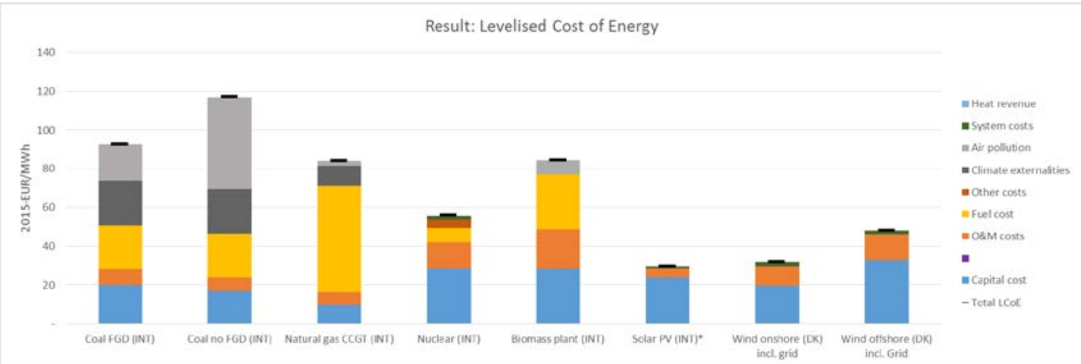


Figure 3: Comparison of the levelized cost of electricity generation.

Key Assumptions: Technology data primarily from "Projected cost of generating electricity 2015" (IEA, 2015). However financial (CAPEX and OPEX) data for PV and wind are from the Danish Technology Catalogue. Annual full-load hours for coal, gas and biomass technologies: 5,000, nuclear power: 7,000, onshore wind power: 3,150, Offshore wind power 4,500, solar PV: 1,700. Discount rate: 4% real. Projection prices for fuel and CO_2 are from the IEA New Policy Scenario 2015, World Energy Outlook, 2015. FGD: flue gas desulphurisation.

Based on the default input data (as described above), the results indicate that photovoltaic (PV) and onshore wind exhibit the lowest LCoE, when all cost elements are considered, as illustrated by Figure 3. The results also highlight the fact that external environmental and system costs can have significant influence on the LCoE.

4.1 Important factors for each generation technology

Wind and solar

The energy generation costs of wind and solar power are very site-specific, as they depend on the available wind and solar resources. Moreover, the costs of system integration are very dependent on the penetration level of intermittent renewable energy sources, and the flexibility of the surrounding electricity system. In the example, the system costs are based on projections for Denmark. Denmark has a very high share of wind power (39 % in 2014), but also demonstrates a very flexible electricity system. For a low share of wind power, the integration costs are likely to be significantly lower. Similarly, in many electricity systems the integration costs of PV are likely to be negative at low penetration levels but more substantial than indicated in the graph, at high penetration levels.

Nuclear power

The LCoE of nuclear power is particularly sensitive to the level of investment costs and the choice of discount rate. The costs reported in the IEA's "Projected cost of generating electricity 2015" (IEA, 2015a) show very large differences in the investment costs from country to country. Also, the external costs of nuclear power, comprising among others the risk of major accidents with long-term effects, are difficult to assess in monetary terms.

If a discount rate of 10 % is applied, the LCoE of nuclear power is more than doubled. Another sensitive assumption is the technical lifetime which is set to 60 years in accordance with the IEA's "Projected cost of generating electricity 2015" (IEA, 2015a). Furthermore, each country can value the environmental externalities from nuclear power differently.

Biomass plant

The cost of the biomass feedstock is an important factor for the cost of generating electricity from biomass. The default calculation assumes that biomass is purchased at a price of EUR 2.6 per GJ. If biomass residues are available at very low or no cost, biomass is close to being competitive with PV and wind power. The default calculation assumes no environmental equipment such as dust filters are applied to the biomass plant.

Coal power

With regard to coal-fired power production, the cost of local air pollution may turn out to be a determining factor for the LCoE. The example investigates the

LCoE of coal power with and without desulphurization equipment. The results show that the cost of increased air pollution by far exceeds the assumed additional capital costs of the environmental installations.

It should be mentioned that the Danish experience demonstrates that it is possible to construct coal-fired power plants with environmental costs that are significantly lower (approx. EUR 5 per MWh) than those of either of the coal-fired power technologies shown in the illustration. However, this implies further investments in environmental equipment and therefore a higher level of capital costs. Climate change costs of the coal-fired power plants are also significant, depending, however, on how the CO_2 emissions are valued.

Natural gas

The LCoE of natural gas-fired power plants is particularly sensitive to the fuel price, which varies considerably from region to region. Both capital costs and environmental costs are moderate.

Overview of technologies

In Table 23 below, we have summarized the cost components of particular importance to the LCoE of different types of technologies.
One dimension is the actual cost contribution of a component, i.e. how large a share of the total LCoE does the factor contribute with. The other dimension is the uncertainty and variability connected with the cost components, as described above, but disregarding if the uncertainty occurs when deciding on an investment or over its lifetime.

The weighting of these two dimensions is reflected by the following colour-coding.

	LOW UNCERTAINTY	**MEDIUM UNCERTAINTY**	**HIGH UNCERTAINTY**
HIGH COST			
MEDIUM COST			
LOW COST			

Technology	Capital costs	Fuel price / Availability of local resources	Heat sales	System costs	Climate change costs	Air pollution/ other environmental costs
Coal			Potentially important revenue stream		Depends on climate regulation	Depends on emission control / filtration equipment costs
Natural gas CCGT		Significant regional differences	Potentially important revenue stream		Depends on climate regulation	
Biomass		Varies with access to local resources	Potentially important revenue stream			Depends on emission control / filtration equipment costs
Nuclear	Large differences in investment costs. Discount rate important			Back-up costs		Storage of radioactive waste. Risk of accidents.
Wind		Access to good wind sites		Depends on wind share and system flexibility		
PV	Considerable technological development	Solar irradiation		Depends on PV share and system flexibility		

Table 22: Cost components of particular importance to the LCoE

Future technological development

The costs hereby presented are based on price and performance assumptions representative of technologies that are available in the market in 2020. The costs of solar and wind power have dropped significantly in the last 20-30 years, and technological progress and economies of scale are expected to drive their cost reductions further. This is an aspect to consider, particularly when comparing technologies with significantly different technical lifetimes. The investment in nuclear power involves a technical lock-in for an estimated 60-year period, whereas the lock-in period for e.g. PV and wind is only 25 years.

The user can generate results with future technical data expected for the years 2015, 2020, 2030, and 2050. The default data for future years' projections are estimates of the expected development of the different power production technologies, based on the Danish Energy Agency's expectations for Denmark.

4.2 Comparing generation costs to energy efficiency investments

The result of the EE-calculations is a cost interval (or single value) indicating the costs of investing in energy efficiency. As with the generation costs, the EE-calculations should be considered as solely illustrative. Regional differences in temperatures, building standards etc. will cause different results. Hence, in order to carry out an assessment of energy efficiency investments in a specific country using the EE-module, it is important to apply the relevant local and national data.

The cost of an energy efficiency investment is expressed as the costs per saved MWh of electricity and can therefore be compared to the electricity generation costs per MWh. This will illustrate the break-even between the chosen EE-technologies and production units. Figure 4 is the default view of this from the LCoEE-calculator. The shaded area for each EE measure represents a span of LCoEE cost for different options.
For instance, it can be seen that the modelled measures for replacing industrial electric motors will – in both options – be able to create cheaper energy savings than producing the same amount of energy with any of the shown generating technologies, especially when the saved distribution costs are also taken into account.

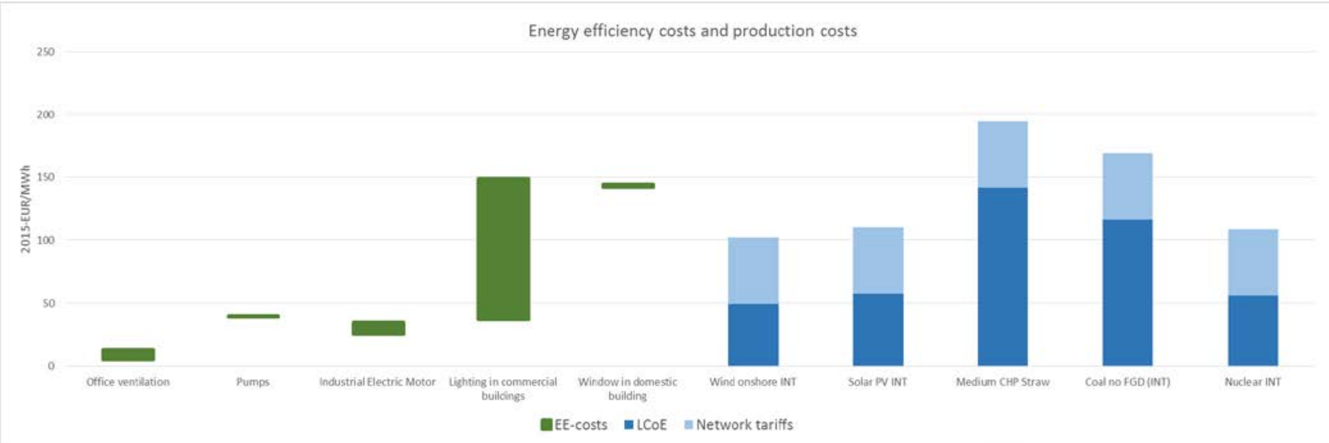


Figure 4: Comparison of levelized cost of energy production (LCoE) and levelized cost of energy efficiency investments (LCoEE)

It shall be noted, that the figure only shows some selected examples of energy efficiency measures. These numbers may vary depending widely on the examples chosen. In general, measures taken for appliances with high energy consumption and high operating times will lead to lower LCoEE costs.

This way of comparing energy savings and energy production costs represent a simplified view. The method is based on average accounts and does not consider when the demand occurs. Thus, it only considers ‘energy’ (MWh/year), assuming that the need is distributed over the year, and does not consider need for ‘capacity’ (MW). The capacity need and energy need does not necessarily follow each other closely.

The need for power vs. energy will be different for appliances with constant loads and higher operating times, for instance pumps in water supply, than for appliances with high short-term power needs during peak hours.
Also, it can be discussed whether and how far investments in new grid capacity can be avoided in case of energy savings. In case of systems with growing energy demands it will be more true than in situations where the demand is constant or decreasing.

5 Usage of the spreadsheet

The LCoE-calculator is an open source model built in MS Excel, and it can be freely customized by the user. That is, no cells are locked, and all calculations are visible to the user.

The spreadsheet consists of three 'types' of sheets, each marked with a different colour. Grey sheets contain guidance and information for the user, the green sheets contains the calculations, the results, and the basic user settings, and the yellow sheets contain all the input data used in the calculation. Two different green colors are applied, a light for the generation cost calculations and a dark for the EE-calculations. On the **UserGuide** sheet, instructions and links as to where to find and change data are given, with further instructions provided in each sheet.

Figure 5: The different sheet types in the spreadsheet

5.1 Generation costs

The user has the option to change the input data or add his or her own in the generation cost calculations. This is defined as advanced user settings in the calculator, while much of the data can be adjusted very easily with the Basic User Settings on the **UserSettings&Results** sheet. Some of the basic user settings have predefined choices, e.g. the technology scenarios, while others (e.g. the interest rate) can be chosen freely. The **UserSettings&Results** sheet also contains a graph displaying the results of the calculation.

The technologies to be compared are set in **UserSettings&Results** and defined by the technologyname ('Technology') and the database to take technology-defintions from (see further details below). If the technology year and first year of operation should differ from the standard setting in the basic user settings, this can also be defined here. Finally a customized name to be shown on the result graph can be defined.

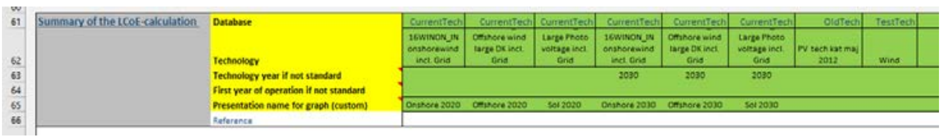


Figure 6: Chosen technologies in UserSettings&Results

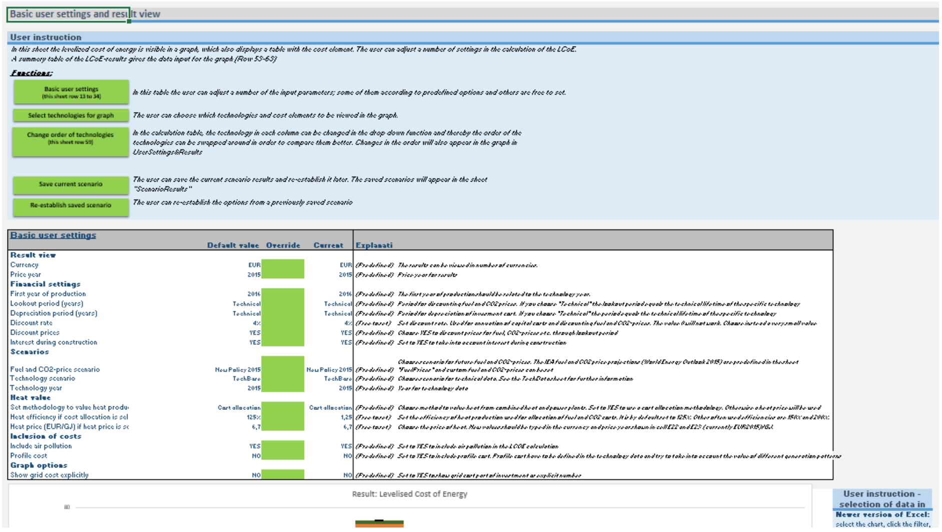


Figure 7: The instructions and Basic User Settings in the Calculation sheet

For both technology data, and fuel data, three pre-defined scenarios are provided in the spreadsheet, and can be chosen by the user under Basic User Settings in the **UserSettings&Results** sheet. The data underlying each scenario is provided in the **TechData** and **FuelPrices** sheets, respectively. In addition, the user can define a custom values for both the technology data and the fuel prices.

Three different 'databases' are available for technology data: **OldData, TechData** and **TestData.** TechData holds the standard technology definitions, while the **TestData** sheet can be used to add own technologies or test different assumptions. Data from the **TestData** sheet can be transferred to the TechBase scenario in **TechData** using the 'Add new technology' button in **TestData**. The existing data in the **TechData** sheet can also be customized by the user. Changes to the technology data in **TechData** can be logged using the **DataLog** sheet. The data log-function will compare the current technology data in **TechData** to the data from the previous log and show the changes in the **DataLog** sheet.

Customized fuel price data can be added in the **FuelPrices** sheet as CustomScenario, CustomScenario2 and CustomScenario3. Corresponding CO2-prices should be added in the **EmissionPrices** sheet. In addition to customizing the already defined fuel types, the user has the option to add his or her own fuel types. New fuels might be relevant to add when e.g. new technologies are added. These can be added under the fuel price scenario, which the user wishes to apply, in the **FuelPrices** sheet.

All emission factors are assumed to be constant. As are the emission prices, with the exception of the CO_2-price, which is linked to the choice of fuel scenario. The user can change either the constant value or insert a time series. Please note that the remaining emission factors (NO_X, CH_4, N_2O, and $PM_{2.5}$) are given in the **TechData** sheet and are not all constant.

A number of pre-defined currencies can be chosen in the Basic User Settings on the **UserSettings&Results** sheet. These are provided in the **CurrencyRates** sheet, where they can also be updated by the user by overwriting the existing ones.

User scenarios

The spreadsheet offers the option to save the current result as a user scenario by using the button 'Save current scenario' in **UserSettings&Results**. This will save the current results and the corresponding basic user settings in **ScenarioResults**. The results can be reestablished using 'Reestablish scenarios'. Note, that changes form e.g. changed technology or fuel data will not be reestablished.

5.2 Energy efficiency investments

The energy efficiency calculations and result viewing is found on the two dark green 'EE'-sheets (**EEUserSettings&Results** and **EETechData&Calculation**).

On the **EETechData&Calculation** sheet two data sets (named as example 1 and example 2) for five different technologies are provided. The user can overwrite or change these if desired. Tables for additional technologies are prepared to the left of these, with the names technology 1 – technology 10. In the same table the calculations are also done. If data in the 'example 2' table is omitted a single value instead of an interval for the technology will be displayed.

On the **EEUserSettings&Results** sheet a number of calculation and illustration options are given in the Basic User Settings table. Some of the settings have predefined choices while others can be chosen freely. Below the settings table a graphical illustration of both the results of the EE-calculations and the generation costs are presented. The user should be aware of particularly the choice of currency and interest rate when comparing the EE-calculations with generation costs, and these are parameters in both calculations.

When comparing EE and generation costs in the **EEUserSettings&Results** sheet, grid costs are as default added to the generation costs in order to reflect the actual socio-economic cost of consuming electricity. The user have the option to deselect the addition of grid costs in the basic user settings. Also the level of grid costs (industry or household/small enterprise) can be designed by the user.

As with the generation cost calculations different currencies can be chosen, and they can be updated in the **CurrencyRates** sheet.

6 Notes on data sources for specific countries

As mentioned, it is vital for obtaining valid results in specific countries or regions that the user provides representative input data. The following notes provide some assistance to the methodology relating to the collection of suitable data sources. In general, there can be to ways to obtain local data, which may be combined

Top-down approach

In a top-down approach data can be taken from generalized technology catalogues and other relevant reports from the relevant country or region. Such data sources can be found in literature studies and some examples are given in this report (see References). In lack of data, one may look for data sources from neighboring and/or comparable countries or more general international sources, like the IEA. Such data can then be corrected for assumed deviations due to country specific conditions, e.g. labor rates and geographical resources. Some cost factors, like the cost of labor or local fuels, will often be lower in developing countries. On the other hand, if a specific investment depends largely on imported equipment or specialized knowledge, it may be more expensive to develop the project in developing countries even though the general cost level is lower.

A report with technology data for South Africa (EPRI, 2012) includes a methodology for adjusting construction costs, in this case from US to South African price level, concerning both labor- and material costs.

Bottom-up approach

In a bottom-up approach data can be derived from actual projects established or analysed in the country or region. Recently commissioned power plants or feasibility studies may provide valid information. The bottom-up approach could also include interviews and surveys of potential supply companies for power plants in the relevant country. Data obtained bottom-up may be biased and project specific and therefore need to be filtered. Preferably, bottom-up data should be collected from multiple sources to take statistical variations into account when generating aggregated values.

Investment, operation and efficiency data

The first choice for technology costs and data sources should be statistical or sample data reporting on actual realized deployment of the technology in question in the relevant country or region.

It shall be noted that variants of a technology, e.g. a power plant, which have high efficiencies and/or advanced environmental systems, are typically linked to higher investment (and possibly operation) costs than a simpler variant. Hence, the cost parameters should always be regarded jointly with the performance parameters.

A benchmark for how investment and O&M costs vary from country to country can be found in the IEA Projected Costs of Generating Electricity (IEA, 2015a), which contains data from 19 OECD countries and 3 other countries. For renewable energy technologies the report “Renewable power generation cost” (IRENA, 2015) contains valuable additional information.

Full load hours	The assumptions on full load hours should take into account the expected need for power. In some countries, there is mainly a demand for baseload power, for example if the general power demand is increasing rapidly, whereas in other countries there is primarily a need for mid or peak load capacity to serve demand in certain periods of the day. The number of full load hours for different technologies may be analyzed by using dispatch and load simulation models. The full load hours for renewable energy technologies depend mainly on the local resources in terms of wind and solar irradiation. Further notes on this is given in section 3.3
Fuel prices	The price of imported coal and oil are largely the same in different regions of the world whereas for example the price of natural gas and many types of biomass may differ considerably. For local fuels such as biomass the prices would have to be estimated on the basis of analysis of available resources, e.g. from agriculture or forestry. This is described in more details in section 3.4 in this report, in (IRENA, 2015), and in (IEA, 2015).
System integration costs	As described in section 3.7 the system integration costs depend largely on the power system to which the plant is applied. Assessments of such costs are generally connected with high uncertainties. IEA’s Harnessing Variable Renewables (IEA, 2011) gives an overview of national and international studies carried out to assess system integration costs of renewables in various countries, and provide case examples and methodology for assessments for various regions and countries. These methodologies and comparisons can be helpful when doing local studies. Detailed power market analyses using simulation tools would normally be required to properly estimate profile costs. It should be noted that in some cases the direct costs of grid connection are included in the investment cost of the technology.

Environmental externalities

The effects of CO_2 emissions are generally worldwide, and hence cost values should be comparable. Projected values for different regions are listed in section 3.8. The effects of air pollution are mainly local and regional, though, and can only be analysed by quite complex methods. Besides the geographical properties such as climate and population density, the costs also depend on how the value of statistical life is assessed in different countries. A study from China (China National Renewable Energy Centre - Danish Energy Agency, 2014), illustrates one possible methodology.

It shall be noted that there may exist local environmental and other externalities, which are not mentioned in this report even though they represent considerable costs. Examples of such could be water use in arid regions, use of land in heavily populated areas, irreversible extinction of species in rain forest areas, and noise from wind turbines. Such costs can be evaluated on the basis of local studies and can be included in the LCoE Calculator as relevant.

7 References

AEA Technology. (2005). *Damaegs per tonne emission of PM2.5, NH3, SO2, NOx and VOC's from each EU memberstate (excluding Cyprus) and surrounding seas.* Oxon: AEA Technology.

AF-Mercados, REF-E and Indra. (2015). *Study on tariff design for distribution systems, Final Report.* EU Commission, DIRECTORATE-GENERAL FOR ENERGY.

China National Renewable Energy Centre - Danish Energy Agency. (2014). *Economic Evaluation of Externalities from air-pollution in the Chinese Energy Sector.*

Danish Energy Agency and Energinet.dk. (2014). *Technology data for energy plants.*

Danish Energy Agency. (December 2014). *Forudsætninger for samfundsøkonomiske analyser på energiområdet (Guide in socioeconomic analysis from the Danish Energy Agency).*

Ea Energianalyse. (2014). *Biomassepriser an forbrugssted.*

Ea Energy Analyses. (2007). *RECABS.* IEA Renewable Energy Technology Deployment, RETD.

Entso-E. (June 2015). *ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2015.* Entso-E.

EPRI. (2012). *Power Generation Technology Data for Integrated Ressource Plan of South Africa.* Palo Alto, CA: EPRI.

European Environment Agency. (2014). *Costs of air pollution from European industrial facilities 2008-2012, EEA Technical Report No 20/2014.* Copenhagen: European Environment Agency.

(2005). *ExternE methodology 2005 Update.* European Commission.

Hirth, L. (2015). *The Market Value of Variable Renewables:.* www.neon-energie.de/publications.

Holttinen, H. e. (2013). *Design and Operation of Power Systems with Large Amounts of Wind.* IEA Wind Task 25.

IEA. (2011). *Harnessing Variable Renewables.* Paris: International Energy Association.

IEA. (2013). *World Energy Outlook 2013.* International Energy Agency.

IEA. (2015). *World Energy Outlook 2015.* Paris: International Energy Agency.

IEA. (2015a). *Projected Costs of Generating Electricity, 2015 edition.* Organisation for Economic Co-operation and Development/International Energy Agency, Organisation for Economic Co-operation and Development/Nuclear Energy Agency.

IEA. (2015b). *World Energy Outlook.* IEA/OECD.

IPCC. (2012). *Renewable Energy Sources and Climate.* IPCC.

IRENA. (2015). *Renewable Poiwer Generation Costs in 2014.* International Renewable Energy Agency.

IRENA. (2015). *Renewable power generation cost.* IRENA.

Mueller, S. (2015). *System-friendly wind power. A grid integration of variable renewables (GIVAR) modelling analysis.* Paris.

Annex 1: LCOEE Example notes

LCoEE of ventilation retrofit

Existing older ventilation systems in office buildings etc. are in most cases designed with constant speed drives where the motor takes up constant electric power and the down regulation is done by means of throttles and vanes to meet the actual ventilation need.

The examples[1] used in the LCoEE calculator consider a forced replacement, i.e. retrofit options of a 20 years old but still operating ventilation system in an office building. The investments include installation work. In all cases, the operation and maintenance costs will be negligible and can be disregarded. The lifetime of the new systems is assumed to be 15 years.

The first example and most simple solution is to fit the existing ventilator motor with a variable frequency drive (VFD) to continuously adapt the motor speed to the actual air-flow need (Option 1). Since the actual need for ventilation in most hours is far below maximum capacity this option alone can cause a huge energy saving.

The second example is to replace the existing motor with a new and more efficient motor, e.g. a permanent magnet type fitted with a VFD, and install a new and more efficient centrifugal fan driven directly by the motor shaft (Option 3).

The following values are used in the LCoEE calculator:

	Electricity consumption (MWh/year)	Investment Cost (Euro)	O&M costs (Euro per year)
Existing Ventilation	96,5	0	0
Option 1: VSD only	26,3	3.776	0
Option 2: New motor w. VSD	17,8	10.276	0

[1] Based on Danfoss presentation HVAC ventilation retrofit models.

LCoEE of pumping in water supply

Pumping of water in domestic water supply systems is used all over the world and takes up substantial energy amounts due to a high yearly number of operation hours. The pumps and electric motors are most often designed for fixed speed operation, and individual pumps in a group stopped and started according to actual flow demand.

However, pumps of the centrifugal type have efficiencies that vary strongly with their pressure head, which also increases with flow. Thus, the fixed speed pumps will very often operate outside their most efficient range. The example is taken from and audited case in Santiago, Chile[2] where an arrangement of pumps with 2x55 kW and 4x55 kW pumps are able to supply 110-290 liter per second at 1,6 – 3,7 bar to 3.200 consumers. A simple PLC controls the pumps, and efficiency ranges from 37% at low flow to 54% at high flow.

A new pump arrangement with 6x37 kW equipped with VSDs (variable speed drive) and a common controller are selected whereby and efficiency of 76-77% can be maintained at all operation speeds.

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10
Oper.	382	1257	1827	1399	584	595	326	207	1316	871
Eff	54,3	54,0	51,0	50,1	46,7	44,2	46,1	46,1	37,1	37,1
Eff	77,5	77,3	77,0	77,0	77,0	77,5	77,6	77,4	76,5	76,0

The diagram shows the pump efficiencies before and after the change and the yearly operating hours at ten flow classes. Lifetime of the new pumps and controller are assumed to be 15 years.

[2] WU Company Santiago, Pump Audit Report, Grundfos 2016.

The following values are used for calculating the LCOEE:

	Energy consumption [MWh/year]	Investment Cost [Euro]	Operation cost (without electricity) [Euro per year]
Before replacement	1.073	-	2.800
After replacement	670	122.333	700

LCoEE of electric motor for industrial application

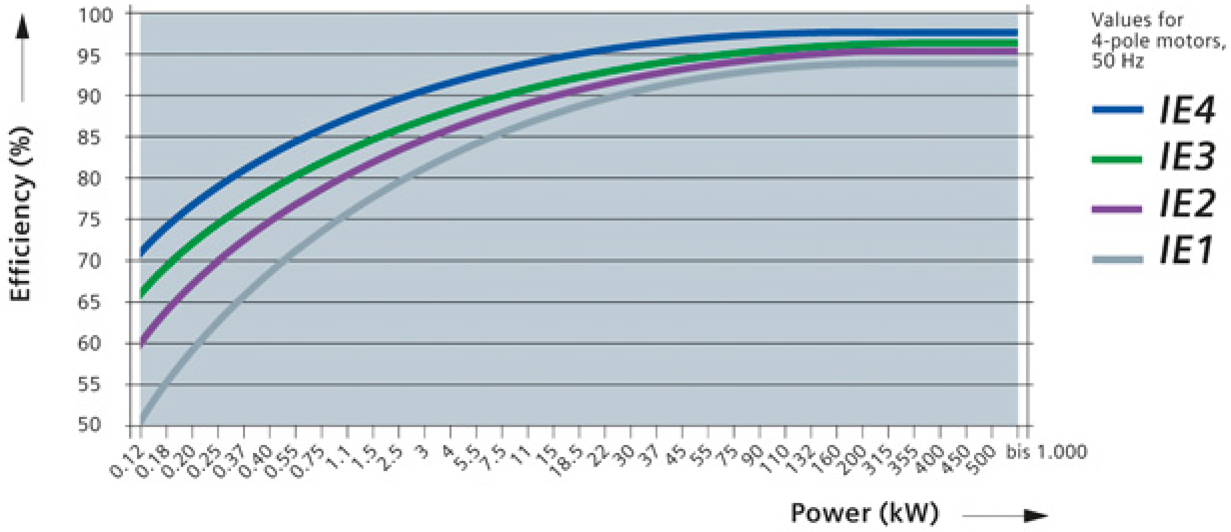
Electric motors are widely used in industry for a variety of applications such as machine drives, transportation systems, fans, pumps etc. In many cases, such motors have more or less constant load and operate with a high number of full-load hours.

The example considers replacement of an older electric motor in an application with continuous production (8000 hours per year) and constant speed. This could be a transportation system in mining, cement production, processing industry, or a machine drive in a factory. The old motor of rated power 22 kW operates at 80% load and has an efficiency of 89%.

The motor is replaced by a new one with better efficiency
The first option is to replace the motor by a "Premium efficiency" motor according to IEC 60034-30-1 IE3. The IE3 standard for electric motors became a mandatory in European Union in 2015. This motor has a minimum required efficiency of 93.0 %[3]. The price of the new motor is 1.318 Euro and the installation cost is 500 Euro, so the total investment is 1.818 Euro.

The second option is to replace the motor by a "High efficiency" motor according to IEC 60034-30-1 IE2. The IE2 standard for electric motors became a mandatory in European Union in 2015. This motor has a minimum required efficiency of 91.6 %[4]. The price of the new motor is 1.135 Euro and the installation cost is 500 Euro, so the total investment is 1.635 Euro.

[3] Requirement for a 4-pole 50 Hz motor according to IEC IEC 60034-30.
[4] Requirement for a 4-pole 50 Hz motor according to IEC IEC 60034-30.



The maintenance costs are considered negligible.

LCoEE of electric lighting in commercial buildings

Electric lighting in commercial buildings has relatively high usage time and causes a relatively high energy use. In recent years, LED lamps have gone through a large development in terms of quality and price. They have high light quality, better life times and lower energy use than other light sources. The example considers a situation where existing lamps with a unit consumption of 1 MWh/year are replaced with LED lamps. The values are average numbers based on Danish experience.

In the first example, the original lamps are of the fluorescent type.
Since these lamps already have a relatively low energy consumption, the necessary investment to replace the lamps is relatively high. Based on experiences from Denmark the investment is expected to be 400 Euro, and the energy use for the same lighting service is reduced to 65%.

In the second example, the original lamps are of the halogen type. These lamps have a higher energy use than the LED lamps so the investment costs is lower (less lamps are to be replaced than in the first example to replace a 1 MWh/year consumption). Thus, the investment is expected to be 200 Euro and the energy use can be reduced to 30%.

LCoEE of windows in domestic application

Windows are a key element of domestic buildings, bringing daylight and fresh air to our houses. Poorly insulating windows cause larger energy loss for heating or cooling than new well-insulated windows. Well-insulated windows can have a positive contribution to the heat balance of the house during the heating season, due to larger amount of solar heat transmitted through the window than the amount of heat lost.

The examples consider replacement of an older window in a house with electric heating. There are two variants of the new window. The energy use is calculated according to Danish building code methodology.

The old window has a U_w-value of 3.5 W/(m²K) and a g_w = 0.56. The window is replaced by a new one with better energy performance. A typical replacement time use is 4 hours for a skilled craftsman at 400 DKK/hour (53 €/hour). The size is according to EN ISO 12567-2, SK08 (1140 × 1398 mm).

The first option is to replace the window to a standard window with a double layer pane (VELUX pane 50). The U_w is 1.3 W/(m²K) and g_w = 0.47. The price of the new window is 4350 DKK including VAT (580 €) and the installation cost is 1600 DKK (213 €), so the total investment is 5950 DKK (793 €), i.e. 634 € excluding VAT.

The second option is to replace the window to a premium window with a triple layer pane (VELUX pane 66). The U_w is 1.0 W/(m²K) and g_w = 0.37. The price of the new window is 5720 DKK including VAT (763 €) and the installation cost is 1600 DKK (213 €), so the total investment is 7620 DKK (976 €), i.e. 780 € excluding VAT.

The energy savings are to be calculated using the “Eref” energy balance equation from the Danish Building Regulation.

Eref = I × g_w – D × U_w and I = 345 kWh/m² and D = 94 kKh.
The following values are obtained for the energy consumption[5]:

	I	gw	D	Uw	Energy kWh/m2/year	Area window m2	Energy loss kWh/år	
Old window	345	0,6	84	3,5	-100,8	1,59	160,6	
First option	345	0,4	84	1,3	18,45	1,59	-29,4	*)
Second option	345	0,4	84	1	43,65	1,59	-69,6	*)

*) A negative value means that the window has a positive contribution to the heating of the house during the heating season.

The maintenance costs are considered negligible.

[5] Values are informed by the Danish window manufacturer Velux A/S.

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