REPORT

Analysis and development of a SubRES techno-economic database for TIMES energy model

Daniel Picot

LULEÅ TEKNISKA UNIVERSITET

SUMMARY

Energy, from its origin to its use, play a great role in the socioeconomic development, but also come with a footprint in the environment. The availability of energy is a key issue for development and constitutes an essential problem for today's society. The growing use of non-renewable energy, the unsustainability of the production model of developed countries and its environmental impact, have caused a problem that requires the development of new energy generation systems, optimization of current distribution methods and their efficient use.

This implies seeking solutions to address the energy dilemma. These solutions involve looking for ways to achieve greater energy generation capacity, improving its distribution, in order to achieve maximum energy savings and minimum environmental impact. One method to combat the energy dilemma is the Energy System Optimization Models (ESOM), which consists of an energy system model made with mathematical functions and some constraints with the objective of optimize the output of the system.

The purpose of this project is to optimize the future costs of generating electricity, where an ETSAP (Energy Technology Systems Analysis Program) - SubRES database with techno-economic data will be generated, and this will be used in TIMES Energy Optimization Model. Thus, the main objective is to prepare a SubRES database file, filled with the techno-economic data from various sources. The datasets for each technology are analyzed (viewing what type of data that is out there and which to use), diagnosed (if the data makes sense) and supplemented (filling the data gaps to have a set of assumptions).

Apart from that, the Levelized Cost of Electricity (LCOE) for the energy technologies which the sources provide is calculated, in order to see the variation between the sources and if the data is reasonable. The results show similar values of LCOE for the technologies which different sources has in common, but with some small variation in some technologies such as Concentrating Solar Power.

The project consists of an analysis, diagnosis and improvement of techno-economic assumptions for the power sector in Energy System Optimization Model (ESOM) based on the TIMES modelling framework. TIMES models are being used and developed at Luleå University of Technology (LTU). The aim is to develop common ETSAP technology databases for energy system models that is integrated with a TIMES SubRES structure.

The following activities are included in the project:

- Review present databases.
- Generate a techno-economic database for TIMES energy model.
- Associate Technology Readiness Level (TRL) for all technologies.
- Prepare an ETSAP SubRES for Power sector.

Keywords: Energy System Optimization Models, TIMES, Energy transition, Climate mitigation strategies.

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CHAPTER 1. INTRODUCTION

1.1. Introducing the energy challenge

The economic, industrial and technological development of the last decades has been more than remarkable, and with an astonishing growth rate. This rapid development has had a great impact on society in general, but above all on the environment (Ritchie & Roser, 2020). Energy is the means by which companies produce their goods, products and services, as well as providing the services of citizens. Energy, from its origin to its use, play a great role but also come with a footprint in the socioeconomic development (Nakicenovic & Swart, 2000).

Energy, in its definition in physical terms, is the capacity to produce work. However, in the economic and industrial terms in which this project is developed, energy is the natural resource, including its extraction, transformation and final consumption technology, which is used to give it a social purpose, including all sectors (Tribus & McIrvine, 1971). Thus, the inappropriate and massive use of these natural resources is what has created the need to develop sustainable energy systems (Kreith & Kreider, 2011).

There are many types of energy: electric, thermal, solar, wind, nuclear, hydraulic, etc. Many of these types of energy come from a limited natural resource, or one that is not renewable in the short term and are called non-renewable energies. On the other hand, renewable energies are those that are generated in cyclical processes with a short period (Twidell, 2005).

The availability of energy is a key issue for development and constitutes an essential problem for today's society. The growing use of non-renewable energy, the unsustainability of the production model of developed countries and its environmental impact, have caused a problem that requires the development of new energy generation systems, optimization of current distribution methods and their efficient use. The development, optimization and efficient use of energy is what is known as energy sustainability (Scoones, 2007).

The need to promote energy sustainability has risen due to the prediction that fossil fuel reserves will be depleted in the coming decades, together with the limited capacity of the environment to assimilate the great impact of economic and productive activities, including the emissions of pollutants that some conventional energy technologies cause (McCollum, Krey, & Riahi , 2011).

1.2. Project Description

The problem of energy availability mentioned in the previous section implies seeking solutions to address the energy dilemma. These solutions involve looking for ways to achieve greater energy generation capacity, improving its distribution, in order to achieve maximum energy savings and minimum environmental impact (IEA, 2020).

The constant change to which companies must adapt is not only at the technological and industrial level, but also at the level of restrictions and requirements. These demands are reflected in increased support for new common energy policies, as well as legal requirements to optimize energy demands and promote the inclusion of renewable energy sources. These requirements are tougher depending on the size of the company, sector of activity, applicable legislation and other factors such as social commitment that directly affect organizations (IEA, 2020).

The transition to a low carbon society is one of the greatest challenges in today's society. This will depend on both resource availability, technology development, economic development, policies in place as well as on our lifestyle and behavior. Some of the key questions in order to achieve our goals concerns how to use limited resources efficiently and how to design efficient energy policies (IEA, 2020).

One way to analyze the transition is by applying energy system optimization models (ESOMs). Within the field of energy modelling, ESOMs are widely used to model the system-wide impacts of energy development using a self-consistent framework for evaluation. Also, ESOMs are widely used to generate insight that informs energy and environmental policy, so they can contribute not only to optimize the costs of generating electricity given some constraints, but also to help politicians to make decisions and write new rules. A widely used ESOM modelling platform is TIMES, which is developed and maintained by the Energy Technology Systems Analysis Program (ETSAP). ETSAP is the longest running Technology Collaboration Programme of the International Energy Agency (IEA). ETSAP currently has as contracting parties 20 countries, the European Commission and two private sector sponsors (IEA-ETSAP, 1976).

A critical part of the modelling is the techno-economic assumption about future available power plants. When all TIMES models follow a similar structure, the model can use the same techno-economic database. The aim of this project is to gather data from various sources and compile them in a generic techno-economic database. To validate the data, the levelized cost of electricity (LCOE) analysis is performed. The collected data will then be used to populate a TIMES based SubRES file for the Power sector.

CHAPTER 2. OBJECTIVE

The project objectives are:

- Review present databases (e.g., EU-JCR-TIMES model SubRES, IRENA, EIA, IEA …).
- Identify if there are technologies missing (e.g., geothermal both for district heating and power).
- Associate Technology Readiness Level (TRL) for all technologies.
- Data validation through LCOE analysis.
- Prepare an ETSAP TIMES based techno-economic database for the Power sector.

2.1. Main objective

The main objective is to prepare a SubRES database file, filled with the techno-economic data from various sources. The datasets for each technology are analyzed (viewing what type of data that is out there and which to use), diagnosed (if the data makes sense) and supplemented (filling the data gaps to have a set of assumptions). Example of sources; International Energy Agency (IEA) or Energy Information Administration (EIA) among others, which will be explained later in the report.

2.2. Academic justification

The project has other academic justification, which is obtaining the master's degree in Industrial Engineering at Universitat Politècnica de València (UPV), being this the last requirement to achieve it.

This project is being executed as an Erasmus Exchange student at Luleå tekniska universitet (LTU). The project is done being part of the TIMES group at LTU, which is a part of the Energy Science Division at the Department of Engineering Sciences and Mathematics.

The project is also needed to demonstrate the skills and knowledge acquired during the studies on both the bachelor's degree and master's degree.

The main tasks that have been developed during the project have been:

- Document and report development.
- Reviewing energy technology databases.
- Gathering and understanding all the techno-economic data available from the sources.
- Associate Technology Readiness Level (TRL) for all energy technologies.
- Prepare and create an ETSAP TIMES SubRES database for Power technologies.
- Calculate the costs of generating electricity (LCOE).
- Analysis of the electricity costs results.

Through the realization of this project a series of competences have been acquired with which it has been possible to develop the project in an optimal way.

General skills:

- Analysis and problem solving.
- Ability to work within a research team.
- Understanding of new knowledge.
- Adaptation to new work methodologies.
- Planning and time management.
- Communication skills.

Specific competences:

- Application of methodologies for process improvement.
- Project planning.
- Implementation of energy optimization model.
- Analysis of energy technology databases.
- Understanding of energy systems.
- Creation of databases.

CHAPTER 3. ESSENTIAL CONCEPTS

In this chapter, some necessary main concepts for the report and project will be introduced and defined.

3.1. Energy System

First, the introduction to the system concept is necessary to approach the report. There are many definitions for a system. Merriam-Webster (Definition of system, 2021) for example tells that a system "*is a set of interacting or interdependent components forming an integrated whole*" or according to the Oxford Dictionary (LEXICO, 2021) a system is "*a set of things working together as parts of a mechanism or an interconnecting network*".

When describing a system, to fully understand the logic and what the whole system represents, Churchman (1984) outlines five basic considerations for thinking about the meaning of a system: total system objectives, environment, resources, components, and management of the system (Churchman, 1984).

- System objectives and performance measures: the objective of a system is where the problem solving starts, and their definition can be wide and open at first sight. The objectives indeed need to be clear, and to see how the system is doing, these objectives need to be measured with performance. Therefore, the performance measures tell how the system is doing. One of the objectives of the performance measurement is to find as many consequences of the system as possible.
- Environment: system environment is a difficult and wide concept to define, but basically it is what lies outside of the system. The environment is also something which is outside of the system's control, but impact the system performance.
- Resources: Basically, they are the means that the system uses to do its job, and they can be used by the system itself to its own advantage.
- Components: they are also called the parts or subsystems of the system. They could be considered as the assignments the resources require, so like maintenance for a machine or staff in a restaurant.
- Management: this is the decision maker for the system, considering all the four topics mentioned previously. The management of the system sets the goals of the system, allocates the resources and controls the performance. Apart from generating the plans of the system, the management also controls that the operation of the system is being carried out in accordance with the original idea. It includes examination of evaluation on how the system should work and also taking into account what will happen if the plan changes. (Churchman, 1984)

Considering this previous definition, an energy system is a system where energy generation and use are the main focus. It is sometimes defined by the letter 4E+, consisting of: Energy, Engineering, Economy, Environment and Society and behavior. All these elements are considered inside an energy system, where the objective is to deliver the benefits that energy offers under given conditions and constraints (Tosato, 2014).

To conclude this definition, a good summary is the one made by Nakicenovic (1996), "*The energy system is a successive series of linked stages, linking energy extraction, energy conversion and energy distribution technologies with energy end-use-technologies that provide energy services*". (Nakicenovic N. , 1996).

3.2. Energy System Optimization Models

An Energy System Optimization Model (ESOM) is a model of an energy system made with mathematical functions and some constraints that pretends to optimize the output of the system. Within the field of energy modelling, energy system optimization models (ESOMs) are widely used to model the system-wide impacts of energy development using a self-consistent framework for evaluation. ESOMs include detailed, bottom-up technology specifications and utilize linear programming techniques to minimize the system-wide present cost of energy provision by optimizing the installation of energy technology capacity and its utilization. The models are subject to a number of constraints that enforce system performance criteria as well as user-defined limits. Outputs include future estimates of technology capacity and utilization, marginal commodity prices, and emissions across the energy system (De Carolis, et al., 2017).

A mathematical program model consists of an optimization problem with an objective function and a set of constraining equations and/or inequalities. In systems perspective, the systems are defined by the function that they perform. A function is a very broad and fundamental concept that is essential to systems theory. Basically, a function is a process that transforms energy or resources from one state to another. So, there are three key things to remark in this definition. We have a set of things that is the input, then we have a process that changes these things in some way and finally we have an output (Meier, 1984).

Firstly, inputs involve the capturing and assembling of elements that enter the system to be processed. An important thing to note is that any given system can only process a specific range of inputs. What a system can and cannot process is a defining feature to its boundary that functions to filter inputs to the system (Systems Innovation, 2021).

Secondly, resources that are successfully inputted are processed within the system. A process is a series of actions performed upon the input in order to achieve a particular end result. Processing is often understood in terms of information that is an algorithm or set of instructions that are performed upon the input in order to produce the output. One way of understanding a function then is simply as the difference between what goes into the system and what comes out (Systems Innovation, 2021).

Energy system optimization models are widely used to generate insight that informs energy and environmental policy. Using ESOMs to produce policy-relevant insight requires significant modeler judgement, yet little formal guidance exists on how to conduct analysis with ESOMs (Krook-Riekkola, 2015).

Energy System Modeling process includes the following steps shown in the *Figure 1*:

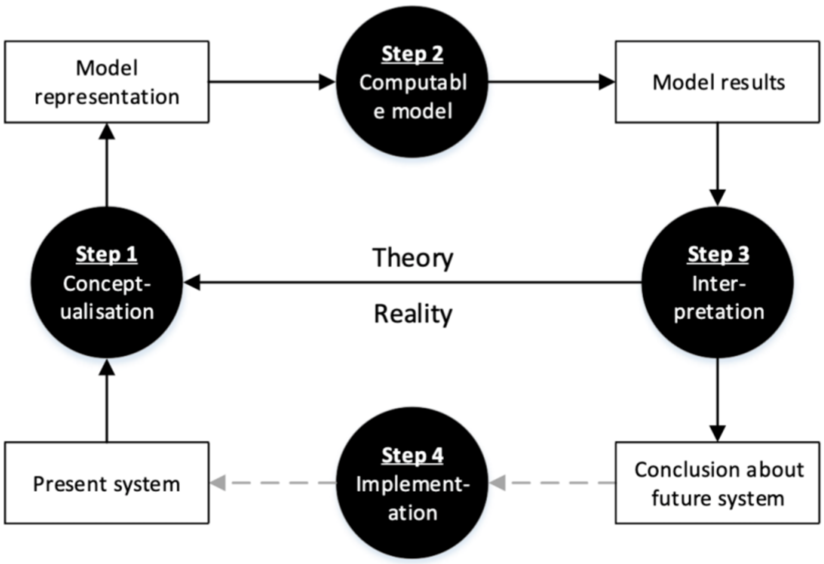


Figure 1. Steps in energy modeling (Krook-Riekkola, 2015).

Usually, with a ESOM it is hard to make the results useful or understandable for everyone, because a model is a simplification and it is limited by its formulation. It is based on the modeler's understanding of the tool and the studied system. Also, transferring knowledge in general is hard. We need to make the decision makers understand the meaning of our result. It only considers information which the modeler choose to include, or that the model is capable of including because of the constraints (Zeng, Cai, Huang, & Dai, 2011). These aspects need to be taken in consideration when transferring model results into the reality.

3.3. Techno-Economic analysis

Techno-economic assessment or Techno-economic analysis (TEA) is a methodology framework to analyze the technical and economic performance of a process, product or service. TEA normally combines process modeling, engineering design and economic evaluation (Kim, 2021).

Examples of applications of TEA include the evaluation of the economic feasibility of a specific project, a forecast on the likelihood of the deployment of a technology at certain scale, or a comparison of the economic merit of different technological options that provide the same service (Burk, 2018).

In this project, the techno-economic analysis is made to the energy technologies generating electricity, studying the feasibility and the cost of generating one unit of electricity (EUR/MWh), known as LCOE (Levelized Cost of Electricity).

3.4. Levelized Cost of Electricity

The Levelized Cost of Electricity (LCOE) is a measure of the average net present cost of electricity generation for a power source over its lifetime i.e., it represents the installed capital costs and ongoing operating costs of a power plant, converted to a level stream of payments over the plant's financial lifetime (Oladokun & Asemota, 2015). The LCOE can also be regarded as the minimum constant price at which electricity must be sold in order to break even over the lifetime of the project, which allows comparison of different methods of electricity generation on a consistent basis (K. Branker, 2011).

LCOE, mathematically can be roughly calculated as the net present value of all investment and ongoing costs over the lifetime divided by the energy output from the asset over that lifetime. Investment capital costs include construction costs, financing costs, tax credits, and other plant-related subsidies or taxes (Chun Sing Lai, 2019). Ongoing costs include the cost of the generating fuel (for that power plants that consume fuel), expected maintenance costs, and other related taxes or subsidies based on the operation of the plant.

Typically, the LCOE is calculated over the design lifetime of a plant, which is usually 20 to 40 years, although it depends on the type of technology. It is important to add that LCOE for a given energy source is highly dependent on the assumptions made to calculate it, such as the financing terms and technological deployment. In particular, assumption of capacity factor has significant impact on the calculation of LCOE (Chun Sing Lai, 2019).

It is interesting to point out the difference between LCOE and LACE (Levelized Avoided Cost Of Electricity). The LACE represents the value that a plant provide to the grid. A generator's avoided cost reflects the costs that would be incurred to provide the electricity displaced by a new generation project as an estimate of the revenue available to the plant. As with LCOE, these revenues are converted to a level stream of payments over the plant's assumed financial lifetime (Sukunta, 2018).

Both measures together, LCOE and LACE, explain the economic competitiveness of electricity generating technologies. Thus, power plants are considered economically attractive when their projected LACE (value) exceeds their projected LCOE (cost) (Sukunta, 2018).

CHAPTER 4. TIMES Model

4.1. About TIMES

TIMES (an acronym for The Integrated MARKAL-EFOM System) is an economic model generator for local, national, multi-regional, or global energy systems, which provides a technology-rich basis for representing energy dynamics over a multi-period time horizon (Loulou, 2016). It is usually applied to the analysis of the entire energy sector but may also be applied to study single sectors such as the electricity and district heat sector, like in the scope of this project.

When running a TIMES model, the end-use energy service demands are provided by the user for each region to drive the reference scenario. In addition, the user also provides estimates of the existing stocks of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials (Loulou, 2016).

Using these as inputs, the TIMES model aims to calculate the supply energy services at the minimum global cost (more accurately at minimum loss of total surplus) by simultaneously making decisions on equipment investment and operation; primary energy supply; and energy trade for each region.

4.2. TIMES Model division at LTU

The TIMES group at Luleå Tekniska Universitet (LTU) forms part of the Energy Science Division at the Department of Engineering Sciences and Mathematics. TIMES LTU group is in charge of making different studies different aspects of the transition to a sustainable energy system, led by Associate Professor Anna Krook-Riekkola, who is also the supervisor of this project. Different energy system optimization models based on the TIMES modelling framework are used to explore different pathways for how the comprehensive energy system can evolve over time, in the horizon of 20-50 years. Specifically, both on a national level (TIMES-Sweden) and on a city level (a generic TIMES-City model) are considered in the group.

4.3. TIMES Attributes

In the Excel files that the JRC-ETSAP model uses as input data, there are two general units for the SubRES database used for every energy technology:

- Energy, units: PJ
- Capacity, units: GW

Apart from this general units, some attributes required by the project supervisor (codes in the excel input data) are described:

Table 1. Requested TIMES attributes.

CODE	**DESCRIPTION**	**UNIT**
CAP2ACT	This attribute allows the conversion between the process capacity and activity units	PJ/GW
START	The starting year where the energy technology is going to be ready in the market and considered into the model calculations	Year

LIFE	Technical lifetime for every energy technology	Year
INVCOST	Parameter representing the investment cost of the technology Parameter representing the investments portion of a regional	M€/GW
FIXOM	Fixed Operational & Maintenance costs	M€/GW
VAROM	Variable Operational & Maintenance costs	M€/PJ
EFF	Efficiency	%
AF	Availability rate factor. There are a variety of availability factors: annual or seasonal.	%
~TFM_AVA	It is used to declare the availability of processes in different regions	-
~TFM_INS	Transformation Insert Tables (in scenario and transformation files) are used to define absolute values via additional	-
~TFM_DINS	Transformation Direct Insert Table: are also used to insert data, but unlike in Insert tables, it is forbidden to define subsets of	-

Note: the symbol ~ is used in the model to specify that this value is written as input data by the model. However, the symbol * means that these columns are not read by the model.

CHAPTER 5. DATABASE ANALYSIS

The purpose of this section is to take a look at the techno-economic data available from different sources, which later will be used to create the final ETSAP-SubRES database.

5.1. Energy Information Administration (EIA)

The first searched source to see which type of data is available and which information is useful in terms if techno-economic data is the Energy Information Administration (EIA).

5.1.1 About EIA

The EIA is the statistical agency which is part of the U.S. Department of Energy. The EIA collects, analyzes, and disseminates policy-independent impartial energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment (EIA, 2021).

5.1.2 Available data: Open Data

The EIA data, forecasts, and analyses programs cover data on coal, petroleum, natural gas, electric, renewable, and nuclear energy.

EIA is the statistical and analytical agency within the U.S. Department of Energy, but by law, EIA's products are prepared independently of policy considerations. EIA neither formulates nor advocates any policy conclusions. They just provide the data available for all the public so each one can use this information and data to make decisions or conclusions related with the energy usage.

Talking about the API and direct Add-ons such as Excel complements, by making EIA data available in machine-readable formats, the creativity in the private, the non-profit, and the public sectors can be used to find new ways to innovate and create value-added services powered by public data.

EIA conducts a comprehensive data collection program that covers the full spectrum of energy sources, end uses, and energy flows; generates short- and long-term domestic and international energy projections; and performs informative energy analyses. Apart from U.S Data, it also has some International data available of every country, and is in that part where the Swedish data, among others, can be founded.

a. Which kind of technologies:

Electricity, coal, crude oil, natural gas, nuclear, petroleum, biodiesel and other renewable fuels, ethanol, geothermal, hydroelectric, solar PV, biomass, waste energy, wood, wind, solar electricity. This source also have other data like CO_2 emissions available to check during different years.

b. Which kind of techno-economic data:

Prices, imports, exports, net generation, consumption, capacity, production, distribution losses (electricity), energy consumption per GDP, energy consumption per capita, population, high economic price, high oil price, low economic growth, low oil price (EIA, 2020).

In the EIA website, one example of the information provided by the source to cover the techno-economic data is showed in the following *Figure 2*:

- Financial indicators

3.1	Fossil fuel production prices, 1949– *Available formats:* PDF XLS PDF (graph)
3.2	Value of fossil fuel production, 1949– *Available formats:* PDF XLS PDF (graph)
3.3	Consumer price estimates for energy by source, 1970– *Available formats:* PDF XLS PDF (graph)
3.4	Consumer price estimates for energy by end-use sector, 1970– *Available formats:* PDF XLS PDF (graph)
3.5	Consumer expenditure estimates for energy by source, 1970– *Available formats:* PDF XLS PDF (graph)
3.6	Consumer expenditure estimates for energy by end-use sector, 1970– *Available formats:* PDF XLS PDF (graph)
3.7	Value of fossil fuel imports, 1949– *Available formats:* PDF XLS PDF (graph)
3.8	Value of fossil fuel exports, 1949– *Available formats:* PDF XLS PDF (graph)
3.9	Value of fossil fuel net imports, 1949– *Available formats:* PDF XLS PDF (graph)

Figure 2. Screenshot of EIA website database (EIA, 2020).

5.2. Joint Research Centre (JRC)-EU-TIMES

The SubRES database analyzed in this section consists of input files (Excel) for the JRC-EU-TIMES model, which is made by the EU Joint Research Centre (JRC). The JRC is the European Commission's science and knowledge service which employs scientists to carry out research in order to provide independent scientific advice and support to EU policy.

5.2.1. About the EU Joint Research Centre (JRC)

JRC-EU-TIMES model is a scientific tool for assessing the long-term role of energy technologies, designed for analyzing the role of energy technologies and their innovation for meeting Europe's energy and climate change related policy objectives. It helps understanding the role of energy technologies and their innovation needs for meeting European policy targets related to energy and climate change. The model covers the representation of the energy system of the EU 28 Member State and of neighboring countries. It produces projections (or scenarios) of the EU energy system showing its evolution up to 2060 under different sets of specific technology and policy assumptions and constraints (EU SCIENCE HUB, 2021).

The main role of JRC-EU-TIMES is the anticipation and evaluation of technology policy. The baseline scenario of JRC-EU-TIMES is always aligned to the latest EU reference scenario. The model can be used to assess which technological improvements are needed to make technologies competitive under various low-carbon energy scenarios.

5.2.2 Available data in the Database:

Analyzing the database available in JRC-EU-TIMES, as it is said, it consists of the input data for the TIMES model, in which the following information can be found for each technology:

Technology description, lifetime, starting year, availability factor, currency, investment cost, fixed costs, and variable operation & maintenance costs.

5.3. International Renewable Energy Agency (IRENA)

Another source researched is the International Renewable Energy Agency (IRENA), which had moderatly less techno-economic data in their database.

5.3.1 About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organization that supports countries in their transition to a sustainable energy future, and serves as a platform for international cooperation, as well as a center of policy, technology, resource and financial knowledge on renewable energy (IRENA, 2021).

5.3.2 Available data in the Database

IRENA helps analysts, policy makers and the public make informed decisions by providing access to comprehensive and up-to-date renewable energy data. This data is organized by categories, according to their website, being those as the *Figure 3* shows:

Figure 3. Screenshot of IRENA website database (IRENA, 2021).

About techno-economic data available from this source, they provide up-to-date information on renewable energy technologies, including their costs and cost-reduction potential to all stakeholders. Also, they provide some data about finance and investment. An important information is their Renewable Costing Alliance (an alliance of companies, industry associations, governments and researchers), which is helping to expand the database by sharing confidentially, their data for real-world renewable energy projects.

5.4. International Energy Agency (IEA)

The last researched source is the International Energy Agency (IEA), which is the main source and the database which containd the most information. This information was extracted from their annual reports about the costs of producing electricity.

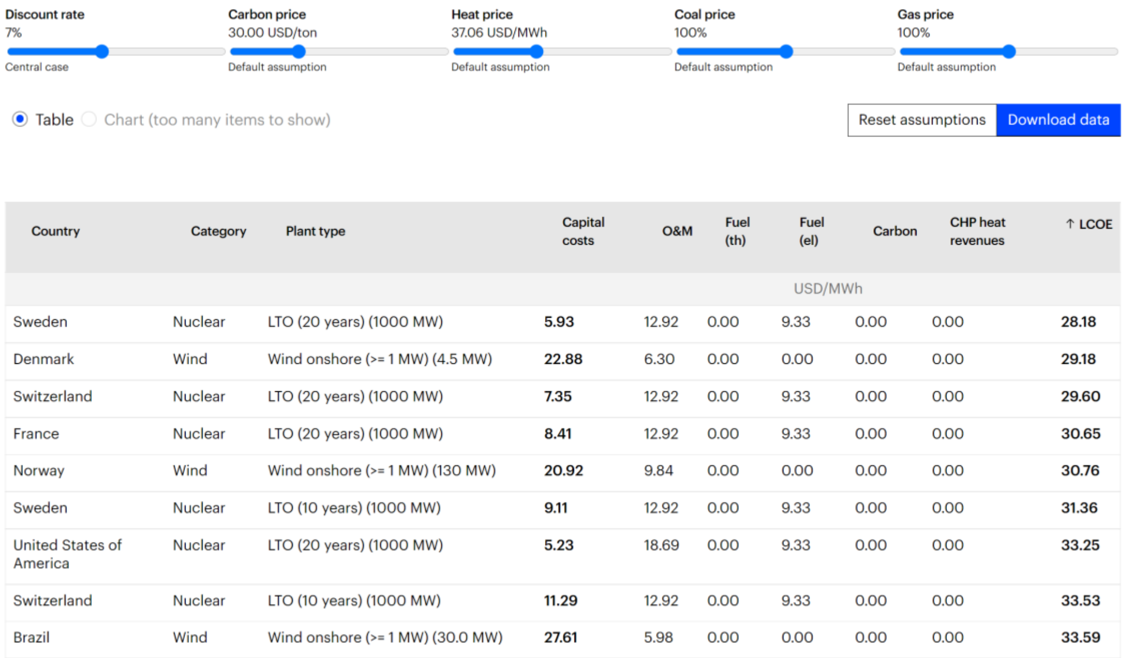
5.4.1 About IEA

The International Energy Agency (IEA) is autonomous intergovernmental organization centered at the heart of global dialogue on energy, providing influential analysis, data, policy recommendations, and real-world solutions to help countries provide secure and sustainable energy (IEA, 2021). The IEA was originally created in 1974 to help co-ordinate a collective response to major disruptions in the supply of oil.

5.4.2 Available data

About techno-economic data, IEA provides annual reports about Projected Costs of Generating Electricity (IEA, 2020). It presents the plant-level costs of generating electricity (LCOE) for both baseload electricity generated from fossil fuel and nuclear power stations, and a range of renewable generation – including variable sources such as wind and solar. It provides specific data about construction, refurbishment, decommissioning, operations & maintenance, and fuel costs, as well as carbon price, CHP heat revenues and the discount rate used to calculate the LCOE.

The report website includes a LCOE calculator where the data can be downloaded. The next image shows how the IEA presents the data:



Country	Category	Plant type	Capital costs	O&M	Fuel (th)	Fuel (el)	Carbon	CHP heat revenues	↑ LCOE
					USD/MWh				
Sweden	Nuclear	LTO (20 years) (1000 MW)	**5.93**	12.92	0.00	9.33	0.00	0.00	**28.18**
Denmark	Wind	Wind onshore (>= 1 MW) (4.5 MW)	**22.88**	6.30	0.00	0.00	0.00	0.00	**29.18**
Switzerland	Nuclear	LTO (20 years) (1000 MW)	**7.35**	12.92	0.00	9.33	0.00	0.00	**29.60**
France	Nuclear	LTO (20 years) (1000 MW)	**8.41**	12.92	0.00	9.33	0.00	0.00	**30.65**
Norway	Wind	Wind onshore (>= 1 MW) (130 MW)	**20.92**	9.84	0.00	0.00	0.00	0.00	**30.76**
Sweden	Nuclear	LTO (10 years) (1000 MW)	**9.11**	12.92	0.00	9.33	0.00	0.00	**31.36**
United States of America	Nuclear	LTO (20 years) (1000 MW)	**5.23**	18.69	0.00	9.33	0.00	0.00	**33.25**
Switzerland	Nuclear	LTO (10 years) (1000 MW)	**11.29**	12.92	0.00	9.33	0.00	0.00	**33.53**
Brazil	Wind	Wind onshore (>= 1 MW) (30.0 MW)	**27.61**	5.98	0.00	0.00	0.00	0.00	**33.59**

Figure 4. Screenshot of IEA LCOE calculator website (IEA, 2020).

After reviewing the technologies available in the IEA database, the following table shows them classified by technology categories:

Table 2. IEA dataset technology classification.

Technology	Number of plants / Countries
Storage	
Lithium-ion battery	4 / 4
Pumped storage	3 / 3
Fuel cell	
Fuel cell	4 / 2
Biomass	
Biomass	4 / 3
Biomass (CHP)	5 / 2
Coal	
Coal	11 / 6
Coal (CCUS)	4 / 2
Coal (CHP)	1 / 1
Gas	
Gas (CCGT)	16 / 11
Gas (CCGT, CCUS)	2 / 2
Gas (CCGT, CHP)	2 / 2
Gas (OCGT/int. comb.)	8 / 5
Gas (OCGT/int. comb., CHP)	3 / 3
Geothermal	
Geothermal	6 / 2
Hydro	
Hydro (reservoir, >= 5 MW)	4 / 4
Hydro (reservoir, < 5 MW)	1 / 1
Hydro (run of river, >= 5 MW)	7 / 4
Hydro (run of river, < 5 MW)	18 / 4
Lignite	
Lignite	2 / 2
Lignite (CCUS)	1 / 1
Lignite (CHP)	1 / 1
Nuclear	
Nuclear	8 / 8
Nuclear (LTO)	4 / 4
Solar	
Solar PV (floating)	1 / 1
Solar PV (utility scale)	21 / 14
Solar PV (commercial)	15 / 8
Solar PV (residential)	15 / 8
Solar thermal (CSP)	4 / 2
Wind	

Offshore wind	23 / 8
Onshore wind (>= 1 MW)	33 / 18
Onshore wind (< 1 MW)	11 / 1

CHAPTER 6. DATABASE DEVELOPMENT

In this chapter, the development of the power sector DATABASE is explained. In order to develop the database, a Microsoft Excel file template provided by TIMES division at LTU is used.

Using this template, the information compiled from the different database sources (described in the previous chapter) is filled in the database., The information filled in the database is explained in this chapter. First of all, the explanation of the KEY naming for each technology is is explained. After that, all the database columns filled with information, and arranged by categories, are going to be named, explaining the parts which need description. Since the database size is large, it is not possible to include the file in this report, but the file is available internally for TIMES division at LTU.

6.1.KEY naming

The KEY is a code defined by the user for each technology. The purpose of the KEY is group the data with the same technology, and at the same time, to have a quick look at the type of technology that the data refers to.

For the KEY naming, the idea is to concatenate some words regarding some classification, following the below rules:

Table 3. First letters for KEY naming (general).

Description	First letters (General)
Combined Heat and Power Plant	CHP
Power plant - Electric Only	ELE
Thermal Power Plant - Electric Only	ELE
Heat plant only	HPL

Table 4. Next letters for KEY naming (technology).

Description	Following letters	CHP (BP: Back-Pressure alt CO: Condense-Variable)	Technology	Pre-defined input	Kind of application
Combined Cycle Gas Turbine	CO.CCGT	CO	CCGT		CHP, ELE
Open Cycle Gas Turbine	OCGT	-	OCGT		ELE
Integrated Gasification Combined Cycle - Coal	CO.IGCC	CO	IGCC	COA	CHP, ELE
Integrated Gasification Combined Cycle - Bio	CO.BGCC	CO	BGCC	BIO	CHP, ELE
Fuel Cell	BP.FC	BP	FC	H2L	CHP, ELE
Internal combustion engine	IC		IC		ELE
Fluidized Bed	FBE	-	FBE		ELE
Fluidized Bed	FBSC	-	FBSC		ELE
Fluidized Bed	FBUSC	-	FBUSC		ELE
Fluidized Bed	BP.FB	BP	FB		CHP

Fluidized Bed	CO.FB	CO	FB		CHP
Fluidized Bed	FB	-	FB		HPL
Conventional Boiler	CBE	-	CBE		ELE
Conventional Boiler	CBSC	-	CBSC		ELE
Conventional Boiler	CBUSC	-	CBUSC		ELE
Conventional Boiler	BP.CB	BP	CB		CHP
Conventional Boiler	CO.CB	CO	CB		CHP
Conventional Boiler	CB	-	CB		HPL
Small scale fuel boiler	SB	-	SB		HPL
Electric boiler	EB	-	EB	ELC	HPL
Hydro run-of-river	ROR	-	ROR	HYD	ELE
Hydro conventional	HYD	-	HYD	HYD	ELE
Hydro	HYD	-	HYD	HYD	ELE
Hydro w storage	HYD	-	HYD	HYD	ELE
Hydro reservoir	RSV	-	RSV	PSI	ELE
Heat pump	HP	-	HP	ELC	HPL
Geothermal	GEO		GEO	GEO	CHP, ELE, HPL
Ocean	OCE	-	OCE	OCE	ELE
Wind onshore	ONWIN	-	ONWIN	WIN	ELE
Wind offshore	OFFWIN	-	OFFWIN	WIN	ELE
Solar PV (residential)	PVR	-	PVR	SOL	ELE
Solar PV (commercial)	PVC	-	PVC	SOL	ELE
Solar PV (utility scale)	PVU	-	PVU	SOL	ELE
Solar PV (utility scale + floating)	PVF	-	PVF	SOL	ELE
Solar (Concentrating Solar Panel)	CSP	-	CSP	SOL	ELE
Nuclear	NUC	-	NUC	NUC	ELE
Nuclear Advanced Light Water Reactor	ALWR	-	ALWR	NUC	ELE
Nuclear Gen III	NUC	-	NUC	NUC	ELE
Nuclear Gen IV	NUC	-	NUC	NUC	ELE
Nuclear Light Water Reactor	LWR	-	LWR	NUC	ELE
Nuclear LTO lifetime extension (10 years)	NUC	-	NUC	NUC	ELE
Nuclear LTO lifetime extension (20 years)	NUC	-	NUC	NUC	ELE
Nuclear Small Modular Reactors	SMR	-	SMR	NUC	ELE
Bioenergy	BIO	-	BIO	BIO	ELE
Biomass	BIO	-	BIO	BIO	ELE, CHP
Battery storage	STG	-	STG		ELE

Table 5. Next letters for KEY naming (Carbon Capture).

Description	**Next letters (Carbon Capture)**
CCUS YES	CC
CC 30%	CC30
CC 90%	CC90
CCUS NO	-

Table 6. Next letters for KEY naming (Fuel).

Description	Next letters (Fuel)
Biogas	BGS
Biomass	BIO
Coal	COA
Derived Gases Other	DGS
Diesel Oil and other	DST
Gas	GAS
Lignite	COL
Lignite or Brown Coal	COL
Municipal Solid Waste	MSW
Natural Gas	GAS
Oil	OIL
Peat	PEA
Wood Products	BWO
Hydrogen	H2L
Ambient heat residential	AHT
Agricultural biomass solid	BAS
Biomass from crops	BCR
Biogas	BGS
Biomass (unespecified)	BIO
Black liquor	BLQ
Black liquor waste	BLW
Bio oil all excl BTR	BOA
Woody biomass Refined	BWR
Woody biomass Unrefined	BWU
Coke oven gas	COG
Hard Coal	COH
Bio synthetic natural gas (SNG)	GASb
Fossil blast furnace gas	GBF
Bio blast furnace gas	GBFb
Fossil TGR blast furnace gas	GOB
Bio TGR blast furnace gas	GOBb
Fossil oxygen furnace gas	GOF
Bio oxygen furnace gas	GOFb
Fossil smelting furnace gas	GSF
Bio smelting furnace gas	GSFb
Gas works gas	GWG
Hydrogen gasuous	H2G
Hydrogen liquid	H2L
Heavy Fuel Oil	HFO
Light Fuel Oil	LFO
Bio light Fuel Oil	LFOb
Fossil LPG	LPG
Bio LPG	LPGb
Bio methanol	MTHb
Fossil methanol	MTHf
Municipal Waste	MUN

Peat	PEA
Recycled plastic	PLA
Electricity Pump Storage INPUT	PSI
Electricity Pump Storage OUTPUT	PSO
Fossil steam cracker gas	SCG
Bio steam cracker gas	SCGb
Sludge	SLU
Tide	TID
Recycled tyres	TYR

Table 7. Next letters for KEY naming (Starting year).

Description	Next letters
Start year in 2006	06
Start year in 2010	10
Start year in 2015	15
….	….and so on

Table 8. Last letters for KEY naming (Source).

Description	LAST letters (Source)
International Energy Agency	IEA
Energy Information Administration	EIA
International Renewable Energy Agency	IRENA
EU Joint Research Center, JRC-EU-TIMES SubRES	JRC

With all these parameters, considering which type of technology is filled in each database row depending on the conditions explained, one example of a KEY for one technology is CHPCO.CCGTGAS19IEA, which is a Combined Cycle Gas Turbine, generating Heat and Power.

6.2. General information

The purpose of this general information is to be able to find the information again for future users, and to understand what kind of data it is.

The general information data is determined by the following parameters:

- Source Info:
  - Source (Short text): code for the source.
  - Source (Long text): long name of the source, indicating from which archive the dataset was extracted.
  - Source Description (Long text): description of the source.
  - Source Link (Long text): link to the website source.
  - Name on provider of information (Long text): name of the user who included the information.
- Translate Info:
  - Capacity unit
  - Energy unit
  - Currency unit

- Data reference year
- Search Info:
  - Technology: plant category.
  - Fuel: fuel for those technologies that require this information.
  - Technology Description: long text of the type of technology.
  - Sector: ELC (electricity) for all the technologies.
  - SubSector: CEN or DCEN (centralized or decentralized).
  - Type (prc_grp): List of process groups; internally established in MAPLIST.DEF, from the official documentation for the TIMES Model, PART II (2016).
  - Typical Size or Capacity
  - Region

6.3. Topology

In the typology group of the database, some necessary information from the TIMES model regarding input and output of each technology is fulfilled.

- Comm-IN: code defined by TIMES documentation for every technology.
- Comm-IN-A: not defined.
- Comm-OUT: ELC (electricity) for all technologies.
- Comm-OUT-A: not defined.
- CAPACT: a default value defined by Energy and Capacity.

6.4. Engineering parameters

In this group, some technical parameters which define the type of technology are presented.

- START: starting year which the model will consider that the technology will start.
- CEH: coefficient of electricity to heat.
- CHPR: heat-to-power ratio.
- EFF: efficiency.
- CEFF: efficiency, in case of different EFF for different fuels.
- CF: historic Capacity Factor, thus based on share when it is commonly being operated.
- AF: annual Availability Factor, which is the share of the year when plant is available, thus not consider when suitable to operate, but when possible to operate (e.g. considering maintenances, etc.)

6.5. Economic parameters

The next information filled consist of some economic parameters, which are the main information and input for the later LCOE calculation. These parameters are the following:

- Investment Cost: are the capital costs of construction and development of a power plant. They are the most significant cost to power generation for many technologies. Capital costs for most technologies include: site preparation, mechanical equipment, electrical equipment, indirect costs (such as contractor overhead, fees, profit and contingency allowances) and owner’s costs.
- Technology readiness level: it is a method for estimating the maturity of technologies.

- Technology uncertainty information: e.g., techno-logical optimism factor, which is a number that shows technological improvements in areas such as production or environmental quality.
- Lead-time: Years to build the plant (excluding permits).
- Refurbishment costs: which are the costs related with renovation of equipment or some parts in the power plants.
- Refurbishment Extension: number of years for the refurbishment operations.
- Decommissioning costs: they are the costs related to the retire and decommission of old power plants.
- FIXOM: fixed Operational & Maintenance costs.
- VAROM: variable Operational & Maintenance costs.
- Technical lifetime: is the total time period during which the asset can technically perform/function before it must be replaced.
- Economic Lifetime: it is the expected period of time during which the power generation technology remains useful and profitable.
- DR: Discount rate

6.6. Comments to the dataset

In this section, the comments, values used and some assumptions to create the final dataset are presented. The reason to do that is, some values are difficult to find within the datasets, and some are not found in the dataset, but are present in the report that the source provide.

6.6.1. IEA Database comments

The most important comment to the IEA dataset is that all the data extracted comes from the report *Projected Costs of Generating Electricity 2020* (IEA, 2020). The IEA allow the users to have access to the LCOE calculator data that they have used for that report. Thus, the data extracted for the final SubRES dataset comes from this LCOE calculator, using a discount rate of 7% (IEA, 2020).

Since this data is the result of their LCOE calculations, all the terms of the LCOE are provided with the same unit, which is USD/MWh. Because of that, in order to extract the investment costs and fixed costs in the same units than usually, the terms are calculated from the general LCOE equation:

$$LCOE = \frac{(C * a) * 1000}{CF * 365 * 24} + \frac{(FOM) * 1000}{CF * 365 * 24} + VOM + \frac{f_c}{\eta}$$

Equation 1. Levelized Cost of Electricity.

Thus, the capital costs C are obtained as the following equation:

$$C = \frac{LCOE_{investment\ costs} * CF * 365 * 24}{a_{7\%} * 1000}\ (USD/kW)$$

Equation 2. Capital costs.

And the fixed costs (FOM) are obtained as follows:

$$FOM = \frac{LCOE_{fixed\ costs} * CF * 365 * 24}{1000}\ (\frac{USD}{kW})$$

Equation 3. Fixed costs.

Related with the fixed and investment costs, also because they provide only Variable Operation and Maintenance (VAROM) costs of the data (in USD/MWh) and don't provide Fixed costs (FIXOM), the decision made is as follows:

- For nuclear and non-thermal technologies, the VAROM result that IEA gives are allocated as FIXOM.
- For non-nuclear thermal, the VAROM result that IEA gives are allocated as VAROM.

Talking about the data reference year, since they do not provide other specific information in their report, the assumed value is 2019. This is because even though the report was published in 2020, they refer the data from 2019. Related with that, the starting year for all technologies is assumed also as the year 2019. Since the starting year is not available in the report, it is assumed that all technologies are available in the same year than the reference year.

The currency unit used, according to the Report (IEA, 2020) is 2018 USD.

For the capacity factors, as the EIA says in the Report (IEA, 2020), a standard capacity factor of 85% was used for all combined-cycle gas turbines (CCGTs), coal-fired, fuel cells and nuclear plants under the assumption that they operate in baseload. For open-cycle gas turbines (OCGTs), a capacity factor of 30% is assumed. For all other technologies, country-specific capacity factors were assumed as they are largely site-specific.

Talking about the lifetime for the technology, according to the report (IEA, 2020), the following table shows the lifetime for different energy technologies:

Table 9. Technical lifetime for IEA technologies.

TYPE OF TECHNOLOGY	**LIFETIME** (years)
Battery storage:	10
Solar PV, onshore and offshore wind:	25
Gas-fired power plants:	30
Coal-fired power and geothermal plants:	40
Nuclear power plants:	60
Hydropower plants:	80
Additional lifetime after nuclear LTO:	10 or 20, depending on regulatory framework

And for the lead time, which is the construction time to build the plant (excluding permits), also according to the Report (IEA, 2020), the following values are used:

Table 10. Leadtime for IEA technologies

TYPE OF TECHNOLOGY	**LEAD TIME** (years)
Non-hydro/-geothermal renewables, fuel cells	1
OCGT power plants	2
CCGT power plants	3
Coal- and biomass-fired power plants	4
Geothermal and hydro plants	5
Nuclear power plants	7 (LTO: 2)

6.6.2. EIA Database comments

The EIA Dataset is extracted from the *Table 8.2 (Cost and performance characteristics of new central station electricity generating technologies)* in the Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2021 (EIA, 2021). That table represents EIA's assessment of the cost to develop and install various generating technologies used in the electric power sector. The costs shown in the table are the costs for a typical facility for each generating technology before adjusting for regional cost factors.

In that table, for some energy technologies, the available data is the following:

- First available year.
- Size (MW).
- Lead time (years).
- Base overnight cost (2020 $/kW).
- Technological optimism factor.
- Total overnight costs (2020 $/kW).
- Variable O&M (2020 $/MWh).
- Fixed O&M (2020$/ kW-year).
- Heat rate (Btu/kWh).

As it is said in the report (EIA, 2021), the data reference year is 2019, and the monetary unit used is 2020 USD.

The lifetime, efficiency and capacity factor used to complete this dataset, since they are not specified neither in the table nor the report, are based on the World Energy Outlook data (IEA, 2019). According to the IEA, the following table shows the technological values used to complete the database.

Table 11. Technical data energy technologies (IEA, 2019).

Technology	Net capacity (MW)	Net efficiency (%)	Load factor (%)	Technical Lifetime (years)	Construction time (years)	CO_2 captured %
Conv CC / 702 MW / Natural gas	702	0,517	60%	25	3	0
Adv CC / 1100 MW / Natural gas	1100	0,542	60%	25	3	0
ICE / 85 MW / Natural gas	85	0,401	20%	25	2	0
IGCC / 650 MW / Coal	650	0,37	87%	35	4	0
IGCC w CCS - 30% / 650 MW / Coal	650	0,35	87%	35	4	0,3
IGCC w CCS - 90% / 650 MW / Coal	650	0,293	87%	35	4	0,9
ST / 50 MW / Biomass	50	0,253	87%	30	4	0
Adv nuclear	2234	0,326	90%	50	6	0
Conv Hydropower	500	1	45%	75	4	0
Solar PV -fixed tilt	150	1	20%	30	2	0
Solar PV -tracking	150	1	24%	30	2	0
Wind onshore	100	1	35%	25	3	0
Wind offshore	400	1	45%	25	4	0

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6.6.3. IRENA Database comments

IRENA Database was extracted from the report *Renewable Power Generation Costs in 2019* (IRENA, 2020). The data on this report consists of some techno-economic data for the following renewable technologies:

- Onshore wind.
- Solar photovoltaics.
- Offshore wind.
- Hydropower.
- Geothermal.
- Bioenergy.
- Concentrating solar power.

As it is said in the report, the technical lifetime for these technologies is the following:

Table 12. Lifetime for IRENA technologies.

Technology	**Lifetime (years)**
Wind power	25
Solar PV	25
CSP	25
Hydropower	30
Biomass for power	20
Geothermal	25

Even tough IRENA provides different data from 2010 to 2019, the assumed and selected value is 2019.Related with that, the starting year for all technologies is assumed also as 2019. Since the starting year is not available in the report, it is assumed that all technologies are available in the same year than the reference year.

At the end, the data provided by IRENA is not used for the final LCOE calculation and comparison, since some important techno-economic data is missing and they only provide renewable technologies data.

6.6.4. JRC IEA-ETSAP Database comments

The JRC ETSAP SubRES database consists of the input data used for the TIMES model, in which the following information can be found for each technology:

- Technology description.
- Lifetime.
- Starting year.
- Availability factor.
- Currency.
- Investment cost.
- Fixed costs.
- Variable operation & maintenance costs.

For the renewable technologies, since the availability factor is not provided, the data used is based on the World Energy Outlook (IEA, 2019). This data can be found again in .

For the later LCOE calculation, some technologies have data only for the first years. For these technologies, in order to fill all the gaps in the database, the same value was used for the next years. For example, if a solar photovoltaic technology has different values for the VAROM costs for different years, but only on value of INVCOST for the first year, the INVCOST values assumed for the next years are the same than for the first one.

Also, for those technologies which the costs and/or efficiency are improving over time, the values used for the LCOE (instead of the average of all the years) are those for the first year when the technology is available.

6.7. Technology Readiness Level

Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology (Mihaly, 2017). TRLs supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology (Mankins, 1995).

TRL's NASA definition consist of a classification between 1 and 9 levels, where 1 is the less prepared technology and 9 is the most prepared and mature technology (Mihaly, 2017). Despite this first definition, in the specific case of this project, a scale between 1 and 11 is decided to use, with the following level descriptions:

Table 13. TRL levels

TRL	Years until availability		Description
	Optimistic	Neutral	
1	50	60	Laboratory/experimental
2	40	45	Laboratory/experimental
3	30	35	Laboratory/experimental
4	20	25	Laboratory/experimental
5	15	20	Pre-Pilot
6	10	15	Pilot plant
7	5	10	Demonstration plant
8	0	5	Full scale demonstration plant
9	0	0	First of a kind commercial
10	0	0	Early adoption
11	0	0	Mature

Once having the 11 levels defined, TRLs are assigned to each energy technology with the help of the project supervisor and the TIMES LTU.The classification, and assumed values are shown in the following table:

Table 14. TRL for the ETSAP-SubRES technologies.

Description	Short name	TRL
Combined Cycle Gas Turbine	CO.CCGT	11
Open Cycle Gas Turbine	OCGT	11

Integrated Gasification Combined Cycle	CO.IGCC	8
Integrated Gasification Combined Cycle	CO.BGCC	8
Fuel Cell	BP.FC	-
Internal combustion engine	IC	11
Fluidized Bed Electric only	FBE	11
Fluidized Bed Electric only - Supercritical	FBSC	11
Fluidized Bed Electric only - Ultra supercritical	FBUSC	-
Fluidized Bed BP	BP.FB	11
Fluidized Bed CO	CO.FB	11
Fluidized Bed heat only	FB	11
Conventional Boiler Electric only	CBE	11
Conventional Boiler Electric only - Supercritical	CBSC	11
Conventional Boiler Electric only - Ultra supercritical	CBUSC	11
Conventional Boiler	BP.CB	11
Conventional Boiler	CO.CB	11
Conventional Boiler	CB	11
Small scale fuel boiler	SB	11
Electric boiler	EB	11
Hydro run-of-river	ROR	11
Hydro conventional	HYD	11
Hydro	HYD	11
Hydro with storage	HYD	11
Hydro pump	HYDPUMP	11
Hydro reservoir	RSV	11
Heat pump	HP	10
Geothermal	GEO	9
Ocean	OCE	-
Wind onshore	ONWIN	11
Wind offshore	OFFWIN	-
Wind offshore floating	OFFWIN	-
Wind offshore shallow water	OFFWIN	-
Wind offshore deep sea	OFFWIN	-
Solar PV (residential)	PVR	10
Solar PV (commercial)	PVC	10
Solar PV (utility scale)	PVU	11
Solar PV (utility scale + floating)	PVF	11
Solar (Concentrating Solar Panel)	CSP	8
Nuclear	NUC	11
Nuclear Advanced Light Water Reactor	ALWR	11
Nuclear Gen III	NUC	8
Nuclear Gen IV	NUC	4
Nuclear Gen V	NUC	1
Nuclear Light Water Reactor	LWR	11
Nuclear LTO lifetime extension (10 years)	NUC	11
Nuclear LTO lifetime extension (20 years)	NUC	11

Nuclear Small Modular Reactors	SMR	4
Bioenergy	BIO	11
Biomass	BIO	11
Battery storage	STG	10

Some technologies do not have an assigned TRL because it was decided to fill them in the future within the LTU TIMES division after a discussion, since some of the technologies were not precisely defined and includes different information from different sources. This *Table 14* was only a first approach for a future assessment on how the TRL affects to the LCOE costs of the technologies.

CHAPTER 7: LCOE CALCULATION

In this chapter, the results of the LCOE are going to be explained, presented and analyzed. First of all, the cost components for electricity generation are briefly explained, and then the results from the database are shown.

7.1. Power Generation Cost Components

To understand in a more detailed way the meaning of the LCOE, it needs to be decomposed. Thus, each energy technology has a single cost profile, including the capital cost to build the plant, the fixed and variable costs associated with operating the plant, and external costs linked to the plant, such as the infrastructure required to connect the plant to the power grid or costs from environmental damage caused by the plant's operations (Bailey, 2012). The components of each of these cost drivers are detailed in the following sub-chapters.

There are several reasons such a great number of technologies and fuels remain competitive and in use despite having widely different cost and performance characteristics. Power plants are capital intensive and have very long useable lives—often more than forty years. As a result, older power plants that have paid off their capital costs remain in service even as newer, more efficient technologies become available (Nakicenovic & Swart, 2000).

Power generation costs are also highly specific to the circumstances of each individual project; two projects using the same technology and similarly priced fuels can still have dramatic differences in total electricity cost due to the regional or site-specific expenses or some externalities.

7.1.2. Capital Costs

Capital costs are the most significant cost to power generation for many technologies (Bailey, 2012). Capital costs for most technologies include:

- Site preparation. Buying and preparing the land where the plant is located, building related fuel storage facilities and the buildings for the plant.
- Mechanical equipment such as the turbine and generator with related installation costs, auxiliary equipment and balance of plant equipment as needed.
- Electrical equipment such as the plant's transformers and switchgear, control systems and instrumentation.
- Indirect costs such as contractor overhead, fees, profit and contingency allowances; labor and materials not otherwise allocated to other categories; and start up and commissioning costs.

- Owner's costs can include development and preparatory studies (engineering, feasibility, environmental assessments), permitting and fees, project management, insurance and taxes.

7.1.3. Fixed and variable operating costs

Fixed operation and maintenance (FOM) costs are incurred during the operation of the plant that are not affected by the amount of electricity produced. These costs can include labor and staffing costs, routine maintenance of the equipment and general facilities, and regulatory fees (Bailey, 2012).

Variable operating and maintenance (VOM) costs are directly related to the amount of electricity produced by the plant. These can include water charges and waste/wastewater disposal charges, consumable materials such as lubricants and other gases or catalysts, ammonia (used in some types of environmental controls) and other chemicals (Bailey, 2012).

7.1.4. Fuel costs

Fuel costs usually are the largest variable cost for non-renewable energy power plants. Fuel costs depend on the price of the fuel and the plant's thermal efficiency i.e., the amount of fuel required to produce a unit of electricity (Bailey, 2012).

The next table shows the fuel prices used for the LCOE calculation on the EIA and JRC databases:

Table 15. Fuel prices for LCOE.

Fuel	Price (EUR/MWh)	Price (USD/MWh)
Biomass [a]	10	13
Coal [a]	5,4	7,02
Natural gas [a]	18	23,4
Uranium [a]	2	2,6
Diesel [b]	45,11	58,64
Oil [b]	35,01	45,51

The currency conversion from EUR to USD considered is $1\ EUR = 1.3\ USD$.

7.1.5. Power Plant Efficiency

Higher efficiency plants can reduce the impact of fuel prices on the price of electricity. Also, plants with higher utilization can spread the capital cost across a greater amount of output than a plant with low utilization, resulting in an overall lower price for the electricity produced (Bailey, 2012).

Power plant efficiency is determined by the technology being used, but is also influenced by the operating conditions, such as the ambient temperature and pressure, and by the condition of the turbine. Poor maintenance, or simply erosion and build-up of impurities as the unit ages, steadily reduce the plant's actual efficiency. This analysis used efficiency levels representative of the current state of the art for each technology (Bailey, 2012).

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[a] Font: World Energy Outlook (IEA, 2019)

[b] Font: Cost and Quality of Fuels for Electric Plants (EIA, 2010)

7.2. Levelized cost of electricity

In this section, the results for the LCOE calculation for all the technologies presented in the final ETSAP SubRES DATABASE are shown. The equation used to calculate the LCOE is the following:

$$LCOE = \frac{(C * a) * 1000}{CF * 365 * 24} + \frac{(FOM) * 1000}{CF * 365 * 24} + VOM + \frac{f_c}{\eta}$$

Equation 1. Levelized Cost of Electricity.

where:

C: Capital costs (EUR/kW)

FOM: Fixed annual operation & maintenance costs (EUR/kW)

CF: Capacity Factor

VOM: Variable operation & maintenance costs

f_c: fuel cost

η: efficiency

And for each technology (t), the annuity factor (a_t) is calculated with the following equation:

$$a_t = \frac{d}{1 - (1 + d)^{-z_t}}$$

Equation 4. Annuity factor.

where:

d: discount rate

z_t: technical lifetime of each technology

Looking at the investment cost part of the equation, the annuity factor is a function of the lifetime of the technology and the discount rate i.e., the value of the annuity factor depends on the technology lifetime and the discount rate (DR). In order to see the consequence of increasing or decreasing the Discount Rate, we need to take a look at the mathematical *Equation 4*. Thus, an increase of the discount rate would increase the investment part, which leads to an increase of the overall LCOE. Also, at the same time, a decrease of the discount rate provokes a decrease of the total LCOE.

7.3 LCOE Comparison: Technology variation

In this chapter, the variation of the LCOE for each technology and the three main sources are discussed. This is to show how the data of the LCOE inside the same type of technology varies, which means that different LCOE results can be obtained for the same technology regarding different size or region, for example.

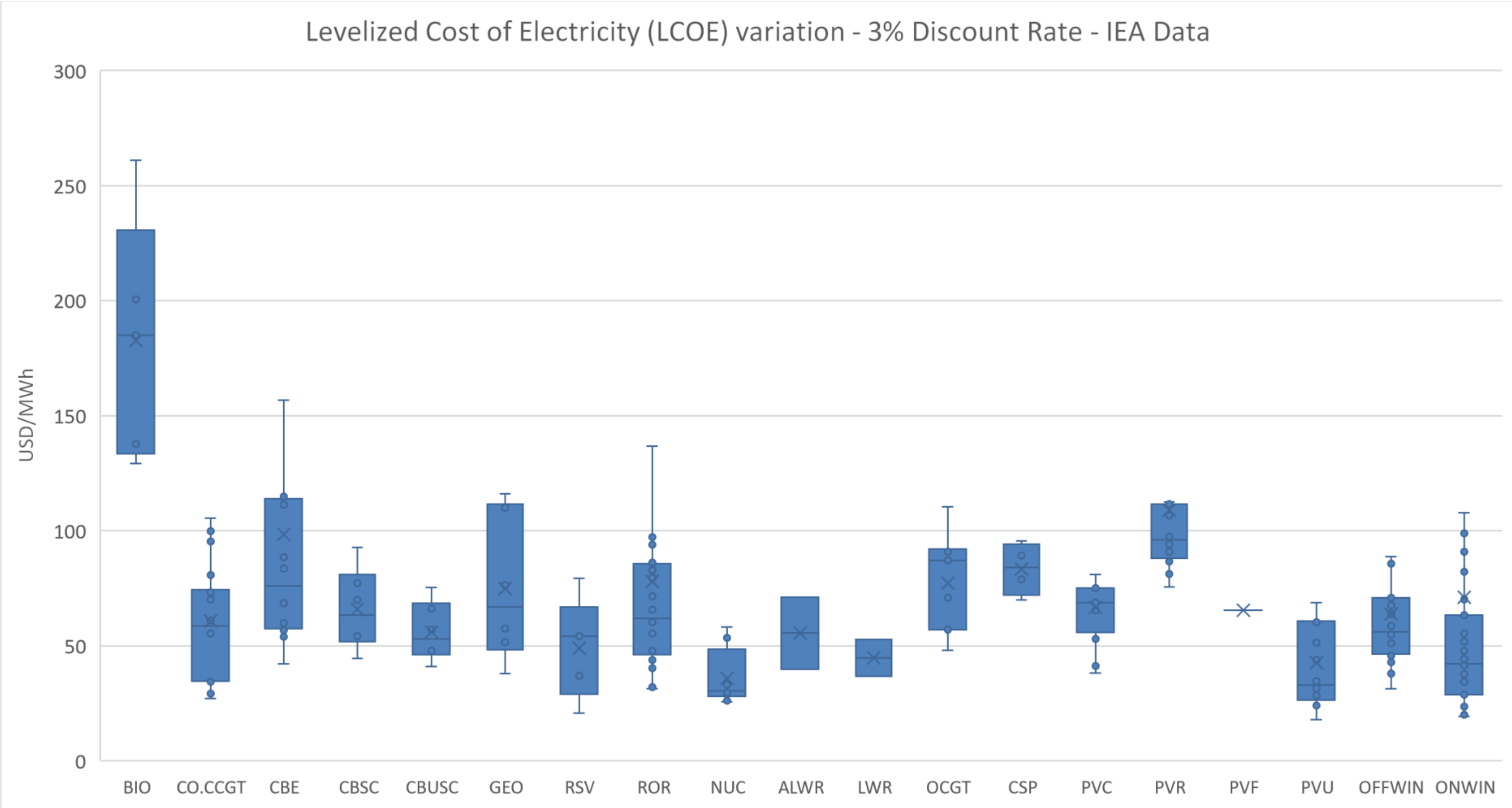

Figure 5. LCOE variation for IEA data.

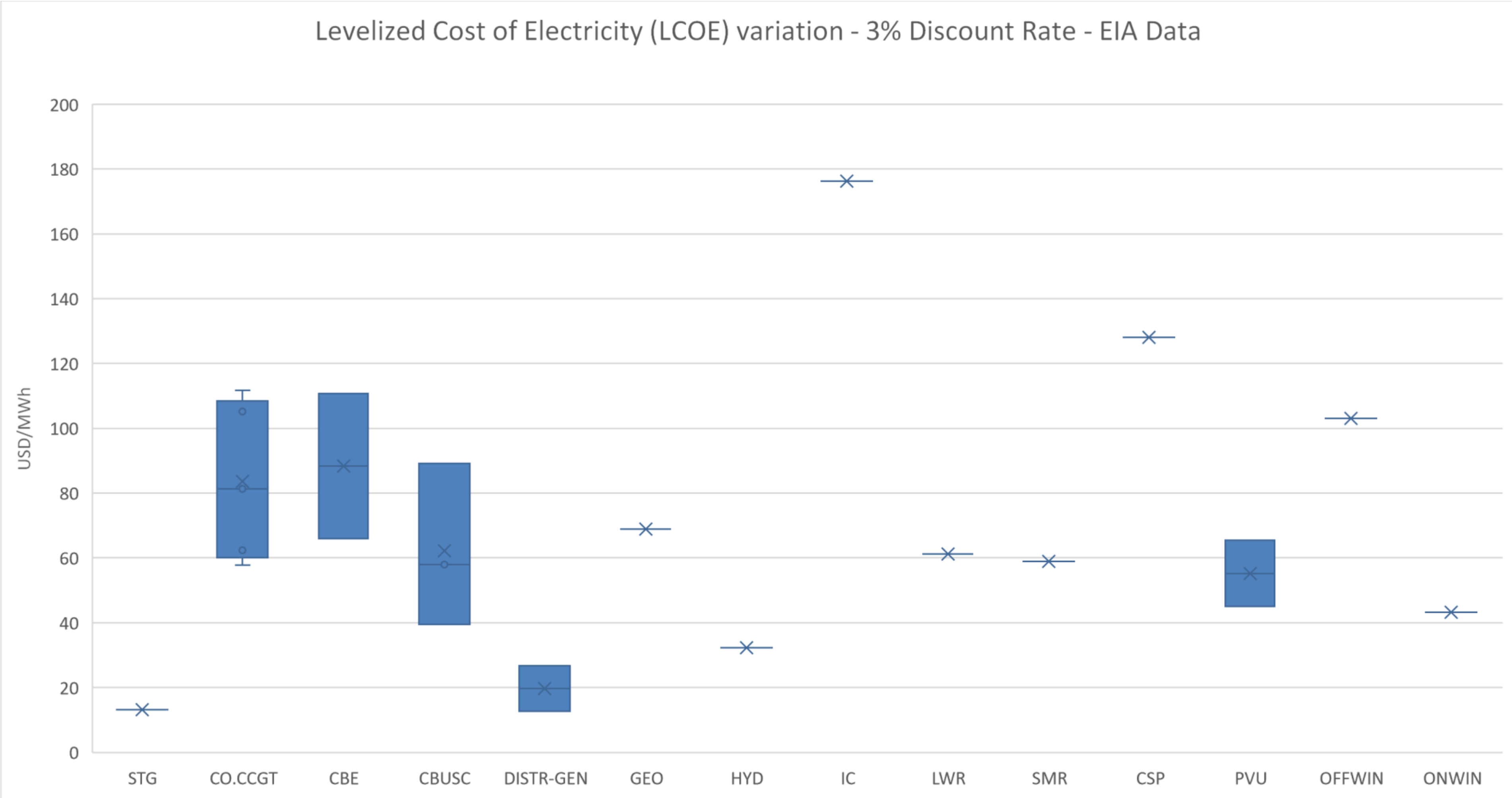

Figure 6. LCOE variation for EIA data.

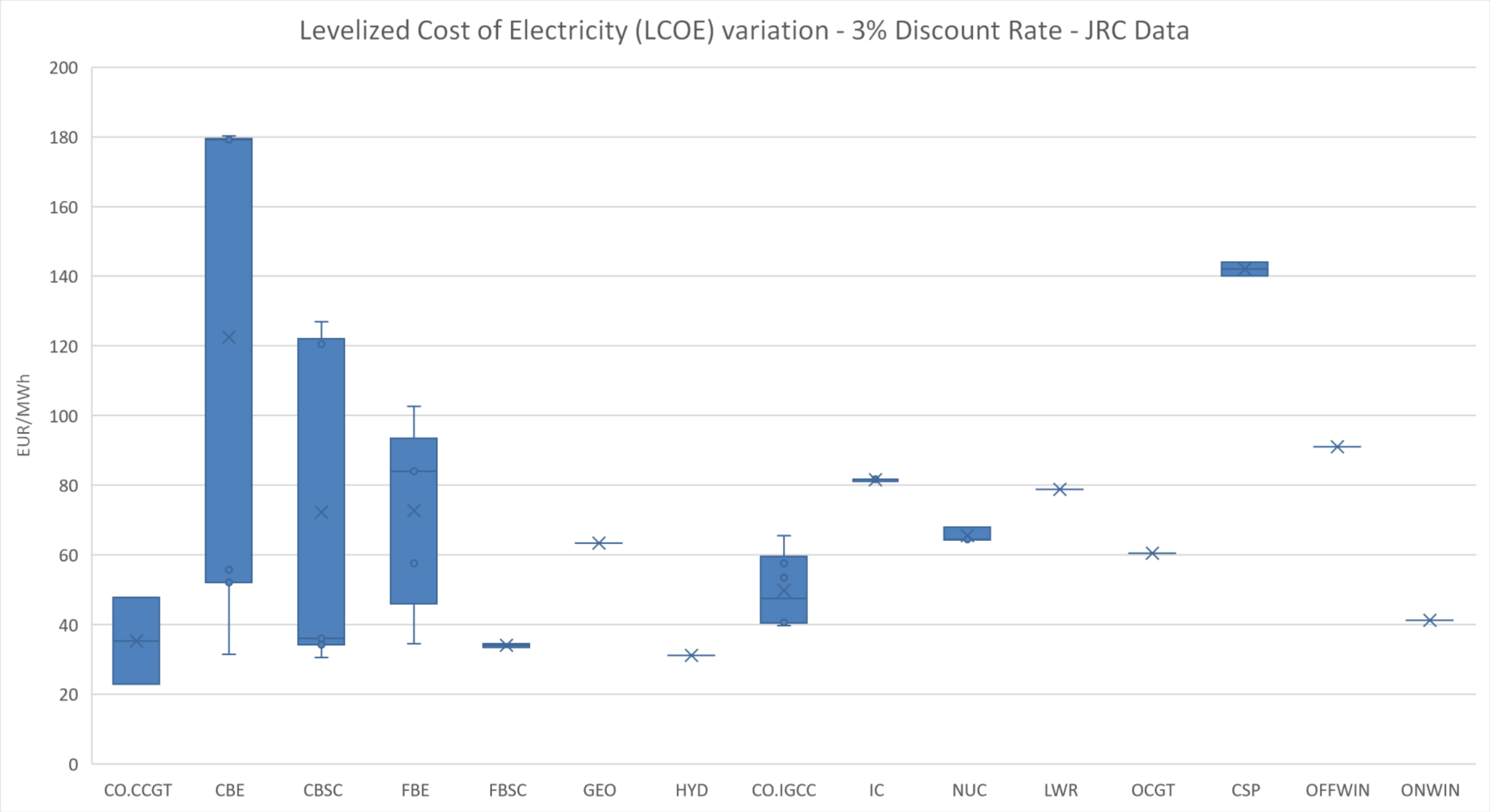

Figure 7. LCOE variation for JRC data

7.4 LCOE Comparison: Varying discount rate

The results of the LCOE in this project are calculated for three different discount rates (DR): 3%, 7% and 15%. One main assumption is that the discount rate used for discounting costs and benefits is stable, the same for all technologies and does not vary during the lifetime of the project under consideration.

Three different values of the discount rate were used to see some different scenarios. 3% discount rate corresponds approximately to the "social cost of capital", a 7% discount rate corresponds approximately to the cost of capital of a large utility in a deregulated or restructured market, and a 15% discount rate corresponds approximately to cost of capital in an environment with relatively higher risks (IEA, 2020). For the IEA discount rates, the third number used is 10% instead of 15%, which is the number finally used in this project. This number is taken because the difference between 7% and 10% is not enough to compare results, considering that is more reasonable to compare discount rates between 7% and 15% to see a better difference.

The LCOE results shown are the three main different sources that make up the final database. The *Figure 5* shows the LCOE of the International Energy Agency (IEA) database, followed by the results of the Energy Information Administration (EIA) in the *Figure 6,* and finally the *Figure 7* shows the Joint Research Centre (JRC) database results. Additionally, the LCOE variation for the three sources is shown, in order to see the deviation between the results for the same technology. This is necessary to show all the LCOE range, instead of only the average of the results for each technology. The results are shown for the IEA, EIA and JRC sources in the Figure 8, 9 and 10, respectively.

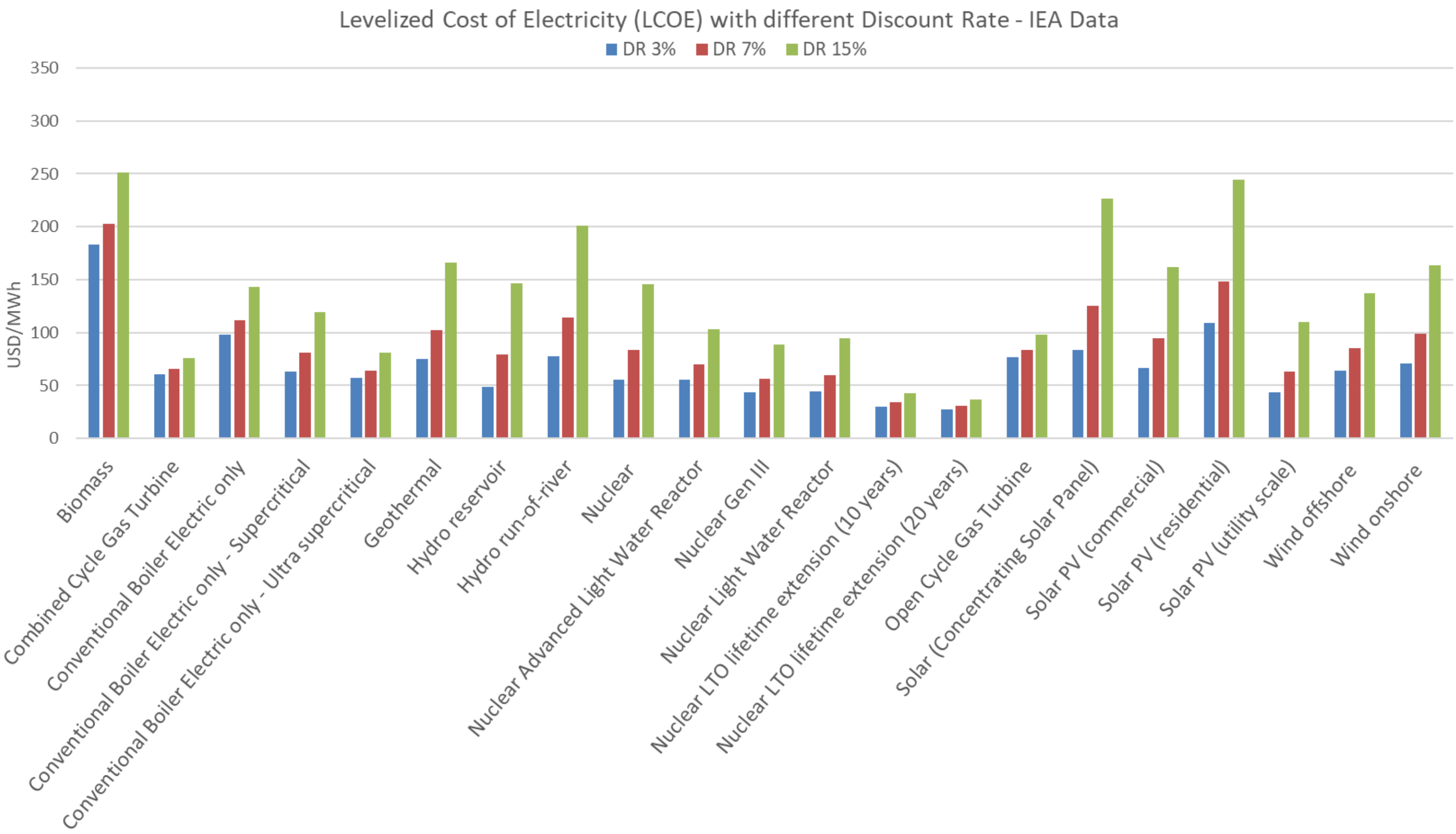

Figure 8. LCOE results for IEA data.

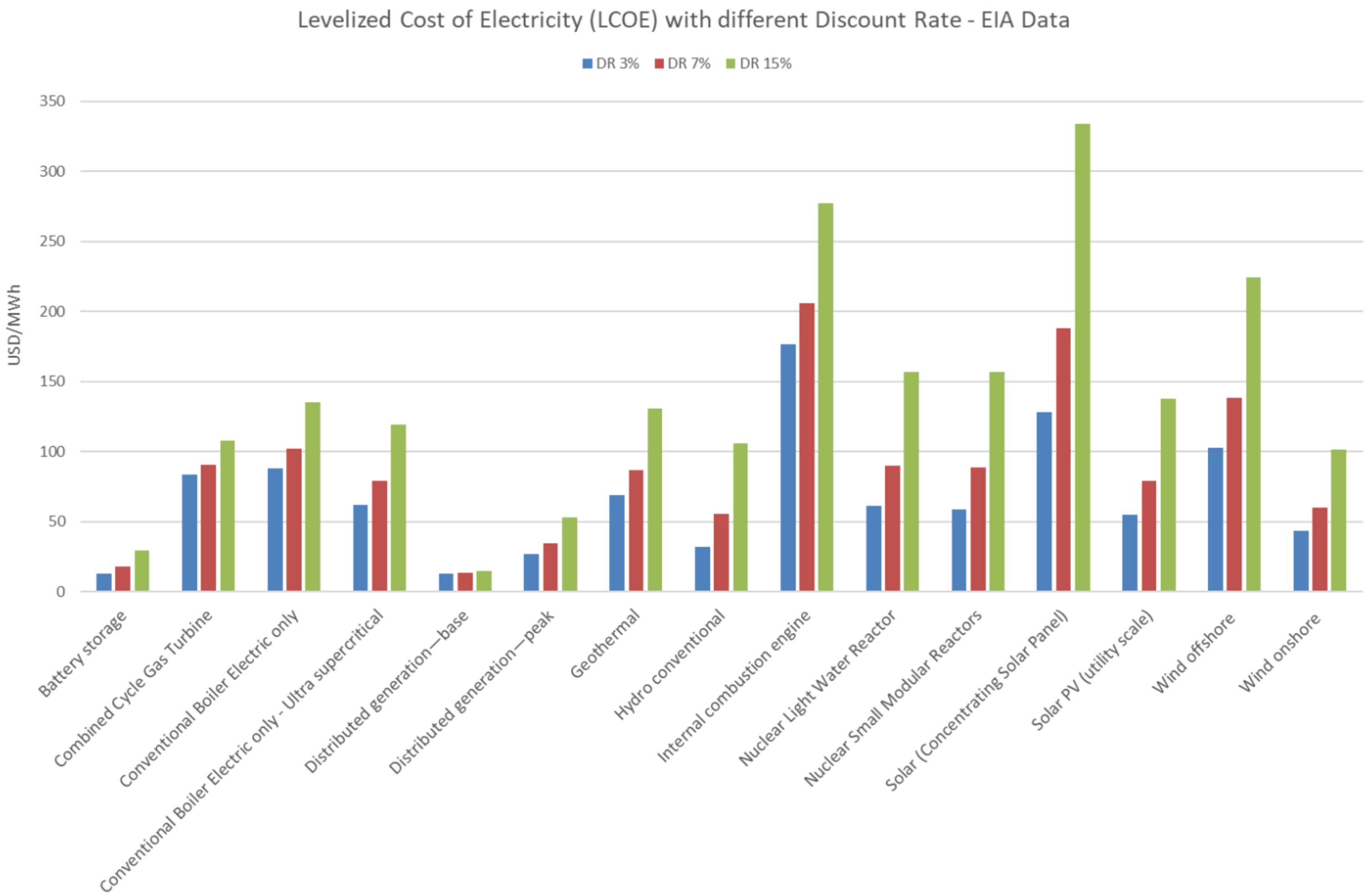

Figure 9. LCOE results for IEA data.

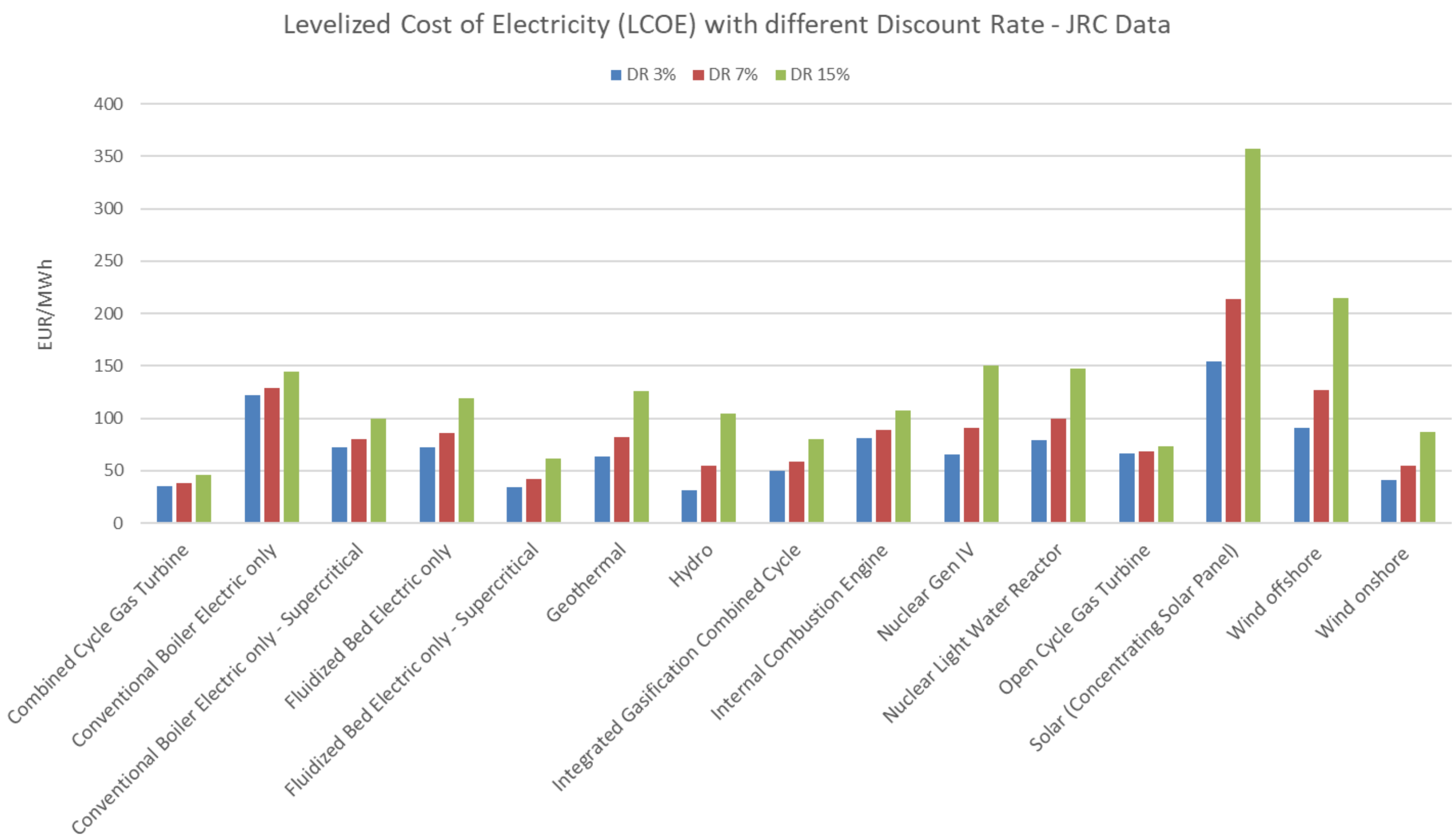

Figure 10. LCOE results for JRC data.

As it can be seen in the above *Figures 8, 9 and 10*, the higher the Discount Rate, the higher the LCOE for every energy commodity. An important comment is that the difference between 15% and 7% Discount Rate is often higher compared with the difference between 2% to 7% in some technologies, affecting already high LCOEs the most. The difference in LCOE when varying the Discount Rate affects only the investment costs of the equation, which depends not only on the DR (and annuity consequently), but also on the lifetime for every technology.

Thus, some technologies are affected more than others when varying the DR, and these technologies are usually the renewable-power technologies. Comparing the conventional with the renewable technologies, the latter ones are more sensitive to the increase of the discount rate. The Discount Rate leads to an increase in the costs of electricity with higher lifetimes. Also, the annuity factor is less sensitive with higher lifetimes. Thus, investments with longer lifetimes tend to be affected less by discount rates, because the compound interest has a lower effect.

Generally, seeing the results for the three sources analyzed, the renewable technologies are competitive regarding the price obtained compared with the conventional technologies. The higher price obtained, comparing the renewable sources among them, is the Concentrating Solar Panel. On the other hand, among the conventional technologies, the boiler electric has higher prices, followed by internal combustion engine and gas turbine cycles.

Analyzing the data variation, the *Figure 8* shows that the IEA data has a variation in all technologies, and that is because the data provided by the source is wide, providing different data regarding size and regions, which affect to the final prices. For the other two sources, the *Figure 9* and *Figure 10* shows that the EIA and JRC data is not as wide as the IEA data, and consequently the variation of data for each technology is lower. This is because the amount of data provided is less, and also among the technologies analyzed, the data provided for the same type is scare. In these two last sources, the variation only occurs in some conventional technologies, but the data provided for the renewable technologies is unique.

CHAPTER 8: LCOE EVALUATION BETWEEN SOURCES

In this chapter, the comparison between the LCOE results obtained is made. The comparison is made between the values obtained for the technologies which are in common at least in two of the three main sources. That means that if a type of energy technology is only included in one of the three sources, this technology is not compared and showed in this section.

This comparison is interesting to see if the data provided by different sources is coherent, or if there are big differences instead. This is the last step to analyze the data provided by the sources, to see if the results make sense and the data is reasonable.

The results are shown again in USD/MWh. For the JRC data, where the results were obtained in EUR/MWh, the currency exchange used is the same than used in previous sections for the fuel prices, being $1\ EUR = 1.3\ USD$. With that exchange, all the results are compared following the same unit.

In order to show that comparison, the next *Figure 8* shows the LCOE results for the three main sources, ordered by-technology.

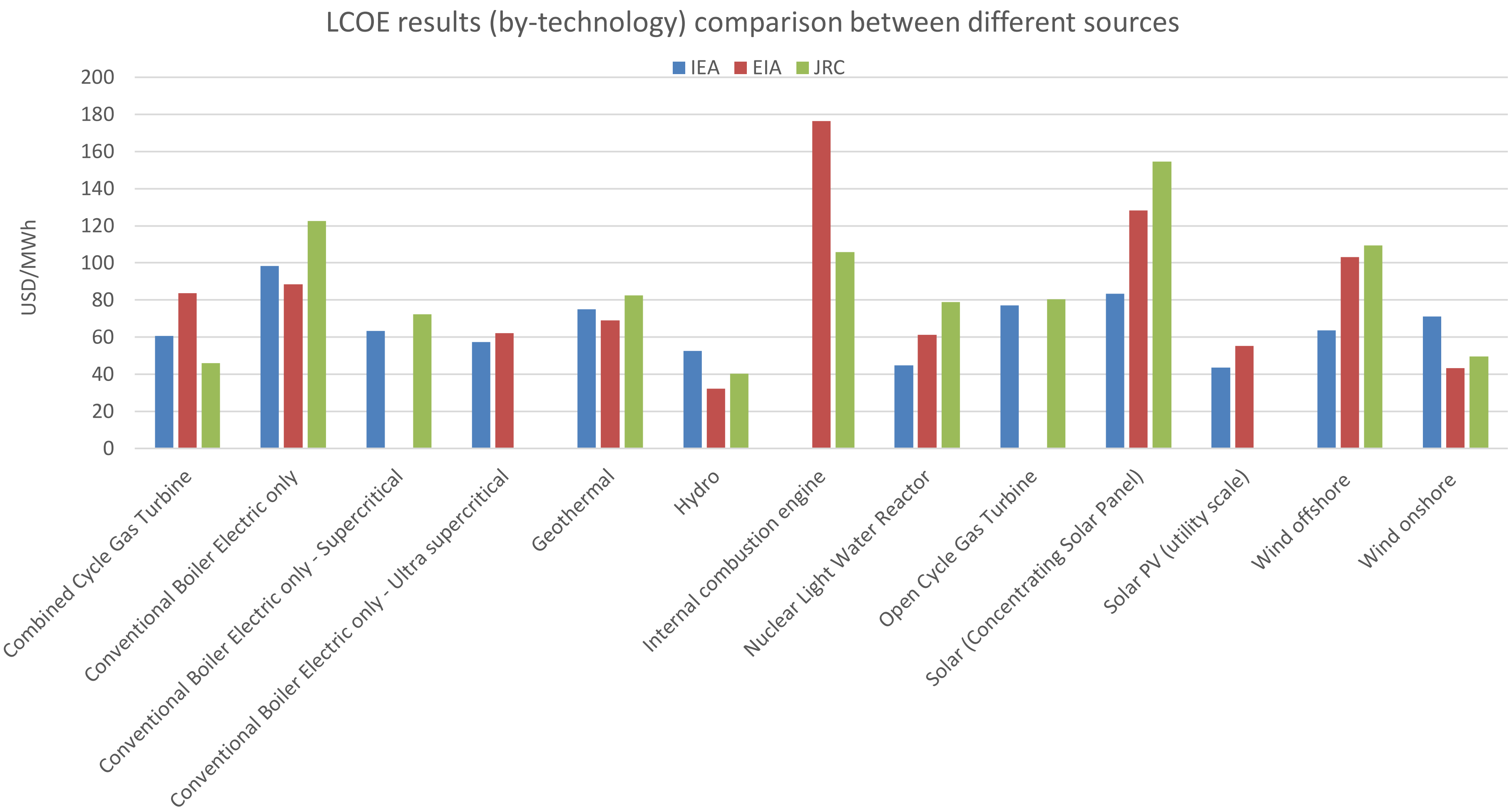

Figure 11. LCOE comparison between the sources.

As it can be seen in the figure, the LCOE values obtained comparing the three sources, are in general pretty similar, except two big differences: Internal Combustion Engine and Concentrating Solar Panels (CSP).

The reason of the variation for the internal combustion engine is that the data compared has a different size, and for the CSP the reason is because is not a mature technology and the techno-economic data from the sources can be uncertain.

Apart from that, all the other values obtained are similar, which means that the data is coherent and the different between the sources is not a big difference, even considering the assumptions made for the LCOE in the calculations or the database filling, or the different areas or regions which has a big impact on the prices.

CHAPTER 9: Discussions

In this chapter, the discussions of the project performed are commented and noted. Starting with the Excel SubRES database, it was a big challenge to create a complete database, filling all the fields required by the model. That is because sometimes it was not easy to find the exact information to include or how to organize all the information, ensuring that it makes sense.

The way and method of how each source gives and provide their data is different, not only in their reports, but also in their websites and databases. Moreover, working with high amount of values and data is not always easy. In addition, to complete the database and have it available to get some results, some assumptions were made. These assumptions have a clearly direct consequence in the results obtained not only on the LCOE calculation, but also in the future usage of this database for the TIMES model.

Talking about the usage of the data found in the different sources, at the end not all the data provided was useful to fill the last version of the database. There are some values and assumptions which need to be studied out of the databases, like the fuel prices, which is also something that changes with the time. Furthermore, the way how the sources present the data is different, and in some cases, like the IEA database, all the information that the sources give is their results, and not how they assessed or which techno-economic information they used to get these results.

IRENA data was not useful at the end to fill the database because some important techno-economic data is missing, and they only provide renewable technologies data. This means that is not a complete techno-economic data to include in the database. About the reliability of the sources, all of them seem to be reliable, but for the final database, some of them are more useful, like the IEA source for example, and this is because it is the most complete database.

Talking about the LCOEcalculation, the values obtained in general are reasonable, but there could be some inconsistencies or differences regarding the assumptions made, like some technology lifetime or fuel prices. The economy is constantly changing, and today's prices showed in the report can quickly change.

One final comment to conclude the discussion is that the LCOE showed in this project does not include subsidies and CO_2 taxes. The real results can differ a bit if the taxes are applied, especially for the conventional energy commodities such as coal or natural gas. Logically, the renewable technologies don't have CO_2 tax penalties. Including these taxes, it could be interesting to see how some renewables become even more competitive at prices against conventional technologies.

CHAPTER 10: CONCLUSIONS

As a conclusion, the database development was a difficult task due to the variation on how each source give the information to the user. But at the end, the filling of the database was possible adding assumptions and values from other sources, as it was explained during some chapters of the report.

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