NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTMENT OF ELETROTECHNICAL AND COMPUTER ENGINEERING (DEEC)

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Analysis of the Future of Hydropower Technologies in the European Union under Project Drawdown Framework

Masters in Renewable Energy Engineering

NOVA University of Lisbon

November, 2021

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European Potential of Hydropower Technologies for Electricity Generation under Project Drawdown Framework

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“The steps you take don't need to be big,
they just need to take you in the right direction.”
(unknown)

RESUMO

As alterações climáticas são um problema inegável e, as soluções disponíveis para as resolver têm que ser entendidas profundamente. A par de várias instituições, o Project Drawdown é uma das principais entidades em termos de investigação e recursos relativos a soluções climáticas. As suas análises globais realizadas em 2017 e 2020, seguida pelos trabalhos de regionalização nos E.U.A e Europa são peças fundamentais deste entendimento e contextualização de soluções para as alterações climáticas em vários setores. Este trabalho procura compreender a contribuição que as grandes e pequenas centrais hídricas podem ter na mitigação das alterações climáticas na Europa, particularmente na redução de emissões de gases com efeito de estufa (GEE), quais custos associados e o seu papel no setor da geração de eletricidade até 2050.

A metodologia é baseada numa extensa compilação de projeções de geração de eletricidade (TWh) e características fundamentais das tecnologias hídricas. A modelação efetuada foi suportada no modelo bottom up Drawdown RRS, onde as soluções de tecnologia de geração hídrica foram individualmente modeladas para vários cnarios de adoção futura.

Os resultados mostram que a eletricidade gerada na Europa e União Europeia irá crescer em todos os cenários analisados. No entanto, este acréscimo varia consideravelmente nos diferentes cenários devido aos modelos e pressupostos socio-económicos e técnicos usados em cada publicação analisada. No que diz respeito à quantidade dessa geração assegurada por hídricas, os resultados mostram uma tendência de estabilização ou, em alguns casos, um pequeno crescimento, com o futuro da tecnologia assentando essencialmente na atualização e melhoria de centrais já existentes e não na construção de novas infraestruturas. Em termos ambientais e económicos, os resultados indicam que a grande hídrica pode trazer uma redução de emissões potencial entre 1,8-2,5 Gt of CO_2eq, nos seus cenários mais prováveis, estando esta redução de emissões ligada a uma poupança média ao longo do seu tempo de vida, em O&M e combustível, na ordem dos 253 mil milhões de euros, quando comparado com a utilização de combustíveis fósseis para geração eletricidade. Enquanto isto, a pequena hídrica terá o potencial para uma redução de emissões até 0,9 Gt of CO_2eq apresentando, no entanto, uma perda monetária que ronda os 300 mil milhões de euros até 2050, face às tecnologias convencionais, ilustrando a necessidade de investigação e melhorias na tecnologia se for pretendido que esta seja uma tecnologia principal na luta contra as alterações climáticas na região.

Termos chave: Project Drawdown, Geração de Eletricidade, Soluções Climáticas, Energia Hídrica

ABSTRACT

Climate change is an undeniable problem, and the solutions available to fight it need to be deeply understood. Along with other institutions, Project Drawdown is one of the leading fronts in research and resources about climate solutions. Its global analysis in 2017 and 2020, followed by regionalization efforts in the US and Europe, are critical pieces of this understanding and contextualization of climate change solutions in multiple sectors. This study aims to understand the contribution that large and small hydropower solutions can have in climate change mitigation in Europe and EU, specifically in reducing greenhouse gas (GHG) emissions, associated costs and its role in future developments of the electricity generation industry, one of the biggest GHG emitters.

The methodology is supported by extensive data collection of electricity generation projections (TWh) and key characteristics of the hydropower technologies. The results show that the electricity generated in Europe will grow in every studied scenario. However, the extent of this growth varies a lot along with the different scenarios from the various publications due to different models used, main socio-economic and technological assumptions. When it comes to the portion of that generation that is accomplished by hydropower, the results show a trend of stabilization or slight growth in some scenarios, with the future of these technologies laying essentially in repowering and improvements in existing powerplants and not in the building of new ones. Environmentally and financially, the findings suggest that large hydropower can bring a reduction of emissions between 1,8-2,5 Gt of CO_2eq in its most likely scenarios with average savings in O&M and from lack of fuel costs close to 253 billion euros, while small hydro can contribute with a reduction of up to 0,9 Gt of CO_2eq but presenting a net cost of about 300 billion euros, in comparison with the implementation of conventional technologies. At the same time, showing the need for improvement of the technology for it to play a significant role in climate change mitigation in the region.

Keywords: Project Drawdown, Electricity Generation, Climate Solutions, Hydropower

INDEX

INDEX OF FIGURES

INDEX OF TABLES

LIST OF ACRONYMS

CH_4 – Methane
CO_2 – Carbon Dioxide
DERA - Drawdown Europe Research Association
ERIRAS - The Energy Research Institute of the Russian Academy of Sciences
EU – European Union
EWG – Energy Watch Group
FOM – Fixed Operating and Maintenance Costs
GDP – Gross Domestic Product
GHG – Greenhouse Gases
HFCs – Hydrofluorocarbons
IEA – International Energy Agency
IEEJ – Institute of Energy Economics, Japan
IPCC - Intergovernmental Panel on Climate Change
IRENA – International Renewable Energy Agency
JRC – Joint Research Center
LH – Large Hydropower
N_2O – Nitrous Oxide
NGO - Non-Governmental Organization
PFCs – Perfluorocarbons
PPS – Pumped Storage
PV – Photovoltaics
RRS - Reduction and Replacement Solutions
RoR – Run-of-River
SH – Small hydropower
TAM – Total Addressable Market
UNIDO – United Nations Industrial Development Organization
VOM - Variable Operating and Maintenance Costs
WEC – World Energy Council

GLOSSARY

ADPT: This acronym is sometimes used interchangeably throughout this work in reference to the projections about the adoption of hydropower technologies for electricity generation, expressed in TWh.

TAM: The Total Addressable Market in the context of this work refers to the total amount of electricity generated during a given year, also expressed in TWh.

VMA: Variable Meta-Analysis refers to a set of technical end economic features that characterize technological solutions. Some of them are First Cost (or Installation Cost), Lifetime Capacity, O&M Costs and Emission Factors.

1. INTRODUCTION

"Energy is the only universal currency" [1]. From the discovery of fire as a thermal form of extra somatic energy in pre-literary history, through the use of kinetic energy for powering windmills, all the way to powerplants we use today powered by coal, energy is a constant need in our day-to-day lives, in addition to being a perennial presence in the universe and human history. Throughout human history, it has allowed us to progress and evolve in ways that would amaze, shock, and possibly frighten our ancestors. For example, the use of the energy stored in coal and utilized to produce electricity in thermoelectric powerplants allowed for the electrification of cities, the building of electric grids, and subsequent development of these urban centers, large and established or smaller and still developing locations, and the connection between them, bringing with it significant social and economic benefits.

This evolution, however, was not without its negative consequences. Our growing demands and the lack of equity within them have brought with this evolution which is very much dependent and aided by energy, ever-growing social, economic, and environmental issues.

These negative consequences started to gain attention in the late 1960s and 1970s, a time where a slew of social movements was gaining traction and emerging, particularly in the United States, such as the civil rights movements, opposition to the Vietnam War, feminism, the beginnings of social activism regarding gay rights, and, among these, environmentalism [2]. Aided by the popularity of Rachel Carson's Silent Spring (published in 1962), the environmental movement gained some attention. Unfortunately, its existence among these undoubtedly social causes, relegated the environmental movement to the periphery, seeing as the environment was seen as a counter-movement opposed to progress, as irrational, and was seen at this point as something external to society.[3] This assessment, however, began to change, aided by publications such as 1972's The Limits to Growth report published by the Club of Rome and 1987's Brundtland Report published by the United Nations. The perception of the environment as an external factor in production or consumption began to shift and its position among the economic and political agendas became more prevalent.

Forwarded by these publications and the creation of entities like the United Nations Environment Program (founded in 1972) and groups such as the Intergovernmental Panel on Climate Change (founded in 1988), environmental issues and climate change became a prevalent and significant topic of discussion among society and world leaders. This importance has only increased since the turn of the 21st century, with world leaders coming together in the Paris Agreement or with environmental activism becoming more widespread as seen by the Fridays for Future movement which has, since 2018, expanded the reach and awareness of these issues, becoming quite clear the importance of action in this matter.

1.1. The Current Climate Problem

To understand this enormous issue, we must assess where we stand on it. What progress has been made? What is still there left to do? And what are the consequences of not accomplishing those goals?

According to EMBER's Global Electricity Review of 2021 [4], the electricity demand worldwide has been growing since 2009, with the exception being the year 2020 (a year marked by the Covid-19 global pandemic where the global electricity demand fell around 0.1%), a statistic that brings with it both positive and negative aspects. For one, it can be argued that it implies the need for improvements in energy efficiency and that this continued increase may not be sustainable. On the other hand, the sources from which this electricity comes from have been changing.

The electricity generation from wind and solar sources has doubled in the last five years, amounting, today, to almost 10% of the world's total electricity in 2020. [4] A slight increase in hydropower generation has also been recorded. The exponential growth in these technologies has contributed to the further fall of coal-based electricity generation, seeing as the amount of generation growth from these renewable sources and the decline in coal use has been very similar. Unfortunately, electricity generation from renewable sources does not seem to be keeping up with the increasing demand mentioned. It led to an increase in overall fossil fuels electricity generation, with an additional 562 TWh of electricity generated from natural gas, for example, leading to around 2% higher emissions in 2020 compared to 2015 when the Paris Agreement was signed. [4]

These numbers bring credibility to the fact that the efforts towards this goal are currently lacklustre and need to be improved, with the IPCC stating that "global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate" [5], making it imperative that GHG emissions are reduced. For example, for the European Union and its member states, the national energy plans proposed do not add up to the necessary changes to meet climate targets for 2030, leaving less and less room for much-needed action in the years up until 2050. This approach, even in financial terms, is not ideal, as an "early and steady path" where the most significant percentage of emission reductions is achieved in the first decade of this period is more cost-effective than following a "late and rapid path" where a sharp decline closer to 2050 is made, requiring bigger depletions from carbon budgets [6].

As the last point illustrates, improving efforts regarding climate change, in addition to obvious environmental and social benefits such as enhancements in energy security, will lead to economic advantages. In Europe, these efforts to achieve a net-zero carbon 2050 can accelerate investment in green technologies and change global industry and markets, representing an opportunity for the EU to be the forerunner and standard of a whole industry [7].

1.2. What Solutions Are There?

Now, we know what the problem is and established that the needed efforts to solve it brings a vast array of benefits, not only environmental ones. So, the question becomes, where to start with these changes?

As shown in Figure 1.1, Industry, Transportation, and Power Generation have historically been the three primary sources of greenhouse gases in Europe. This suggests that these should be the most significant points of interest in reducing emissions on the continent.

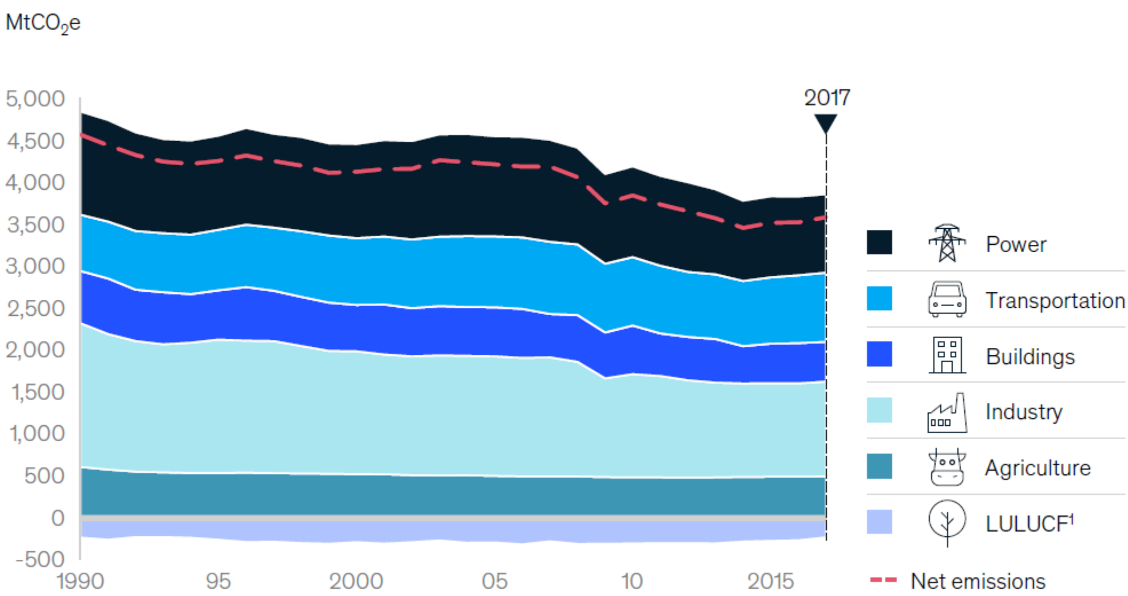
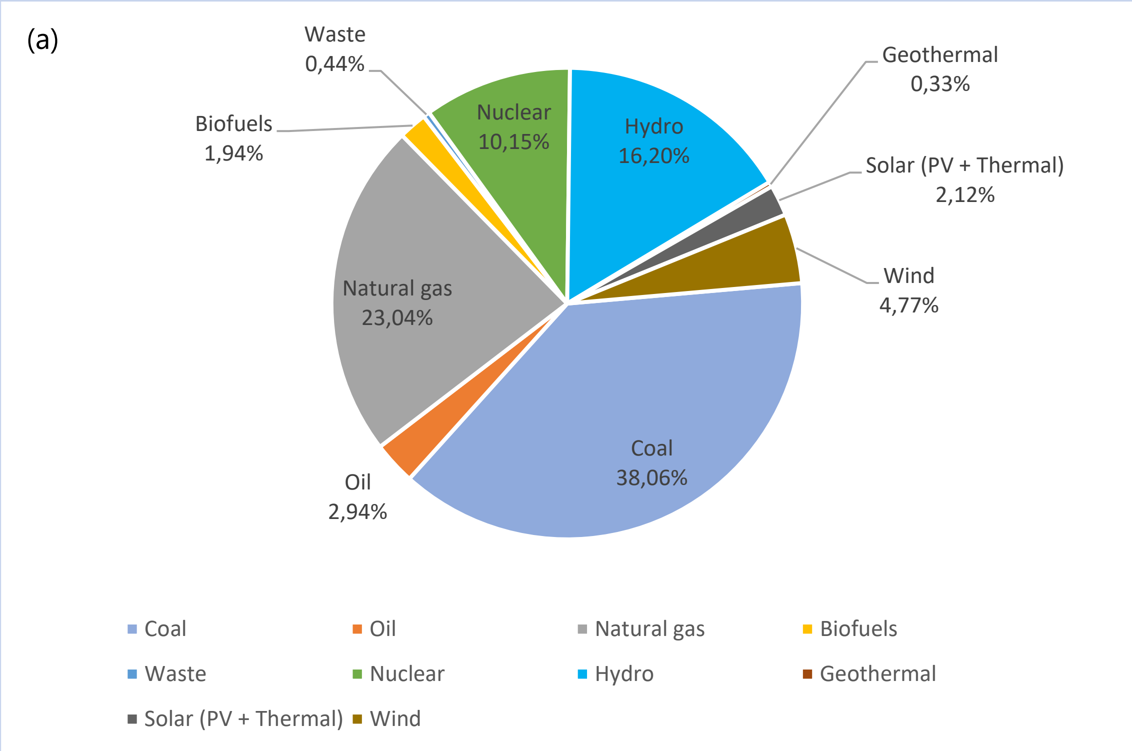


Figure 1.1 - Historic Emissions by Sector in Europe (1990-2017). [6]

In the Power sector, even though renewable energy can be associated with emissions, these are only indirect emissions that result from their supply chain (such as the production of components or material extraction, for example). The bulk of emissions in the sector comes from the use of fossil fuels, which, as seen in Figures 1.2a and 1.2b, represent around 64% of the World's electricity generation and about 44% of the European Union's. This point is further illustrated in the map for Figure 1.3, where it is easy to assess the hold that these greenhouse emitters have on the Power Sector in various



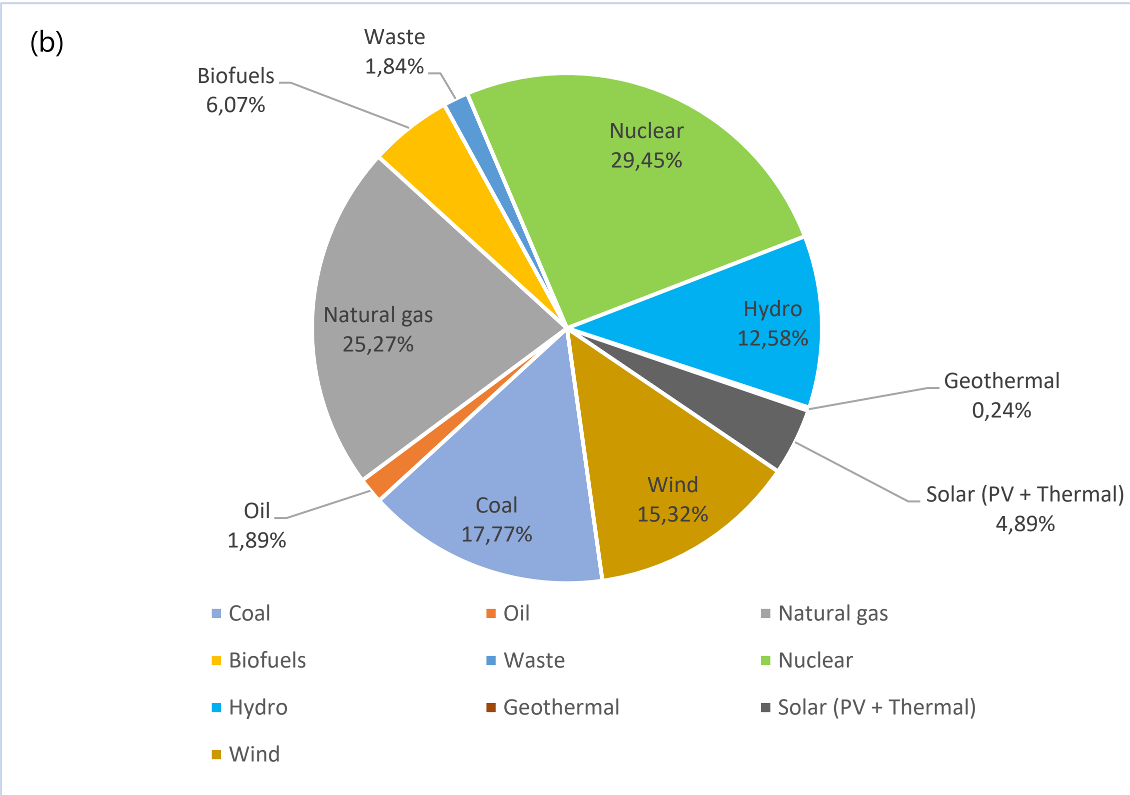


Figure 1.2 - World (a) and European Union's (b) Electricity Generation Mix by Technology in 2019. [7]

countries of the continent, presenting a vast opportunity to improve, reducing the share that these fossil fuels possess in the world's power mix.

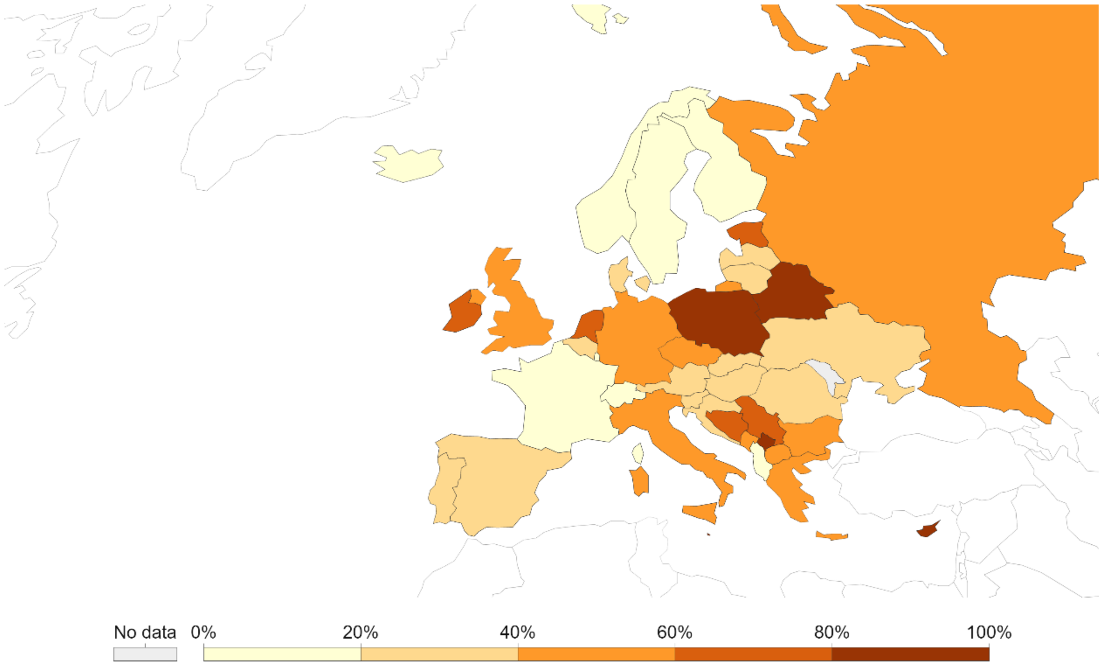


Figure 1.4 - Share of electricity production from fossil fuels in Europe (2021), according to data from EMBER and BP's Statistical Review of World Energy.

Therefore, these improvements need to be focused on the phasing out of these fossil fuels, as has been discussed widely in the last decade. This phasing out should be coupled with a bigger portion of renewables in the electricity generation market, with the cost reduction of wind energy and solar photovoltaics (PV) playing a major role in this transition [6]. It has been shown that a combination of these two energy sources, with hydropower, could supply Europe's demand for electricity with better interconnections between countries to smooth the fluctuations inherent to these sources and provide proper balancing [6]. These changes, aligned with better energy efficiency, improved storage, wider implementation of carbon capture and storage, could revolutionize the power sector and help achieve the goals of a net-zero economy by 2050.

With this in mind, the work along this thesis will focus on hydropower technologies and their use as solutions to climate mitigation. The reasons for the choice of technology, in the vast array of solutions available, were two-fold.

Firstly, this work is being framed as a part of Project Drawdown [8] and its Framework of Solutions (which will both be explained and expanded in the next chapter), so it made sense to approach technologies included in this framework. With this in mind, the Small Hydropower technology (SH) was chosen, and, as an extension of this work, it was also decided to work on Large Hydro technologies (LH) (not explored on Project Drawdown solutions global analysis, for the reasons explained in chapter 3.1.).

Secondly, hydropower technologies, on the one hand, are a very significant part of the World's and European Union's electricity generation mix [9], as seen in Figures 1.2a and 1.2b, respectively, being the biggest renewable energy source worldwide with 16,2% of electricity generation (corresponding to 4325 TWh in 2020) and the second biggest in the EU with 12,58% of generation (corresponding to 353 TWh in 2020), being overtaken by Wind generation in the last few years. On the other hand, these solutions present several advantages and benefits.

In addition to electricity generation, hydropower technologies can help control water flows, having a big impact on water supply and demand through the ability to smooth out fluctuations and to use reservoirs as large-scale storage, an essential part of the energy transition problem.

Additionally, being able to be used as a water management mechanism, with flood and drought control or irrigation for nearby agricultural prospects, crucial in the era of adaption to climate change and increasing water scarcity issues, is also an advantage.

Furthermore, this form of energy not only brings advantages in terms of power or agriculture but also tourism, as the reservoirs created can also be used for navigation and recreational activities [10].

Over the years, the perception of hydro technologies, especially when it comes to large hydro, has soured, with concerns about its actual environmental-friendly status and its potential, further expanded in chapter 3.1. According to the International Energy Agency (IEA), the technology keeps evolving and being developed regarding capacity, efficiency, security, or environmental friendliness, proving this perception mostly wrong and how valuable they can be towards the energy transition. In addition, there's potential to refurbish existing dams and build new ones in developing countries, not only large but also small hydro schemes. [10]

1.3. Objectives

With the energy transition problem laid out and how hydropower technologies can possibly help, it is important to establish the goals that this work aims to accomplish.

The dissertation's focus will be to contribute to the technical aspects of the puzzle that is climate change and its solutions. The main objective is the analysis of the potential of hydropower solutions for electricity generation and the reduction of greenhouse gas emissions, mainly CO_2, in the time frame between 2020 and 2050 in the European Union, replacing coal, oil, and natural gas, hereby referred to broadly as conventional technologies.

To better hold this very vast objective and allow the progress of work to be quantified, certain intermediate objectives were established. Firstly, an analysis of the total electricity generation in the European Union (hereby referred to as TAM – Total Addressable Market) is to be made, followed by a study of the contribution of the hydropower technologies in the Union's power mix (hereby referred to as Adoption) and the various future pathways for these technologies presented in energy and emissions projection studies. Additionally, research will also be conducted to obtain several financial, technical, and social indicators regarding these technologies, such as investment costs, capacity factors, or jobs created, with an emphasis on exploring the impact that some of these critical indicators can have when it comes to the future of these technologies by performing a sensitivity analysis.

Naturally, this research will also be divided by the already mentioned technologies, large and small hydro. An additional effort will be made to obtain data regarding TAM and Adoption for Europe (which includes data from different countries, depending on the source, but most prominently Russia, Turkey, UK, Norway, Belarus and Ukraine) as a whole and explore the differences between these two geographical dimensions and the representation of these variables in the different studies.

The center choice of this work around the European Union and Europe is not an accidental one, and the reason is essential to highlight. The work will be done in the context of the Drawdown Framework for Climate Solutions and its regionalization efforts being led by DERA - Drawdown Europe Research Association [11]. While this global study provides an important start point for the realization of the Project's goals, these solutions must be tailored to meet the unique needs, resources, and preferences of specific localities, since not every solution will apply in the same pattern to every region, state or municipality, or be able to be applied at all. This importance becomes apparent when taking a look at the results for other studies in these regionalization efforts, such as the one conducted by Brown et al. [12], focused on the state of Georgia in the United States, where a solution like refrigerant management features quite prominently in Project Drawdown while being much less promising in Georgia due to local regulations.

1.4. Work Structure

The second chapter will be dedicated to shedding some light on Project Drawdown, how the work being conducted fits into its objectives and mission, a concise explanation of how its Excel-based RRS (Reduction and Replacement Solutions) Model is used to achieve the objectives stated in chapter 1.3.

The third chapter of this thesis depicts a brief description of the hydropower technologies, how they work, their advantages, disadvantages, recent improvements, and their place in the current power mix, both worldwide and in Europe. This chapter will be brief and succinct as these are very mature technologies, as opposed to ocean or tide renewables, for instance. This description Is followed by the literature review section, where some particularly important publications are analyzed both in the context of collecting data for electricity generation in different future scenarios or financial, technical, and social indicators, as mentioned previously.

To accomplish the goals that have been established, a careful methodology was followed to successfully obtain verifiable and logical results, being quite important, especially when it comes to dealing with large amounts of data, as is the case in this study. This methodology is clarified step-by-step in the fourth chapter, along with a brief explanation of the RRS Model.

These results and their discussion will be exposed in the fifth and sixth chapters, along with comparing the results regarding TAM and Adoption between Europe and the European Union. In addition to this and the previous methodology used in the Drawdown global analysis, a discussion of how the projected evolution of these technologies can impact society in terms of jobs created and the environment, beyond the stated electricity generation related emissions, with an overview of materials that are used for these technologies and the impact these may also have.

The seventh and final chapter comprises the conclusions of this work, what was learned from it, the limitations of the methodology that was used and detailed in the fourth chapter, and future research that might be conducted in the regionalization efforts of the Project Drawdown umbrella or in regard to the energy transition as a whole.

Last but not least, it is worth pointing out that part of the work of this thesis was submitted as a paper at the 7th Meeting on Energy and Environmental Economics, that took place online and was organized by the Universidade de Aveiro, International Association for Energy Economics (IAEE) and Portuguese Association for Energy Economics (APEEN). The abstract for this paper is presented in Annex B.

2. PROJECT DRAWDOWN AND DERA

This work follows up on the global scale analysis developed by Project Drawdown. So, to understand it, the project itself must be first understood as well. It is a non-profit organization that aims to be "the world's leading resource for climate solutions", helping the world reach "Drawdown", a future point in time when levels of greenhouse gases in the atmosphere stop climbing and start to decline [13].

Created in 2014 by Paul Hawken and with the contribution of cities, universities, corporations, philanthropies, policymakers, communities, educators, and activists, the organization has emerged as a leading resource for information and insight about climate solutions since the publication of the book Drawdown [14]. In it, 100 viable and existing technologies or practices to help not only stop climate change but to reverse it in a quick, safe, and equitable way are compiled, with a deep analysis of each solution encompassing their potential costs, savings, and reduction of CO_2 emissions.[8]

With this objective in mind, to reach Drawdown, it is first imperative that the emission sources and natural sinks of greenhouse gases (GHG) that exist to rebalance the climate system are assessed and understood, from the burning of fossil fuels, deforestation, manufacturing of steel and cement which emit carbon dioxide (CO_2), to rice fields or landfills who release methane (CH_4) or refrigeration systems and industrial sites contributing with nitrous oxide (N_2O) and fluorinated gases (like HFCs and PFCs). These sources and natural sinks were condensed in Figure 2.1 as part of the Drawdown Review report released in 2020 [15]. It shows a clear disparity when it comes to the endpoint of emissions, with only 41% of greenhouse gases going to natural sinks while 59% of them remain in the atmosphere.

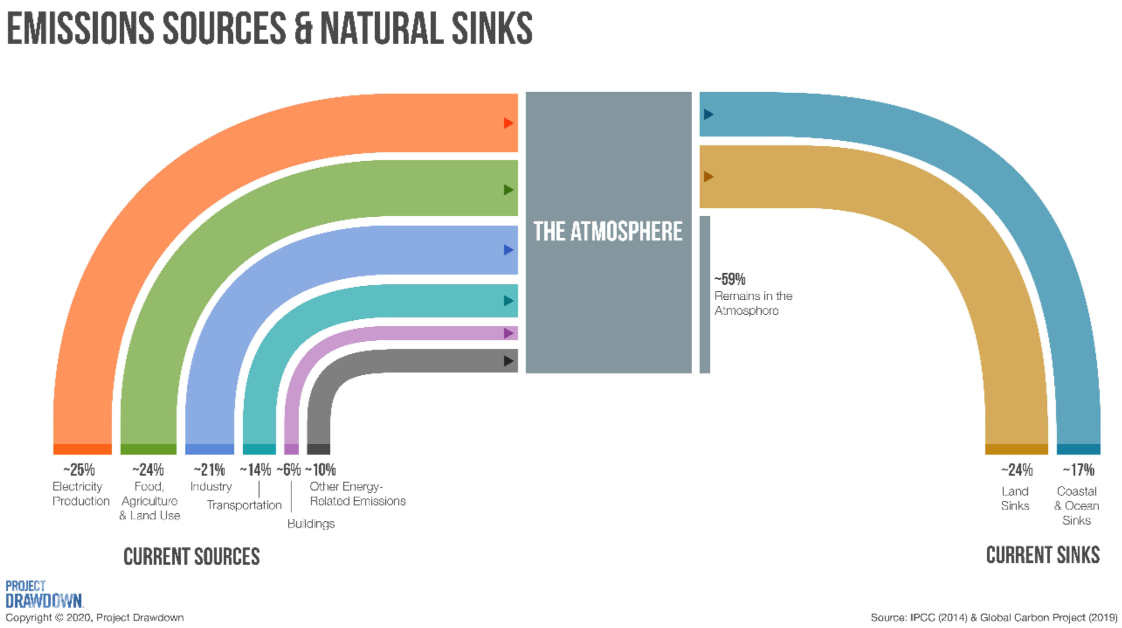


Figure 2.1 - Emission Sources and Natural Sinks considered in Project Drawdown. [10]

These solutions consider a holistic approach, as opposed to the approaches that are many times used, focused only on one single aspect of the climate change issue like fossil fuels or only on the environmental sphere of the issue, not considering the economic or societal consequences of the problem. They were then divided into three categories according to their main goals: reduce sources bringing emissions to zero, support sinks uplifting nature's carbon cycle, and improve society fostering equality for all. Each of these categories was then comprised of the different sectors for the chosen solutions:

- Electricity
- Food, Agriculture & Land Use
- Industry
- Transport
- Buildings
- Land Sinks
- Engineered Sinks
- Coastal & Ocean Sinks
- Health & Education

This amalgamation and categorization of solutions constitute the Drawdown Framework for Climate Solutions, shown here in Figure 2.2, once again from the Drawdown Review report [13].

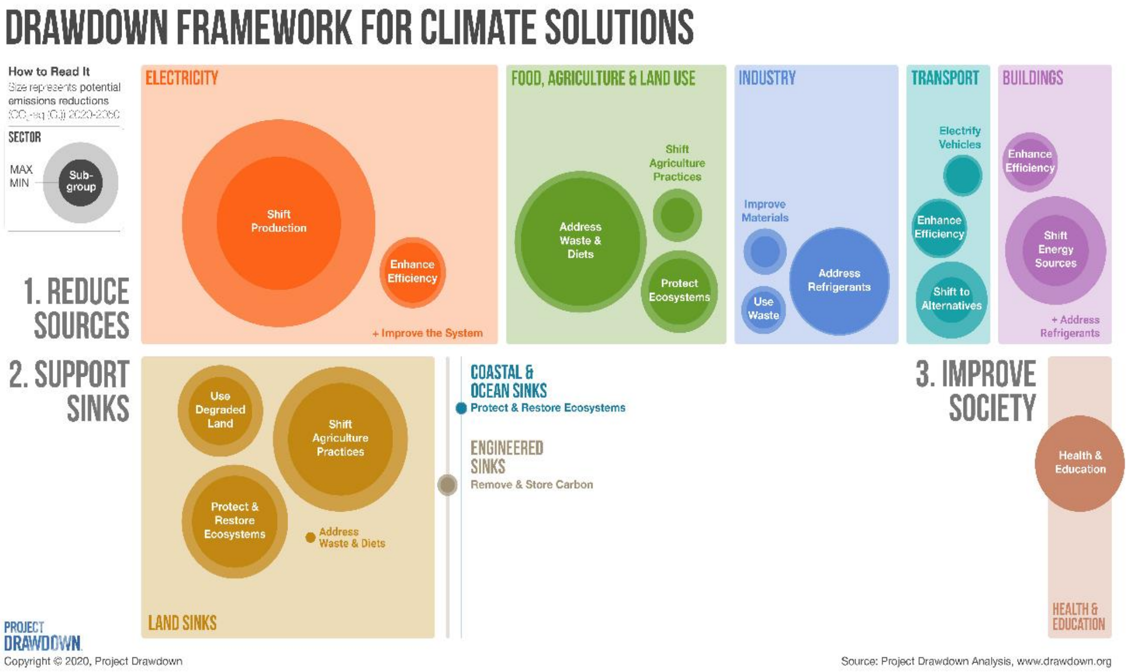


Figure 2.2 - Drawdown Framework for Climate Solutions. [10]

As suggested previously, the results published in Drawdown's book and Drawdown Review result from the individual analysis of each solution on a global scale. Moving forward, an important complementary step for the project is to pursue a regionalization endeavour, with the same type of research being conducted on a more regional or local level, taking into account the intricacies of each location and what solutions can be applied, in which way. It is as part of these efforts that the work in this thesis comes about, being interlinked on the activities of the Drawdown Europe Research Association (DERA) by helping to translate the global drawdown solution set to the European context [14] following in the steps of the already presented study of solar solutions in the European Union [16], for example, or the investigation conducted for the state of Georgia in the United States. [12]

3. LITERATURE REVIEW

3.1. Hydropower Technologies

As was mentioned, this chapter will encompass a brief overview of the available hydropower technologies, with a particular focus on the ones being studied in this thesis, Large Hydropower (LH), and Small Hydropower (LH) technologies. As stated previously, SH is one of the more than one hundred solutions that are part of Project Drawdown, while LH technologies are not, mainly because of their impacts on the environment surrounding them, such as swallowing up vast swaths of habitats, impacting water quality and flow, sedimentation, and fish migration [17], factors that will be discussed further on.

Nonetheless, as demonstrated in Figure 1.2 their combined representation in the current power mix is undeniable, making these technologies a potential substitute for conventional ones when it comes to a shift in electricity production.

Initially, for irrigation or the grinding of grain, humans have been using the movement of water as far back as the 6th millennium BC in Mesopotamia and Ancient Egypt [18], having eventually evolved into using it as an energy source, with the hydropower of today being much more complex than the simple windmills used for grinding grain, relying currently on turbines to convert water flow into power, with the first modern hydroelectric plant beginning operation in the United States in 1882, for example. [19]

With centuries of existence at this point, hydropower has been widely researched and is considered a very mature technology. Relying entirely on the hydrologic cycle, particularly on precipitation, dots this kind of technology with additional complexity when it comes to the analysis of its electricity generation since these solutions do not follow a consistent or predictable pattern as solar-based technologies for example, with the volume, frequency, and duration of precipitation being estimated and predicted, but with far more uncertainty when compared to temperature [20]. The probability of a big hydropower plant generating significantly different levels of electricity in subsequent years is not a small one, particularly as the effects of climate change become more severe, with droughts and floods becoming more prevalent in some regions of the world, as can be seen by the historical database for these kinds of technologies in the methodology chapter, further on in this work.

3.1.1. Technological Description of Hydropower Technologies

Hydroelectricity results from the conversion of potential energy that exists in water that is stored in an elevated reservoir. It can also result from kinetic energy in water when we talk about rivers and water flow in general. When water is freed, in the case of reservoirs, or follows its natural flow, in the case of rivers, it can be guided through a turbine, activating a generator and producing electricity. [21][22]

The most common way of creating this elevation to provide the water with the potential to fall is the creation of a reservoir, constructing a barrier that allows the level of water to be elevated, or the redirection of the flow of water. Concisely, the main components of the most common hydropower systems are as follows:

- Reservoir: stores water, allowing for a constant source of potential energy ready to be used and converted into kinetic energy;
- Conveyance system: pipe system where the water is directed to the turbine and potential energy is converted into kinetic energy;
- Turbine: where the kinetic energy of the fluid is converted into mechanical energy, making the turbine's rotor spin until a certain rotation speed is reached;
- Generator: receives the mechanical energy from the spinning turbine through a connecting axis between the two and produces electricity according to the electromagnetic laws;
- Connection to the grid: the electricity that is generated is conducted and transformed to establish a connection to the electrical grid, is then transported to homes and places of consumption;

An example of a typical system and its component can be seen in Figure 3.1. [23]

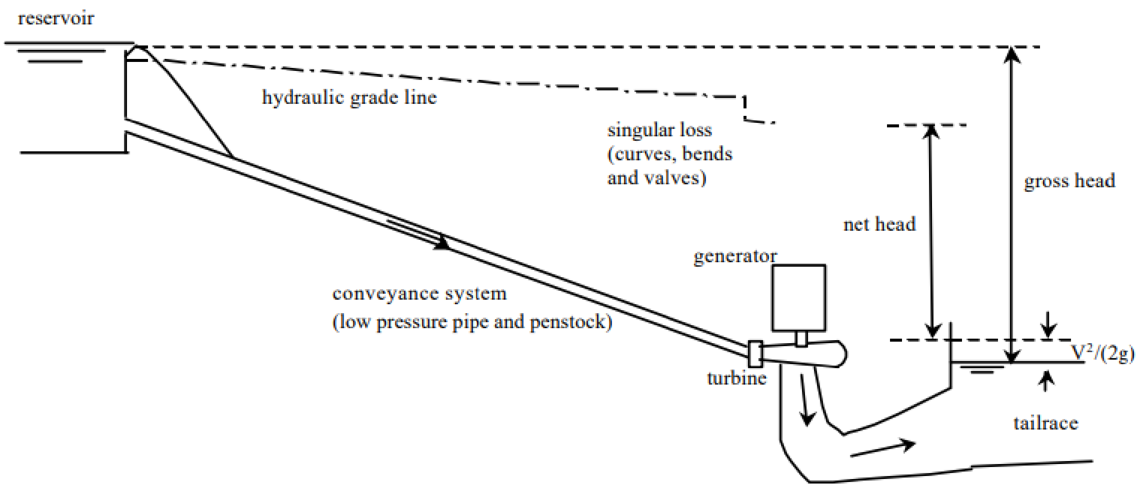


Figure 3.1 - Components of the Hydroelectric System. [22]

Lastly, when it comes to the turbine itself, several kinds of machines can be used in hydropower, with different characteristics that are best suited for different types of situations, depending on the gross head (the total vertical distance between the intake and turbine [24]), the volume of water flowing through it and consequently the type of hydroelectric plant that is being used, with Kaplan turbines being optimal for lower gross heads and larger volumes of flow, for example. The most common types of turbines and their range of optimal operation can be seen in Figure 3.2.

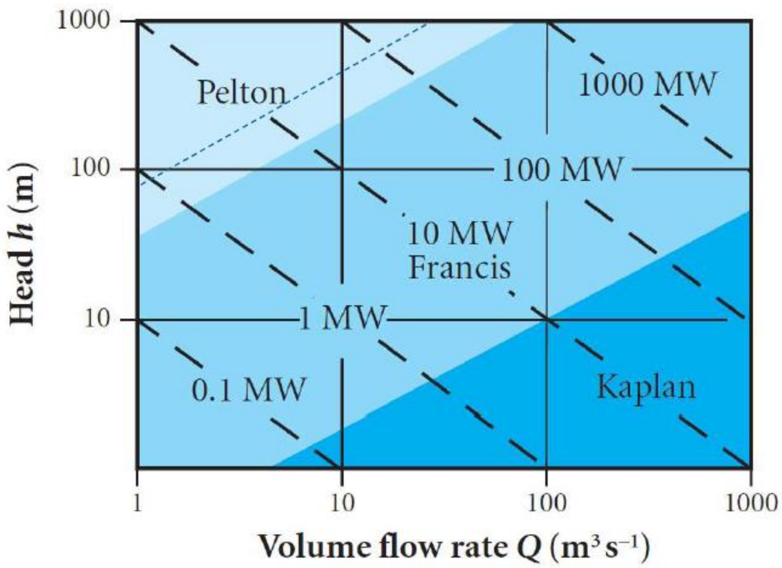


Figure 3.2 - Types of turbines and range of operation. [19]

3.1.2. Different Types and Classifications of Hydropower Technologies

It is also important to understand that there are other kinds of hydropower renewable energy sources classifications other than Large and Small Hydro. These can be classified according to their mode of operation or the installed capacity.

When it comes to mode of operation, these technologies can be classified as follows:

Run-of-River (RoR): the electricity generation in these plants comes from water flow in rivers, with little to no water storage. Typically, part of the water flow is redirected from its original course and into the turbine, allowing for electricity generation, as was mentioned previously. It presents the disadvantage of being entirely dependent on precipitation since storage is not an option, and therefore its output may vary significantly. On the other hand, it has the advantage of being relatively cheap compared to other typologies and having lesser environmental consequences.

Storage (reservoir): the most common hydropower plants allow for less reliance on weather conditions as they offer the option to store water, producing smaller variations in electricity output. They present, however, several disadvantages. Higher investment costs and larger environmental impacts contribute to the idea that this technology will evolve towards improvements in existing plants instead of building new ones.

Pumped Storage (PPS): similar to the reservoir typology, these plants can pump water back to the reservoir, usually done during periods where energy is cheapest. The water flow is then reversed during the remaining hours of the day to generate electricity, allowing for larger flexibility and supply to variable demand. On par with batteries, it is currently one of the most relevant storage systems in operation.

In-Stream Technologies: extremely similar to RoR, they consist of installing small turbines to take advantage of already existing canals or natural drops in elevation.

Examples of these different types of hydropower can be seen in Figure 3.3.

Additionally, a simpler way of classifying hydropower is according to the installed capacity. This kind of classification varies regionally, with classifications dividing hydropower among four categories [25]:

- Micro Hydro (1 kW to 100 kW)
- Mini Hydro (100 kW to 1 MW)
- Small Hydro (1 MW to 10-30 MW)
- Large Hydro (Above 10-30 MW)

Or classifications such as Project Drawdown's, the one being used for this work, with only two categories[17]:

- Large Hydro ($>$ 10 MW)
- Small Hydro ($\leq$ 10 MW)

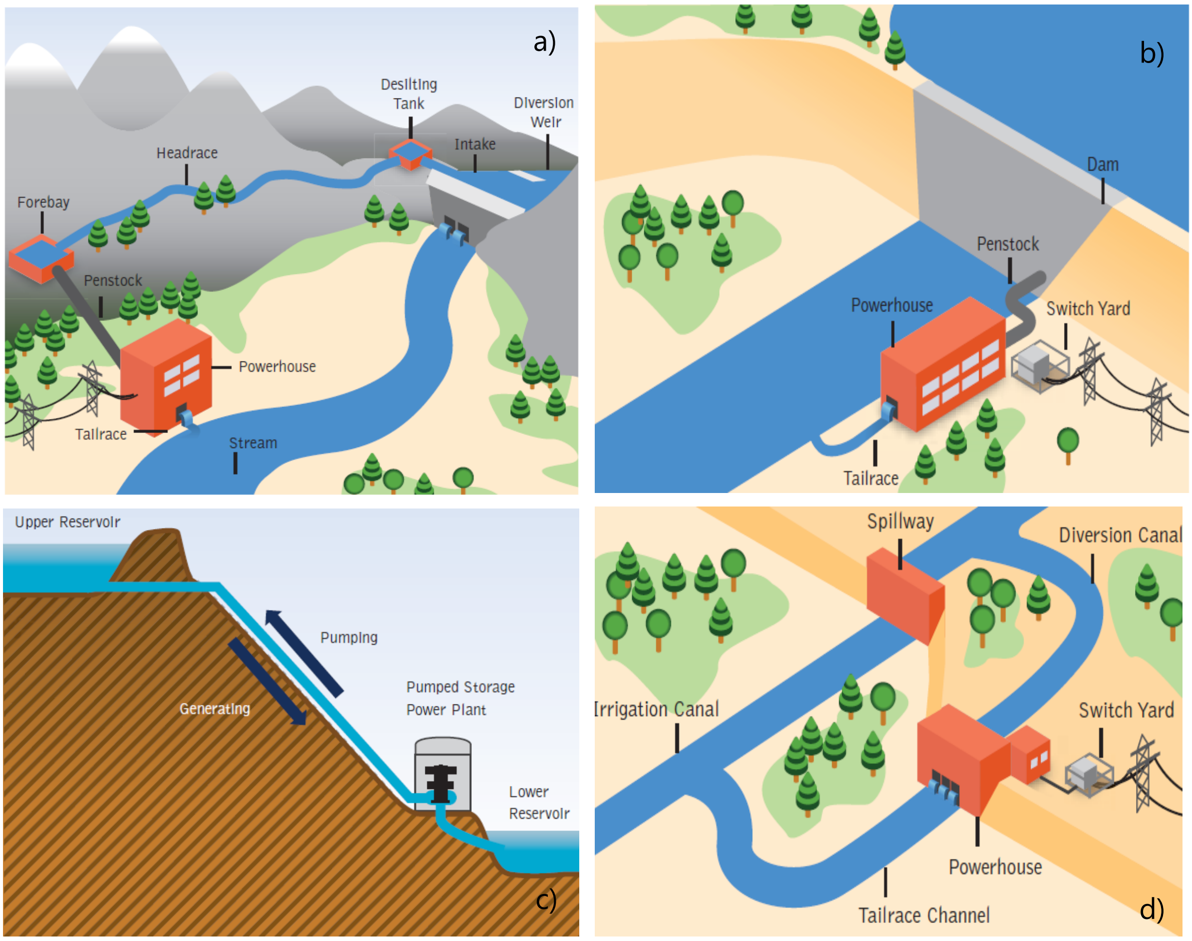


Figure 3.3 - Classification of Hydropower Technologies: Run-of-River (a), Storage (b), Pumped Storage (c) e In-Stream (d). [30]

3.1.3. The Current State of Hydropower

As stated earlier in the chapter, hydropower technologies are very mature and have been extensively researched. With them being so established, the technology is not looked at as much as solar or wind, for example, being expected that the growth of hydropower plants worldwide will slow significantly in this decade [26], in contrast with the rise in Adoption of these other solutions.

This seemingly stagnating ADPT is also supported by its disadvantages. Among others, there are significant environmental concerns. The construction of large hydropower projects, in particular, can bring with it several negative environmental impacts, such as the destruction of large natural areas by flooding or changes in water flow [27], impacting water availability and ecosystems [28].

Additionally, public acceptance is one of the major issues when it comes to hydropower. [28] With the flooding of valleys being a part of the creation of reservoirs, the people living in villages and towns in these areas must be relocated [27], with 1.3 million people having been relocated due to the construction of the Three Gorges dam in China, for example [29]. Lastly, projects have high investment costs, long payback periods, and construction cycles, presenting a few barriers to entry when it comes to the Adoption of these technologies [28].

However, according to the International Energy Agency, around half of hydropower's economically viable potential worldwide is untapped. It may present several benefits, especially as support in the transition to clean energy. [26]

With its ability to store their own source of power, hydropower plants can easily use their flexibility and storage to aid the management of the power grid, being able to ramp up and down their electricity generation very rapidly [26].

At the moment, however, the focus in the hydropower industry is on the modernization and upgrading of existing plants, with an estimate 127 billion USD set to be spent modernising plants until 2030, [26] the emphasis being on the remote operation of plants and the advancement in equipment and materials for large hydro projects or low-impact turbines for fish populations and wind-hydro storage systems for small hydro plants [28].

3.1.4. Hydropower in the World's and European Union's Electricity Generation Mix

In the context of the global and EU power mix, the two technologies being analyzed have vastly different representations. Large Hydro, according to IRENA's most recent data shown in Figure 3.4 dominates the electricity mix worldwide, accounting for 63% of renewable electricity generation, more than three times the contribution by wind technologies, who hold second place, justified by the maturity of the technology, as well as by the long lifetimes of hydropower plants.

At a European level, there is a slightly different scenario. Hydropower still holds the number one spot for electricity generation, having, however, a very small advantage over wind electricity generation, less than 1%, corresponding to around two TWh. This data clearly shows the considerable investment made into wind energy over the last years and the stagnation of hydropower technologies in the European Union.

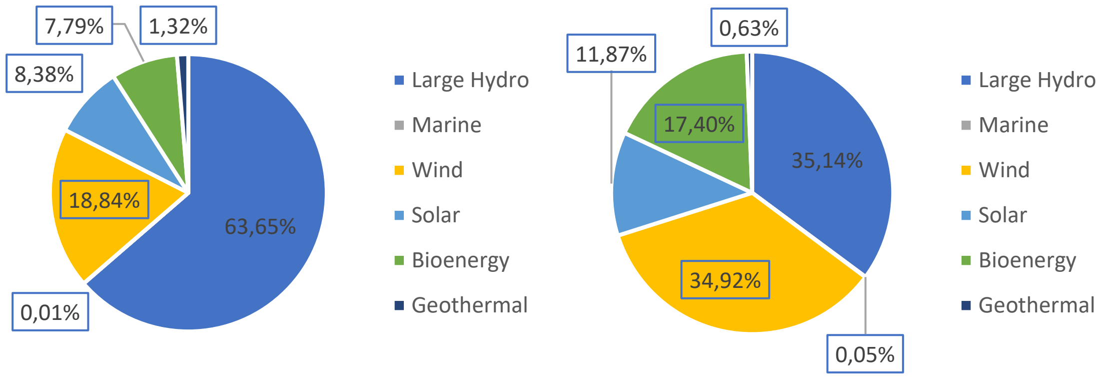


Figure 3.5 - Global (left) and European Union's (right) Renewable Electricity Mix in 2020. [7]

In respect to Small Hydropower, however, the analysis of its place in the power mix is more complex, since the most recent IRENA data regarding this solution is from 2015, henceforth the annual reports for Renewable Energy Statistics that the association produces yearly do not have data specifically for small hydropower. For this reason, the data for the power mix for 2015 will be shown as raw data in TWh, as opposed to percentages, since the growth in solar and wind electricity generation has brought a considerable paradigm shift when it comes to the energy sources for power generation.

As can be seen in Figure 3.5, small hydropower represented around 580 TWh at a global scale, a considerable amount on par with bioenergy which is often more discussed and publicized, or a similar value as the current electricity generation from solar technologies, being much more prominent than one may think.

In a European context, it gathers a generation of only around 45 TWh, a much smaller contribution, being only superior when compared to more niche and less developed technologies, like geothermal and marine electricity generation, respectively. One could assume that this pertains to the more common applications of smaller hydropower plants, places with smaller population density, or more rural regions where access to electricity might be sparse due to geographical isolation or lack of infrastructure. This kind of place might be less common in the European Union, bringing with it perhaps less of a need for this kind of generation technology. Other reasons for this might be that in the EU, the centralization of electricity generation would be more prevalent or a larger allocation of resources and investment into the already mentioned emerging technologies. However, these hypotheses are presented here as exactly that, mere hypotheses, since this research was not conducted.

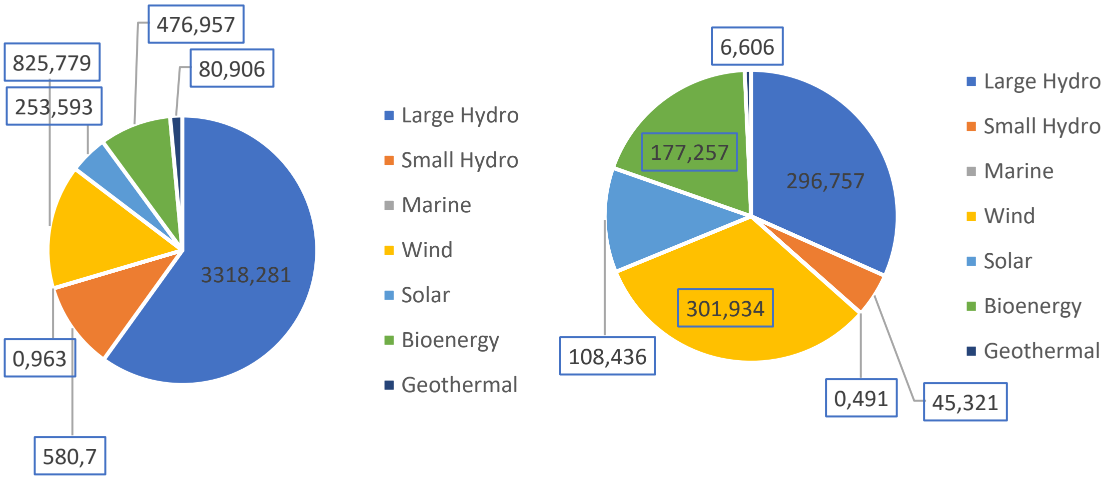


Figure 3.6 - Global (left) and European Union's (right) Electricity Mix in 2015. [7]

Lastly, it is also important to understand the state of affairs of these technologies in the context of Project Drawdown on a global scale since this research follows roughly the same objectives and methodologies, contributing to the regionalization of information efforts for the European Union.

As was mentioned, large hydropower was not one of the solutions considered in the project, and therefore no analysis regarding it is available. Concerning small hydropower, globally, it is considered that these solutions could generate between 994 and 1.136 TWh and allow a reduction of somewhere between 1,69 and 3,28 Gt of CO_2eq by 2050.

When it comes to the financial side of things, it was estimated that implementation costs would be around 40,36 to 80,07 billion $USD, with lifetime savings totalling at 315,1 to 543,67 billion $USD [17].

3.2. Historical and Long-Term Projection Studies for Energy and Climate

This chapter shows, firstly, an overview of the literature review process that led to the execution of this dissertation and secondly, a brief analysis and exposure of the main publications that supported the core of this work and that we believe are essential to strengthen this kind of analysis around projections in the power sector.

It is important to note that several reports used as sources for the long-term energy projections are based on energy system models developed to represent and project future energy and related emissions pathways. As examples of this, we have JRC's Learning Curve Method, heavily reliant on the technologies' learning curves for its projections or IEA's World Energy Model, used in its World Energy Outlook (WEO) report [30], a large-scale simulation model designed to replicate how energy markets function, that takes into account economic growth, population, policies and the trends in energy and CO_2 prices and, in the case of WEO 2019 incorporated crucial new aspects in the creation of future pathways such as storage.

The various steps will be explained in detail in chapter 5, but the initial tasks conducted for this research centered around the procurement and compiling of recent publications relating to the energy sector, containing the main type of information necessary that will be explained further on. In this phase, a particular emphasis was put on assembling documents that were both recent, containing recent data and projections for the desired time period and created by different types of institutions. This second focus was an important one. It was taken with the goal that the diversity in sources could prevent bias from over-relying onto a single source or that the analysis leaned into any kind of agenda. For example, while reports from companies in the fossil fuels sector could project future scenarios where these types of fuel are still very prevalent, a scenario that would be economically beneficial for them, documents from NGOs may present scenarios very much focused on renewable energy and its growth. Therefore, a large variety and quantity of sources would help amortize these intentions behind the reports. Additionally, this vast array of sources allows the use of data resulting from various methods and models (i.e., top-down and bottom-up models, optimization models, etc.), producing significantly variable forecasts for the development of technologies and energy.

Taking this objective into account, publications from various entities were used, namely: recognized and renowned international and European agencies in the energy sector like the International Energy Agency (IEA) or the International Renewable Energy Agency (IRENA), non-governmental organizations (NGO's) like Greenpeace, the World Energy Council (WEC) or Energy Watch Group (EWG), universities and academic institutions as LUT University or The Energy Research Institute of the Russian Academy of Sciences (ERIRAS), technical reports from various entities such as the Joint Research Center (JRC) and Wind Europe, sectoral documents from Eurelectric or SolarPower Europe and lastly, companies in the fossil fuel industries such as BP, Equinor or Shell.

From all of the publications that were gathered, the data that was procured centered around three main subjects: future electricity generation scenarios in the European Union and Europe (also known as TAM), the amount of that electricity generation that comes from the two hydropower technologies under study (also known as Adoption), and technical/financial aspects of these two technologies in particular. As it might be obvious, there is not only one kind of report which includes all this information. Table 3.1 shows several examples of the type of report used in this first collection of literature for this work.

Table 3.1 - Examples of reports that served as the Literature base to support this work.

Publication Name	Entity	Scenarios
Energy Technology Perspectives 2017 [31]	IEA	Reference Technology Scenario
		2°C Scenario
		Beyond 2°C Scenario
Energy [R]evolution 2015 [32]	Greenpeace	Reference Scenario
		Energy Revolution Scenario
		Advanced Energy Revolution Scenario
Global and Russian Energy Outlook 2019 [33]	ERIRAS	The Conservative Scenario
		The Innovative Scenario
		The Energy Transition Scenario
Statistical Review of World Energy 2020 [34]	BP	Reference Scenario
Achieving The Paris Climate Agreement Goals [35]	Sven Teske	The 5.0 °C Scenario (Reference Scenario)
		The 2.0 °C Scenario
		The 1.5 °C Scenario
Energy Perspectives 2020 [36]	Equinor	Reform Scenario
		Rebalance Scenario
		Rivalry Scenario

3.2.1. International Energy Agency (IEA) World Energy Outlook 2019

It is possibly the most significant publication among the ones researched; it features as a blueprint for this kind of document. Its first publication was in 1977 and is published annually since 1998. It approaches not only the energy sector but its diverse interactions with other industries as well.

The 2019 report [30] is composed of an initial segment where the future global trends are analyzed, touching on fossil fuels, electricity, energy efficiency, and renewable energy. In its second part, it approaches the specific case study of the African continent, outlining its potential and space for growth and development in different spheres (it is customary for the report to always include one or more special chapters like this one, with the 2017 report having sections focused on natural gas and China while the 2016 report had a segment dedicated only to renewable energy for example) and lastly, in its final large chapter presents some future perspectives for infrastructure when it comes to natural gas and the evolution of offshore wind technologies. The annex section of the document possesses numerous tables with the relevant data for this work in particular, such as electricity generation in the EU and Europe as well as the Adoption of LH technologies, which were used to plot the evolution of TAM and Adoption according to its three different growth scenarios. These scenarios are generated by the World Energy Model, a large-scale simulation tool designed to replicate how energy markets function. These scenarios explore different futures of action or inaction regarding energy, environmental, social, and economic prospects.

The Current Policies Scenario attempts to estimate what will happen if the policies in place are maintained, without any substantial change, including growth in energy consumption and lack of action regarding energy efficiency or growing disparities in energy security.

In the Stated Policies Scenario, the policies, goals, and targets to stop emissions are met. It predicts around 1% of growth in energy demand until 2040 with photovoltaic technologies and natural gas, specifically liquified natural gas (LNG), growing substantially, while the call for oil stagnates and coal becoming less and less prevalent. Despite numerous advances, particularly from countries with net-zero targets, it will not be enough to counterbalance an expanding global economy and growing global population, bringing an increase of emissions until 2040, even if less significant than the previous scenario.

Its most ambitious scenario, the Sustainable Development Scenario, serves as a roadmap to achieve sustainable goals in full, with fast action and change being mandatory encompassing the entire energy system to meet the goals of the Paris Agreement, more equity in access to energy, and improved air quality.

3.2.2. International Renewable Energy Agency (IRENA) Renewable Energy Statistics

In conjunction with the International Energy Agency, IRENA constitutes one of the most important entities worldwide in respect to the energy sector. Its annual report presents comprehensive, reliable data in renewable energy statistics for capacity and generation for each type of renewable energy for the decade and the nine prior years, respectively, existing as an essential source for the projections created in this dissertation.

Alongside the 2020 report [9], the most recent one at the time of writing, the document for 2017 [37] was also crucial. In this statistical compilation, the hydropower renewable energies are divided in terms of capacity, allowing for a solid historical base of the Adoption of small hydro technologies in the EU and Europe, crucial for the intended projections for this technology. This data is not presented this way in the reports from the last four years, with the divisions in hydropower being made according to technology instead of capacity, making this publication vital for the current analysis. The specifics of how this was done are explained more thoroughly in section 5.2.3.

3.2.3. Institute of Energy and Economics of Japan (IEEJ) Outlook 2019 & 2020

This publication presents global energy and environmental perspectives, with some economic indicators, but with a particular focus on the Asian continent, showing a slightly different context to the most commonly shown focusing on Europe and North America.

Both reports [38][39] are quite similar, with the 2020 one acting as an update in values for the previous document. They both present two possible scenarios for future trends.

Firstly, the Reference Scenario shows the expected trends for various indicators like energy consumption, where it predicts substantial growth in Asian countries, highlighting China in accordance with other publications, and the stabilization and improvement in terms of energy efficiency in the United States and Europe, to the evolution of fossil fuels where it predicts a considerable evolution in natural gas which will place it as the second most-used fuel on the planet, only trailing behind oil, continuing a state of energy consumption with a level of dependency on fossil fuels around 79%.

About renewable energy, it predicts slight improvements in the ADPT of photovoltaic and wind technologies and a slight decrease in the percentage of hydropower when it comes to total installed capacity and electricity generation.

In its alternate scenario, the Advanced Technologies Scenario, it is assumed that to ensure a steady supply of energy, fighting climate change and atmospheric pollution, the storage of energy and low-carbon technologies must be implemented as much as possible in every country, considering their applicability in practice. It considers savings in energy consumption around 41% compared to the previous scenario and roughly 2.3 Gtoe of energy savings in 2050.

3.2.4. Joint Research Centre (JRC) Assessing the long-term role of the SET Plan Energy technologies

This 2013 report [40] from the Joint Research Centre, the European Commission's "science and knowledge service", is one of the most thorough documents examined in this research. Not only does it possess TAM and Adoption data, but much like the ones also mentioned before, it shows several different technical, environmental, and economic aspects of every electricity generation technology, including hydropower, such as investment costs, capacity factors, lifetime or direct and indirect emissions, all data that is crucial for the variable meta-analysis that constitutes part of the methodology of this work.

The data gathered from this report was two-fold: firstly, It presents different projections for hydropower generation until 2050, useful In the Adoption scenarios, and secondly It possesses more technical data about the technology, being therefore useful for the meta-analysis phase of the work. In brief, there are two scenarios relating to the type of policies applied: Current Policies or Current Policies with a CAP on CO_2 emissions. A scenario pertaining to energy consumption, the Low Energy Scenario, and five different scenarios with each one focusing on the high or low use of different technologies, Delayed CCS (Carbon Capture and Storage), High Renewables, Low Biomass, Low Solar, and Wind and High Nuclear.

These scenarios all result from different assumptions that serve as the input for the JRC-EU-TIMES Model, designed for analyzing the role of energy technologies and their innovation for meeting Europe's energy and climate change-related policy objectives.

3.2.5. LUT & Energy Watch Group - Global Energy System Based On 100% Renewable Energy

This section broadly approaches the report developed in partnership between the Energy Watch Group and the Lappeenranta-Lahti University of Technology and published in April 2019 [41]. It is among the most ambitious reports from the large number that were analyzed, with their main premises being ones of technically viable pathways to a European continent (in contrast with the data regarding the European Union collected from the previous two documents) in which a power sector (encompassing electricity, heating, transport, and desalinization) with 100% renewable energy and zero GHG emissions exists.

It suggests a scenario in which there are enormous gains in terms of energy efficiency, around 85%, the emergence of photovoltaic and wind technologies, vastly superior to the current day, estimating that these could represent about 94% of the supply of electricity in 2050, while also giving batteries a large role in the energy system, amounting to 83% of storage in this scenario. About heating, it proposes a significant focus on heat pumps and highlights fuel conversion technologies such as Fischer-Tropsch or water electrolysis for transportation, allowing for it to be powered by 100% renewable energy.

In addition to the TAM and ADPT values that it possesses, much like the reports previously mentioned, it presents several economic aspects supporting the idea that a 100% renewable system in Europe is not only possible but more efficient and competitive in terms of costs.

Lastly, it is also worth highlighting that its holistic approach allows it to show analysis to the energy system mentioned above without forgetting social parameters as well, complementing the energy-related data with regional information about demographics, emissions of different technologies, and job creation, very important points for the analysis that we hope to perform with this work.

3.2.6. "A framework for localizing global climate solutions and their carbon reduction potential" by M. A. Brown *et al.*

The last document that we choose to highlight in this literature review section diverges from the ones previously mentioned in that it does not provide data with which projections of electricity generation are being made or that is used for technical or financial analysis of the hydropower solutions. Still, it serves as an application of the Project

Drawdown method to a specific location, in this case, the state of Georgia in the United States, and can be used to learn from its findings and benchmark the results that this work produces [12].

The paper highlights the necessity for localized carbon-reduction strategies in regions that lack top-down leadership and defined climate goals or plans, such as the state of Georgia, and how the solutions in Project Drawdown need to be researched in the context of the socio-ecological-technological systems of the regions that they're to be applied to, bringing to light the requirement of regionalization of the Project's findings.

In the case of Georgia, it is estimated that a system of a series of 20 complementing solutions could cut the state's carbon footprint by 35% in 2030 in comparison to business-as-usual projections and by 50% relative to Georgia's emissions in 2005, making the potential of the application of the Drawdown methodology very clear.

Alongside this paper, other efforts in the regionalization endeavour of Project Drawdown have been published, such as a very similar analysis to this thesis conducted regarding solar technologies [16], showing that this is a work in progress, part of a bigger picture like the whole of the Project and DERA.

4. METHODOLOGY

In this chapter, the methodology followed to accomplish this work objectives will be detailed, explaining all the steps taken and the reasoning behind the decisions made along the process of completing it.

As mentioned in chapter 1, the main goal is to analyze the potential of hydropower technologies for electricity generation and the consequential reduction of greenhouse gas emissions, in the time frame between 2020 and 2050 in the European Union, in the context of Project Drawdown. To accomplish this, the Project's Excel-based model was used and will therefore be explained, comprising the first part of this chapter. The second and last part of this section will be dedicated to a step-by-step explanation of the developed work. The decision to separate these two aspects of the methodology was made in the hopes of making it clearer, even though, due to the nature of the type of work, they are undoubtedly interlinked.

4.1. Project Drawdown Model

As was stated, the analysis within this work was made resorting to Project Drawdown's Excel-based model, also known as the Reduction and Replacement (RRS) model, a bottom-up style model developed to help define and describe existing individual social, ecological, and technological solutions that reduce and sequester greenhouse gas emissions in the atmosphere [42], allowing, therefore, the assessment of the potential emission reduction impact due to different future Adoption pathways.

This section will first offer a brief explanation of the most significant pieces of the model used along the conduction of this research. Firstly, it is worth pointing out that every single part of the model is essential for its correct functioning, with many of the calculations being made "in the background", having several formulas linked between different pages, some of which were not directly interacted with in order to obtain the intended results.

The following pieces of the model were most prominently used and interacted with:

- <u>Advanced Controls:</u> this first sheet is where the major adjustable parameters of the model are prominently displayed, along with many Financial and GHG reduction results. The main input in this section was the current Adoption of every electricity-generating technology currently used as a percentage of TAM (the way to obtain this power mix is explained in section 5.2.2). The sheet also shows the financial, emission reduction, and additional inputs derived from the Variable Meta-Analysis sheet. These inputs represent the major assumptions used in the model.

Additionally, it allows the user to select between a Reference Adoption Scenario (REF Adoption Scenario), a scenario where the Adoption of a technology remains as a constant percentage of TAM throughout the years, or for a customizable reference scenario. One of these two scenarios will serve as the standard to compare the different projections made, also called Project Drawdown Solution Adoption Scenario (PDS Adoption Scenario), which can also be selected in this sheet.

So, to sum up, the Advanced Controls sheet allows the user of the model to easily change technical, financial, and environmental parameters of the solutions and different scenarios and see their impact on results.

- **Variable Meta-Analysis:** this sheet presents several tables in which data can be inserted for the historical values of Adoption of the technology, large or small hydropower in this case, as well as the financial, emission reduction, and additional inputs (these include jobs created by the implementing of solutions and materials used, an additional analysis in this methodology) mentioned in the Advanced Controls sheet, serving as a simpler way to manage the collection and analysis of this large amount of data on several variables and from several sources. In this sheet, the same variables for conventional technologies are also inserted.

In each table, the datapoints for these different variables are inserted, along with the source, accompanied by a link to it when available, the region to which it pertains to, the year, original units, which are then converted into the common units of the model, and lastly, any assumptions or observations regarding this data point. Lastly, the tables will automatically calculate a low, average, and high estimate based on a range around the mean, as well as the standard deviation of values. This range is, by default, 1 standard deviation around the mean. Additionally, the tables automatically exclude values falling outside 3 standard deviations of the mean.

- **Adoption and TAM Data:** two very similar sections, they provide a sheet where the different future TAM and Adoption scenarios found in the literature or created can be included (the creation of these future TAM and ADPT scenarios will be explained in section 5.2.2), with annual values provided by regression fits (least squares, 2 or 3 degree polynomial, exponential).

These scenarios come from the various sources mentioned in the Literature Review chapter plus several others and are then divided into Modest, Intermediate, Ambitious, and Extremely Ambitious according to where they rank in electricity generation in 2050, for TAM or Adoption. In the case of hydropower technologies, Modest cases are considered the ones where their Adoption has a downward or stagnating trend. Intermediate cases show a slight increase in the Adoption of these technologies, while Ambitious cases are scenarios showing a high increase in Adoption. Lastly, the Extremely Ambitious scenarios are the ones that show the highest Adoption of the technology in 2050.

These scenarios can then be chosen individually or as an average of categories (i.e., an average of all Intermediate cases) and compared with the reference scenarios, as mentioned previously.

- Data Interpolator: a simple but essential sheet where the user can interpolate and extrapolate data (for both TAM and Adoption) for missing years before entering it into the model. Its use is explained in more detail in section 5.2.2.

- Custom REF Adoption: lastly, the Custom REF Adoption sheet was also used. As was mentioned before, the different Adoption scenarios that come from the literature are compared with either a reference scenario (REF Adoption Scenario) or a customizable reference scenario to obtain the intended results. This customizable reference scenario can be created in this sheet by inputting different projections from different sources and using the average of these projections as this Custom REF Adoption to be compared with the PDS Adoption Scenario.

These various sheets of the RRS Model constitute the different tools that can be used to run the model and perform the intended analysis. Each run consists of the selection of a particular TAM and Adoption or an average of the categories in each one (i.e., average of Intermediate TAM projections and average of Ambitious Adoption projections) and the selection of high, average, or low values from VMA data that characterize each solution and conventional technologies. The selected scenario is then compared with one of the two reference scenarios mentioned previously. The financial/technical and emissions aspects of the analysis are done comparing the impact of increased solution ADPT versus the continued use of conventional technologies.

After each run of the model, among others, the model presents Adoption, Financial and Emission Results, when compared with the continued use of conventional technologies, as can be seen in the example of Figure 4.1, with the most significant ones being Implementation Unit Adoption Increase in 2050, Functional Unit Adoption Increase in 2050, Marginal First Cost, Net Operating Savings, Lifetime Operating Savings, and Total Emission Reductions in the analyzed time period (2020-2050).

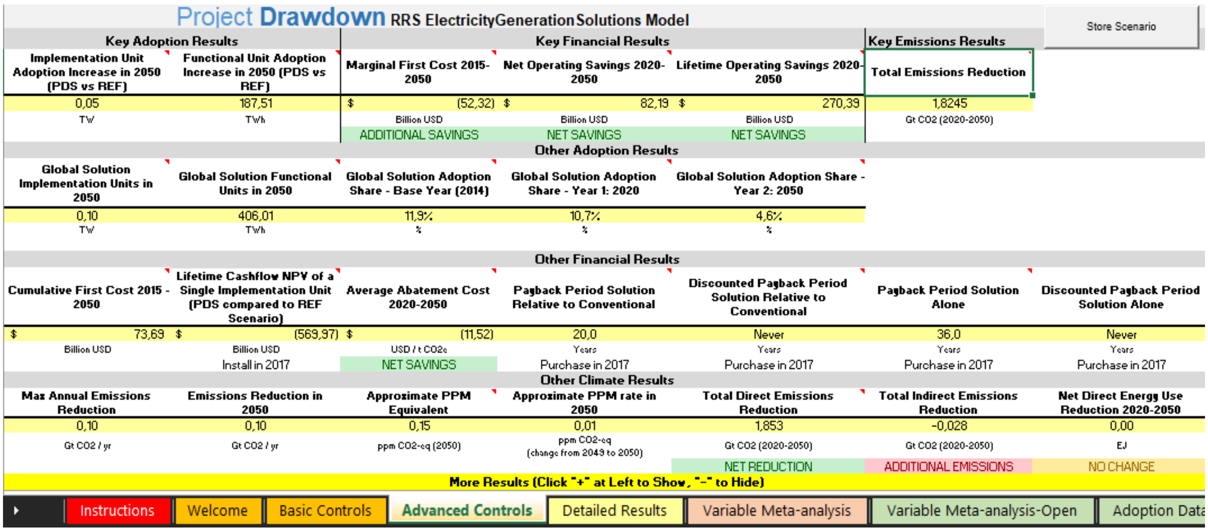


Figure 4.1 - Results of an example run in the RRS Model.

Lastly, it is worth highlighting that a more interactive Python-based model for Project Drawdown is in development, being much more user-friendly and available for scenario testing online.

4.2. Step-by-step Analysis of Methodology

As stated, this work's objective is to analyze electricity generation and the potential penetration of hydropower solutions in the European Union and reduce greenhouse gas emissions, mainly CO_2, that come with it, in the time frame between 2020 and 2050.

This research had previously been conducted on a global scale for the small hydro technologies, in particular, part of Drawdown's Framework of Solutions. This work expands this analysis to the large hydropower plants and contributes to the regionalization efforts of Project Drawdown in the European context.

It is important to note, however, that even though the main goal is to perform this analysis with the European Union in mind, a lot of the steps taken were also executed for data regarding Europe, in hopes of having some results for the continent as well that could serve as a term of comparison with the main EU-28 results and ultimately provide some insight in this context as well.

4.2.1. Data Gathering

The first step in this analysis was the compilation of data pertaining to the subject. This research consisted of the gathering of documents from various entities such as IRENA's Renewable Energy Statistics 2020 [9]or IEA's World Energy Outlook (WEO) 2019 [30] and their subsequent analysis for the type of data that was desired. This included: historical data and future scenarios with projections for electricity generation as a whole and specifically for the hydropower solutions in Europe, present and future scenarios with projections for macro indicators, such as population, GDP and economic growth, CO_2 emissions in the region, technological and financial aspects for both solutions and conventional technologies such as fixed and variable costs, fuel prices, capacity factors, lifetime, learning curves or rates, as well as any particularities of each scenario, like projections for the evolution of nuclear power or hydrogen, for example. To organize and assess this data, an excel file was created, cataloging each publication, with its corresponding scenarios and data points for each scenario.

This type of collection of data soon presented a few challenges. In terms of the data itself, not every document presented the same kind of information. For example, Greenpeace's Energy Revolution [30] contains different scenarios with projections of future electricity generation but no information regarding technological aspects. This problem can be solved by resorting to other documents such as JRC's Energy Technology Reference Indicators 2014 [20], which has precisely the opposite kind of data.

Secondly, the data points in each document pertain to different time intervals, particularly when it comes to future projections, like IEEJ's Outlook 2020 [39] with TAM and Adoption data for 2030, 2040, and 2050 while IEA's Energy Technology Perspectives 2017 [31] possesses this projection data with 5-year intervals instead of 10. This challenge was solved with interpolations, which will be explained in the next section. In addition to this, the data didn't always feature in tables but only in graphs, like in the case of SolarPower Europe's 100% Renewable Europe [43], making the extrapolation of this data from the document onto the Excel document more challenging to perform with precision.

In the specific case of gathering data about the Adoption of small hydropower technologies, the discoveries were scarce, with no findings of documents that featured future projections for the solution and very few data points for historical values such as ESHA's Small Hydropower Roadmap [44] or IRENA's Renewable Energy Statistics 2016 and 2017 [45] [37]. The workaround for this issue will be explained later in the chapter.

Lastly, a geographical issue comes about when gathering all this data. When going through all these documents, the definitions of what constitutes Europe varies considerably. Some of these studies consider the European Union pre-Brexit and some post-Brexit, some consider OECD Europe in their projections, others analyze Europe with countries like Turkey included. These disparities in the region that is being treated make a difference in the resulting data, specifically in cases where large countries, like Turkey or Ukraine, are included, so some data harmonization is necessary. When this research was conducted around solar technologies [16], it was decided that, where possible, the removal of the data from these individual countries would be done only to gather data about the European Union. In this case, the decision was made to collect data on the European Union (pre-Brexit) which would be the main focus of work, and, when present in the several studies that were analyzed, collect the data regarding Europe, for a smaller and simplified analysis and comparison of results at the end. So, unless stated otherwise, every step in this methodology was followed with both EU-28 and Europe in mind.

During this first step, a total of 37 documents were researched, including the ones that have already been mentioned, encompassing 68 different scenarios, each with its characteristics and unique data points, with figure 4.2 showing an example of the organization of the data that was gathered.

	A	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR
1																	
2		istorical EU Market (TWh)							T2 - Future EU Electricity Market (TWh)								
3	SCE Short Name	TAM 2012	TAM 2014	TAM 2015	TAM 2016	TAM 2017	TAM 2018	TAM 2019	TAM 2020	TAM 2025	TAM 2030	TAM 2035	TAM 2040	TAM 2045	TAM 2050	TAM 2055	TAM 2060
40	JRC PRORES																
41	EWG BPS			3787					4170	5297	6291	8483	11778	14407	17781		
42	BP REF	4019	3938	3982	4023	4062	4067	3993									
43	EDP SC1								3750	3900	4150	4450	4800	5050			
44	EDP SC2								3750	4000	4400	5050	5500	6200			
45	EDP SC3								3750	4100	4600	5100	6200	7000			
46	SPE LGSC								4 200		6 000		8 050		14 100		
47	SPE MSC										6 900		12 000		17 100		
48	SPE LSC										7 500		17 300		18 500		
49	EQ RF						3251				3 398		3 572		3 473		
50	EQ RB						3251				3 591		3 966		3 529		
51	EQ RV						3251				3 418		3 488		3 183		
52	OI RFSC			3042					3 205		3 391		3 640		3 923		
53	OI VSC			3042					3 080		3 555		4 221		4 640		
54	ST 5C			3600						4000	4 200		4 500		4 800		
55	ST 2C			3600						3800	4 100		5 050		5 550		

Figure 4.2 - Example of data curation and organization in an excel spreadsheet used to manage references.

4.2.2. Interpolations for TAM and Large Hydro Adoption

Following this collection and curating of data, the next step was use of the several projections of TAM and Adoption datapoints in each scenario to, through interpolation, obtain yearly data for the time frame in analysis, 2020 until 2050.

However, as mentioned before, the data in the different documents referred to single years in this period, with studies such as Wind Europe's Breaking New Ground [46] only having projections for 2030 and 2050, while others like Eurelectric's Decarbonisation Pathways [47] having six future data points. Additionally, a solid base with past data points from which these projections can go off is important when working with future projections. With these two aspects in mind, before the interpolations were made, this historical base was needed.

One would think that since we are talking about historical data, there would be a consensus amongst sources; however, this is not the case. In this step, it became clear that different sources not only projected different future values for TAM and Adoption of technologies, but they also presented different numbers about the past. With this problem in consideration, it was decided that the source for this historical data would be two-fold: data regarding fossil fuels (coal, natural gas, oil), nuclear, hydropower, and geothermal electricity generation was obtained from IEA's website, in its interactive display showing data from their Electricity Information 2020 [48] document. The data for the remaining sources of electricity generation (solar photovoltaic, concentrated solar power, tidal and wave, wind onshore and offshore, biomass and waste) was obtained from the downloadable excel datasheet present on IRENA's website. This decision to have different sources for the historical base came from the necessary data for the RRS model, which needs a certain separation in different technologies, such as wind onshore and offshore technologies. The two sources were chosen because of their status in the power sector and renewable energy, respectively. This step produced the electricity generation mix table mentioned in section 5.1 and shown in figure 4.3.

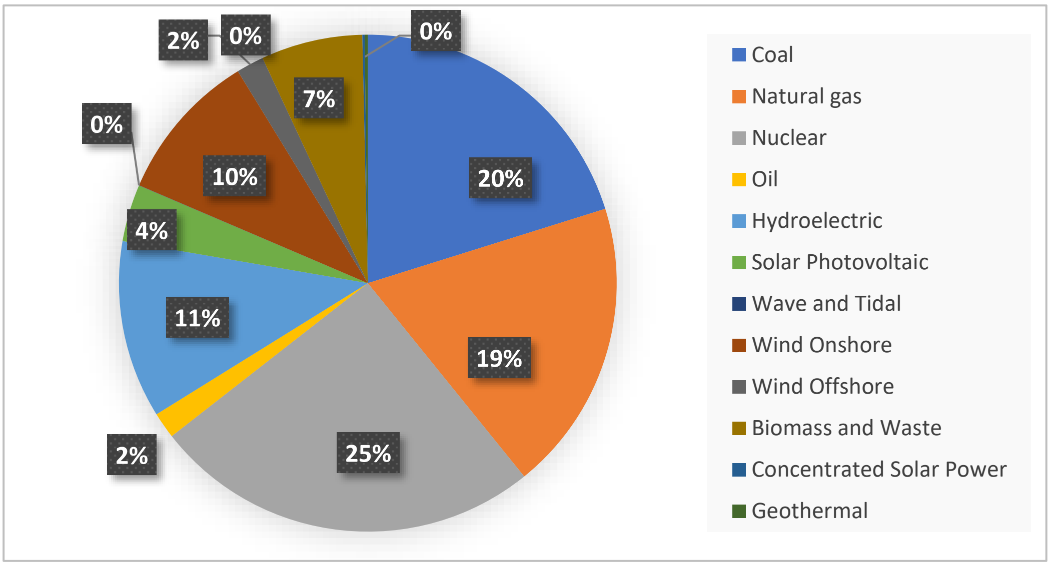


Figure 4.3 - Power mix obtained from the gathered historical database.

With a historical database already assembled and from which to go from, the interpolations could be started for TAM and the Adoption of Large Hydro technology, once again for both the European Union and Europe data. The process for the Small Hydro solution interpolations differed and will be explained in the following subchapter.

For these interpolations, the data interpolator that's part of the RRS model was used. In summary, as shown in Figure 4.4, the document, respective scenario, and original units of the data would be identified in the interpolator. Next, the historical data would be inserted in its respective time period alongside the projection data points. From this point on, the best fitting trend line would be selected (the 3rd polynomial in most cases), and the yearly values resulting from the interpolation would be stored.

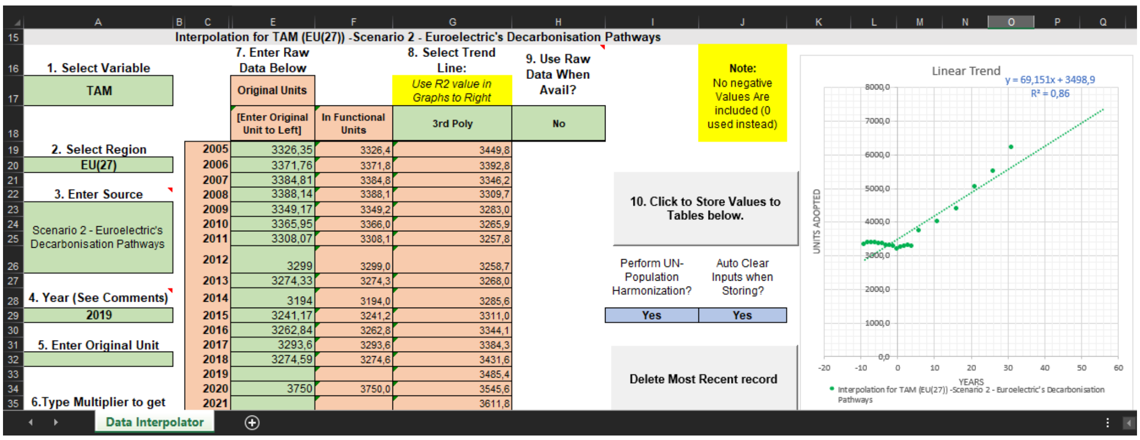


Figure 4.4 - RRS Model's Data Interpolator that was used to obtain yearly projections. In this example, for Scenario 2 from Euroelectric's Decarbonisation Pathways.

It is worth pointing out the 9th step of the interpolator use. This step asks the user of the model if the raw data should be used when available. Since the data points gathered from the different studies were few for the 30-year time period that's being analyzed, and the interpolation is adjusting the values around these data points, using the raw data would cause peaks and valleys in the projection graphs, which wouldn't make much sense, as shown in Annex A, so the decision to not use the raw data and the resulting interpolation was made.

This process was repeated for the 68 scenarios mentioned previously, for the TAM and Large Hydro Adoption indicators individually, resulting in 68 TAM projections and 58 Large Hydro ADPT projections. Not every single document possessed data regarding Large Hydro technologies.

From all these scenario projections, some issues arose. In some cases, like the scenarios in IRENA's Renewable Energy Prospects for the European Union 2018 [49], the resulting interpolation presented a trend that wouldn't make sense when talking about projections, with the values for electricity generation having a downward trajectory for around a decade and then suddenly starting to grow. These issues may have happened due to the existence of only one future data point with which to interpolate or the fact that the historical database for large hydropower does not follow a particular trend (due to wet or dry years changing electricity generation outputs), causing a lot of possibilities for error to be present. These issues had to be accounted for in the next step while selecting scenarios for the RRS Model.

Since the analysis was made using Project Drawdown's Reduction and Replacement model and it can only use up to 15 scenarios when it comes to TAM and 16 when it comes to the Adoption of a solution, the 68 TAM and 58 Adoption projections for LH had to be whittled down. For this to happen, the following selection criteria were used for TAM scenarios, in order of relevance:

1. As was mentioned, in some cases, the interpolation resulted in projections in which the values for electricity generation have a downward trajectory for decades followed by a rise in numbers before 2050, for several years following a surge in numbers in the next decade or a decline in 2019 followed by a steady growth from thereon. These scenarios were disregarded and are mostly a consequence of the polynomial trend used;
2. The entity that produced the study with its different scenarios was taken into account. The aim is to include a large variety of sources since these scenarios deal with projections for the future. Therefore, depending on the entity producing them, they can have different agendas. The diversity in inclusions would help combat this;
3. If the data collected came from older studies, these would be given less priority to fill the 15 slots;
4. If the data was collected from charts in the original documents and not from tables, this scenario would not be prioritized since it would be less accurate;
5. The last criteria for selection was the accuracy of the interpolation results (measured by the determination coefficient of the interpolations, R^2). The resulting scenarios presenting a lower value were also given less priority in selection.

For the scenarios considering LH Adoption, similar criteria were followed to achieve the desired 16 scenarios, except for criterion number 3, since a particular study, JRC's Assessing the long-term role of the SET Plan Energy technologies [40] from 2013, presented several scenarios with very different characteristics and focuses on different technologies, which was considered an advantage when it comes to a variety of perspectives.

Lastly, the scenarios were then divided by tiers, according to the electricity generation each presented in 2050, which is a requirement to running the model. For the Total Addressable Market, this division of the 15 scenarios goes as follows:

- Four scenarios for Modest Growth (green), encompassing scenarios with electricity generation in 2050 inferior to 4500 TWh;
- Five scenarios for Intermediate Growth (yellow), including scenarios with electricity generation in 2050 between 4500 TWh and 6000 TWh;
- Five scenarios for Ambitious Growth (blue), containing scenarios with electricity generation in 2050 between 6000 TWh and 12500 TWh;
- One scenario for Extremely Ambitious Growth (white), with the scenario with the highest electricity generation in 2050;

For the Adoption of Large Hydro technologies, the same process was repeated for its 16 scenarios, as follows:

- Four scenarios for Modest Growth (green), encompassing scenarios with electricity generation in 2050 inferior to 415 TWh;
- Five scenarios for Intermediate Growth (yellow), encompassing scenarios with electricity generation in 2050 between 415 TWh and 430 TWh;
- Six scenarios for Ambitious Growth (blue), encompassing scenarios with electricity generation in 2050 between 430 TWh and 550 TWh;
- One scenario for Extremely Ambitious Growth (white), with the scenario with the highest electricity generation in 2050;

4.2.3. Interpolations for Small Hydro Adoption

During the collection of data, it became evident that values for electricity generation from small hydropower technologies were scarce, with no projections available from the primary sources (IRENA or IEA) and historical datapoints existing only in IRENA's Renewable Energy Statistics 2015 and 2016 [50][45], consequentially providing data only until 2015 for electricity generation and 2016 for installed capacity. With this in mind, a different approach had to be taken.

When it comes to the European Union's data, a historical database for the technology was built from IRENA's two documents mentioned in the previous paragraph and a single 2020 datapoint from ESHA's Small Hydropower Roadmap [44], with a small interpolation in between, resulting in a historical base spanning 2006 to 2020.

For data regarding Europe, this 2020 data point was not available, so a slightly different approach had to be adopted once again. Since UNIDO's World Small Hydropower Development Report from 2019 [51] presented capacity data for 2019, the historical database for Europe was created based on historical capacity values, then converted to electricity generation values considering a reference capacity factor of 37%, based on European Commission's ETRI 2014.[22]

The next step in this process would be to interpolate data for electricity generation until 2050, based on the historical and future data points. However, as was mentioned, these future data points were not found in the literature, so these different future scenarios had to be created using two distinct methods:

1. The average growth rate in electricity generation and capacity between 2006 and 2020 was calculated, and it was proposed that the Adoption of the technology would continue to grow at this rate, at half this rate and double this rate, creating twelve different scenarios for the future (six for EU-28 data and six for Europe data);
2. Based on the 2018 historical data point from both technologies (Large and Small Hydro), it was calculated that SH represented 13,9% of the electricity generation from LH. It was postulated that this percentage would be maintained, resulting in eight different scenarios for the EU-28.

4.2.4. Reference Scenario

To understand the potential of the hydropower technologies through all the obtained adoption scenarios, a default scenario with which to compare the evolution until 2050 is needed. Named the Reference (REF) scenario, in this, the Adoption of a technology is fixed as the percent of current Adoption in the defined TAM. It considers that the percent of solution Adoption remains constant throughout the chosen time frame [42].

Using this reference scenario, it would be one of constant growth, which, taking into account the current status of hydropower, is not a likely one. Therefore, in efforts for a more realistic analysis, the customized Adoption scenarios feature was used. This feature allowed for the input of several scenarios for both technologies and regions and the use of the average of these scenarios as a single reference with which to compare the ones mentioned in the previous two subchapters.

In all four versions of the model, the scenarios used to make up this reference were always a minimum of two. They encompassed projections where the technology was expected to have moderate growth or even decline in use.

4.2.5. Variable Meta-Analysis (VMA)

As was mentioned previously, the Excel-based solutions-oriented Drawdown model used for this work possesses a sheet tailor-made for the variable meta-analysis of data. To run the model and execute this analysis, different types of information are needed to perform this variable meta-analysis. The gathering of this type of information constituted the next step of this methodology and encompassed four different categories:

- Financial variables: First Costs per Implementation Unit, Fixed Operating and Maintenance Costs (FOM), and Variable Operating and Maintenance Costs (VOM). These variables were collected for both hydropower technologies and the conventional powerplants these solutions aim to replace. Additionally, as the standard monetary unit in the model is 2014 USD, all the values were converted from their original units to this one.
- Technical variables: Lifetime Capacity, typically in years and then converted into the established unit in the model TWh/TW, Average Annual Use (also known as Capacity Factor), typically in percentage and then converted into the established unit in the model TWh/TW*Year, Learning Rates, typically in %. The data for the first two variables being gathered for both solutions and conventional technologies while the learning rates were only stored for the solutions.
- Environmental variables: Direct and Indirect CO_2 emissions, typically in tons of CO_2eq/TWh. This data was collected for both solutions.
- Materials/Jobs: in addition to previous works in Project Drawdown, it was also procured information about the number of jobs and resources (namely water, iron, cement, copper, and aluminum use) tied with the solutions. Unfortunately, this data was only found in the literature for Large Hydropower technologies.

All the information for these four kinds of variables was then inserted and organized in tables. It is worth mentioning that the financial and technical data was also gathered for the conventional technologies, serving later as a term of comparison with the solution data. To this effect, the data for these technologies was collected in the same tables but given different weights in the calculations corresponding to their 2020 representation in the power generation mix, 20,16% for coal, 1,71% for oil, and 19,02% for natural gas. The next step was to curate all of this information and best assess which data was more relevant for the financial and technical analysis that was to be made.

Since the goal is to conduct this analysis for the European Union, ideally, all the figures regarding these four kinds of variables would pertain to this region and be as recent as possible, so inventory was taken on all the information gathered in this step to assess if the number of data points for each of the variables was enough to perform the intended analysis, resulting in a table such as tables 4.1, 4.2 and 4.3, for each of the technologies (conventional, large hydropower and small hydropower).

Table 4.1 - Comparison of the amount of data points for each of the researched variables, the specific region, and the date, for Conventional Technologies.

Conventional Technologies				
	World data (with pre-2015 data included)	World data (with pre-2015 data excluded)	EU-28 data (with pre-2015 data included)	EU-28 data (with pre-2015 data excluded)
First Cost	2196,713	2132,912	2183,175	2010,564
#First Cost datapoints	95	75	36	30
VOM	0,005	0,004	0,005	0,004
#VOM datapoints	27	17	23	17
FOM	47,933	44,677	49,880	46,934
#FOM datapoints	53	37	31	25

Table 4.2 - Comparison of the amount of data points for each of the researched variables, the specific region, and the date, for Large Hydropower Solutions.

Large Hydropower Solutions				
	World data (with pre-2015 data included)	World data (with pre-2015 data excluded)	EU-28 data (with pre-2015 data included)	EU-28 data (with pre-2015 data excluded)
First Cost	3970,042	4014,367	4007,398	3568,268
#First Cost datapoints	64	29	51	23
VOM	0,010	0,003	0,010	0,003
#VOM datapoints	19	9	19	9
FOM	36,541	36,496	36,541	36,496
#FOM datapoints	22	12	22	12

Table 4.3 - Comparison of the amount of data points for each of the researched variables, the specific region, and the date, for Small Hydropower Solutions.

Small Hydro Solutions				
	World data (with pre-2015 data included)	World data (with pre-2015 data excluded)	EU-28 data (with pre-2015 data included)	EU-28 data (with pre-2015 data excluded)
Average First Cost	4492	3776	5208	4023
#First Cost datapoints	132	47	81	26
Average VOM	0,060	0,005	0,082	0,009
#VOM data-points	11	3	8	1
Average FOM	219,6	102,7	219,6	72,8
#FOM data-points	40	10	40	4

Facing this amount of information, it was considered that for the conventional and large hydro technologies, there was enough of it to exclude all data points that did not pertain to the EU and that were older than 2015, while for small hydro technologies, as shown in table 4.3, with a smaller quantity of information, it was considered that excluding data points outside of the EU was valid. Still, it would be necessary to use the information before 2015 to have a solid number of data points. This exclusion was performed directly in the model, which possesses a built-in function for this purpose.

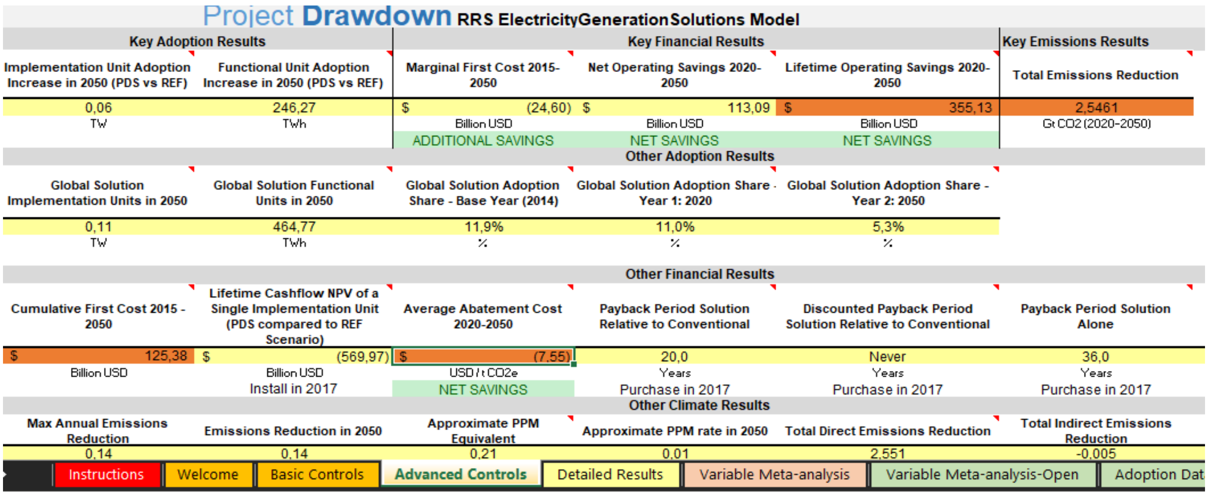
4.2.6. Running the RRS Model

Once all of this information is gathered, the conditions are met for the model to run and produce results. Firstly, for each run, the data for the different variables present in the VMA datasheet are kept at their average value, calculated by the model itself, as was explained earlier, to obtain the most representative analysis.

Secondly, to run the model, an Adoption scenario must be selected. In this case, the 16 scenarios gathered from the literature and the resulting interpolations, explained in section 5.2.2 and 5.2.3, were the ones used, alongside an average of each tier of Adoption scenarios (Modest, Intermediate, Ambitious and Extremely Ambitious), making a total of 19 runs for Large Hydro technologies. The Extremely Ambitious tier, as was explained, only contains one scenario, the one with the largest Adoption value for 2050, making the average of the tier and the scenario the same, and therefore a total of 19 runs for this technology in the case of the data for the European Union and 9 runs for the data regarding Europe.

The same methodology was used for the Small Hydro technologies, with runs amounting to 17 for the European Union data and 9 runs for the European scenarios.

In total, 54 runs of the model were performed, each with its own results shown in the next section of this work. Each run produces results for 25 different financial and environmental variables, with some being worth highlighting, such as "Total Emissions Reduction", the principal environmental result, showing the number of emissions of CO_2eq that can be avoided by transitioning from conventional technologies to hydropower solution being analyzed. "Cumulative First Cost" serves as an indication of the total investment that would be needed for the installation of these solutions. "Lifetime Operating Savings" shows the savings that the implementation of the solutions can bring over the course of its lifetime, In other words, if the plant can be profitable. Lastly, "Average Abatement Cost" attempts to merge the financial and environmental indicators. All of these are highlighted in orange color in figure 4.5 and will be discussed further on.



Project Drawdown RRS ElectricityGenerationSolutions Model

Key Adoption Results		Key Financial Results			Key Emissions Results
Implementation Unit Adoption Increase in 2050 (PDS vs REF)	Functional Unit Adoption Increase in 2050 (PDS vs REF)	Marginal First Cost 2015-2050	Net Operating Savings 2020-2050	Lifetime Operating Savings 2020-2050	Total Emissions Reduction
0,06	246,27	$ (24,60)	$ 113,09	$ 355,13	2,5461
TW	TWh	Billion USD	Billion USD	Billion USD	Gt CO2 (2020-2050)
		ADDITIONAL SAVINGS	NET SAVINGS	NET SAVINGS	

Other Adoption Results				
Global Solution Implementation Units in 2050	Global Solution Functional Units in 2050	Global Solution Adoption Share - Base Year (2014)	Global Solution Adoption Share - Year 1: 2020	Global Solution Adoption Share - Year 2: 2050
0,11	464,77	11,9%	11,0%	5,3%
TW	TWh	%	%	%

Other Financial Results					
Cumulative First Cost 2015 - 2050	Lifetime Cashflow NPV of a Single Implementation Unit (PDS compared to REF Scenario)	Average Abatement Cost 2020-2050	Payback Period Solution Relative to Conventional	Discounted Payback Period Solution Relative to Conventional	Payback Period Solution Alone
$ 125,38	$ (569,97)	$ (7,55)	20,0	Never	36,0
Billion USD	Billion USD	USD / t CO2e	Years	Years	Years
	Install in 2017	NET SAVINGS	Purchase in 2017	Purchase in 2017	Purchase in 2017

Other Climate Results					
Max Annual Emissions Reduction	Emissions Reduction in 2050	Approximate PPM Equivalent	Approximate PPM rate in 2050	Total Direct Emissions Reduction	Total Indirect Emissions Reduction
0,14	0,14	0,21	0,01	2,551	-0,005

Figure 4.5 - Key Results from the Runs of the RRS Model.

4.2.7. Sensitivity Analysis

The complexity and large scope of the data gathered and used and the various functionalities of the model make it possible for different types of analysis, other than the one discussed in the previous section, which produces the main results for this work.

In this case, a further sensitivity analysis will be performed in hopes of better understanding the impact that the various variables utilized in the VMA section can have in the results shown above. To achieve this, new runs of the model will be executed.

The average of the Modest and Ambitious tiers of Adoption will be used for these sensitivity analysis runs. These seem to be the most realistic and probable trends in electricity generation for hydropower solutions.

After selecting the Adoption, each of the VMA variables will be altered while keeping every other one constant to understand better the impact that each of them has on the final results of this analysis. For example, changing the First Cost per Implementation Unit variable from average to high and keeping the average of every other variable, and seeing its effect on the key results.

These new sensitivity analysis runs will then be performed for First Cost per Implementation Unit, Lifetime Capacity, Average Annual Use, Variable (VOM) and Fixed (FOM) Operating Cost, Direct and Indirect Emissions, as well as for Jobs created and Materials used, producing a total of 48 runs for Large Hydropower technologies (24 runs for each of EU-28 and Europe data) and 36 runs for Small Hydropower technologies (18 runs for each of EU-28 and Europe data).

5. RESULTS

This section will provide the results and their discussion. It is important to highlight that, due to the nature of this research and the steps that were followed, different kinds of results were obtained and will be presented, with this presentation being handled in the same order as the steps shown in the step-by-step subchapter of the methodology, in the hopes of showing the several different types of results more clearly.

5.1. Data Gathering Results

The first type of results that were achieved came from the first step of this process, the gathering of data from several different documents produced by numerous entities in the energy sector at large, as was mentioned previously.

Resulting from the necessity of this varied and large amount of data to accomplish the main goals of this study, more than 60 publications were analyzed in this data-gathering effort, totaling 69 scenarios for TAM and/or Adoption. After the selection explained in section 5.2.2, a set of scenarios for TAM and Adoption of both technologies remained, coming from a set of 20 most useful reports. The most significant of these reports are listed in Table 5.1, which shows the document's name, the institution that produced it, the scenarios it presents, and for which RRS model input they were used for (future TAM and/or Adoption for the EU or Europe).

Table 5.1 - Main publications used for data collection in this work.

Publication Name	Entity	Scenarios	Output used for
The Vision Scenario for the European Union 2017 [52]	Öko-Institut	Reference Scenario	TAM (EU)
		Vision Scenario	
Global Renewables Outlook: Energy Transformation 2050 [53]	IRENA	Planned Energy Scenario	TAM (EU)
		Transforming Energy Scenario	
EU Reference Scenario 2016 [54]	European Commission	EUREF16 Scenario	TAM (EU)
Deployment Scenarios for LowCarbon Energy Technologies 2018 [55]	European Commission	Baseline Scenario	TAM (EU) + Adoption
		Res_7_Near_Zero	
		Div 1	
		Res 1	

Net Zero by 2050: From Whether to How [56]	EFC International	EFC Technology EFC Shared Effort EFC Demand-Focus	TAM (EU) + Adoption
Annual Report 2018 [47]	Eurelectric	Scenario 1 Scenario 2 Scenario 3	TAM (EU)
Gas Decarbonisation Pathways 2020–2050 [57]	Navigant	Accelerated Decarbonization Pathway	TAM (EU)
		Global Climate Action Pathway	
World Energy Outlook 2019 [30]	IEA	Current Policies Scenario	TAM (Europe)
		Stated Policies Scenario	
		Sustainable Development Scenario	
100% Renewable Europe How To Make Europe's Energy System Climate-Neutral Before 2050 [43]	SolarPower Europe	Laggard Scenario	TAM (Europe)
		Moderate Scenario	
		Leadership Scenario	
Global Energy System Based On 100% Renewable Energy 2019 [58]	LUT & EWG	Best Policy Scenario	TAM (Europe)
Outlook 2020 [39]	IEEJ	Reference Scenario	TAM (EU) + Adoption
		Advanced Technologies Scenario	
The JRC-EU-TIMES model 2013 [40]	JRC	Current Policies Scenario	Adoption
		Current Policies with CAP Scenario	
		Delayed CCS Scenario	
		High Renewables Scenario	
		High Nuclear Scenario	
		Low Energy Scenario	
		Low Biomass Scenario	
		Low Solar and Wind Scenario	

5.2. Results from the Interpolations of TAM and Large Hydro Adoption

5.2.1. Interpolations of TAM Data

One of the main and earliest results from this thesis are the projections for the evolution of the Total Addressable Market in the European Union and Europe, shown as electricity generation for the time period between 2020 and 2050.

For TAM data, a total of 68 interpolations were performed, stemming from various scenarios and publications such as the ones mentioned in subchapter 6.1.. Since the main focus of this work was the European Union and the data for Europe as a whole is being used mainly as a term of comparison or for benchmarking purposes, it was considered that, after the selection process mentioned, these projections could be whittled down to 15 scenarios in the case of the data regarding the EU-28 (the maximum number of scenarios that the Project Drawdown model allows for TAM data) and to only 12 scenarios in the case of the values coming from the whole continent of Europe. The resulting projections can be seen in Figures 5.1 and 5.2.

In the case of Figure 5.1., at the higher end of the spectrum, three scenarios project an evolution of electricity generation in the EU clearly distinct from the others, with values above 12.000 TWh for JRC's ProRES Near Zero Scenario [59] and European Commission's RES7_Near_Zero Scenario. [55] At the same time, another JRC Scenario, LCEO Zero Carbon, shows an evolution peaking at around 10.500 TWh in 2050. All three of these scenarios present the same general philosophy, with a clear focus on electricity generation from renewable energy and a considerable reduction of carbon emissions, zero or near zero at that.

In contrast, scenarios such as JRC's Diversified Scenario [59] present an evolution of generation that only climbs until around 5600 TWh, with this scenario focusing on only a mid-range deployment of renewable energy systems in concert with improvements in energy efficiency and technologies such as Carbon Capture and Storage to mitigate the amount of emissions released into the atmosphere.

At the lower end of the spectrum, there are cases like IEEJ's Advanced Technologies Scenario [38] who propose a considerable focus on energy efficiency or projections IRENA's Planned Energy Scenario where the approach is closer to business as usual, providing a perspective based on government's current energy strategies and targets, with both, therefore, presenting lower values of electricity generation in 2050 with close to 4000 TWh, a slight increase over the historical value used for 2018 of 3275, about 18%.

With six different scenarios projecting an evolution of TAM in the range of 4600 to 5600 TWh, however, this seems to be the most likely development, with situations such as Eurelectric's Scenario 1 [47] where the assumptions used for the scenario show only an intermediate, but perhaps more realistic, level of ambition, proposing a level of decarbonization at 80% with an acceleration of the current technological trends and policies.

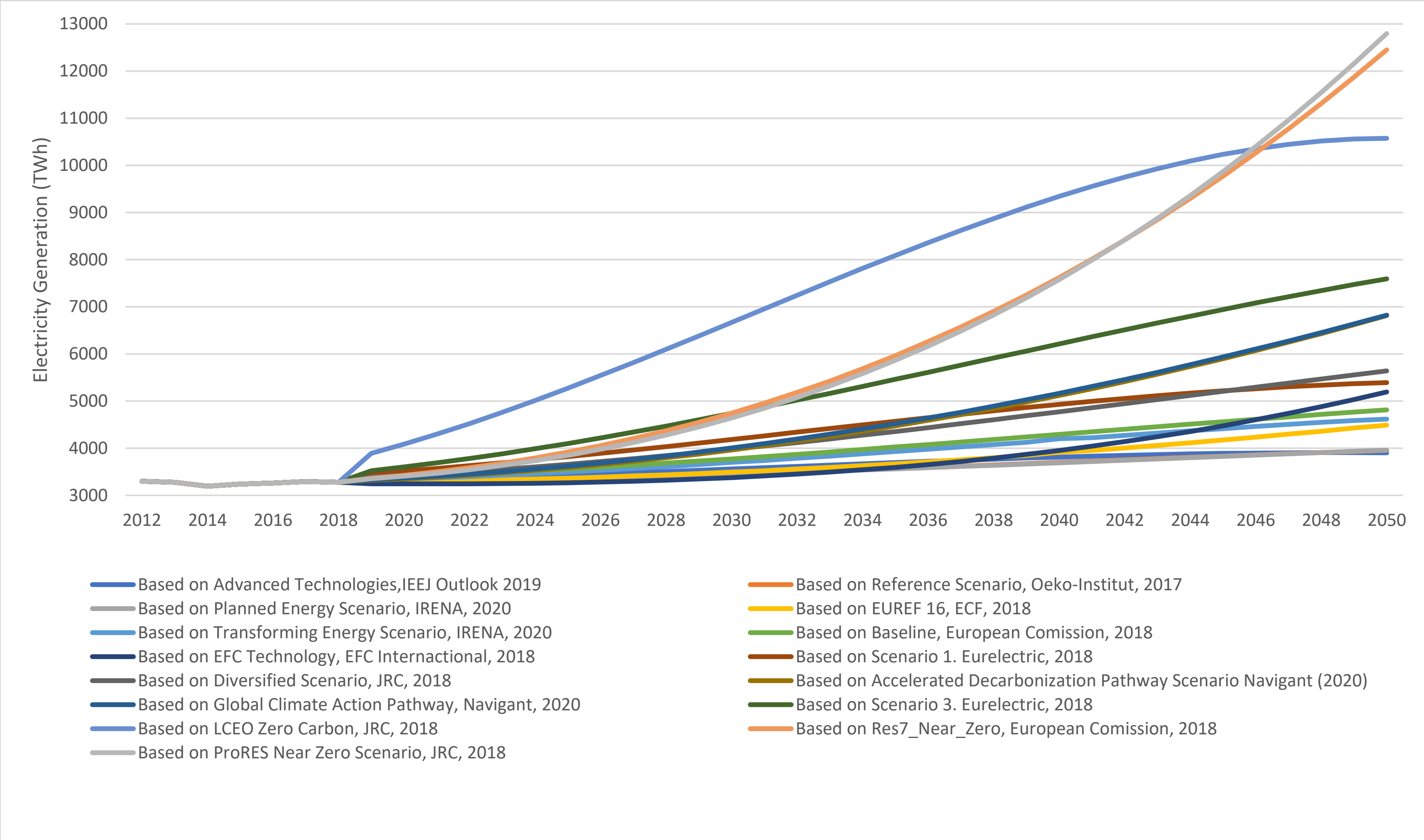


Figure 5.2.1 - Projections for the evolution of TAM in the European Union until 2050.

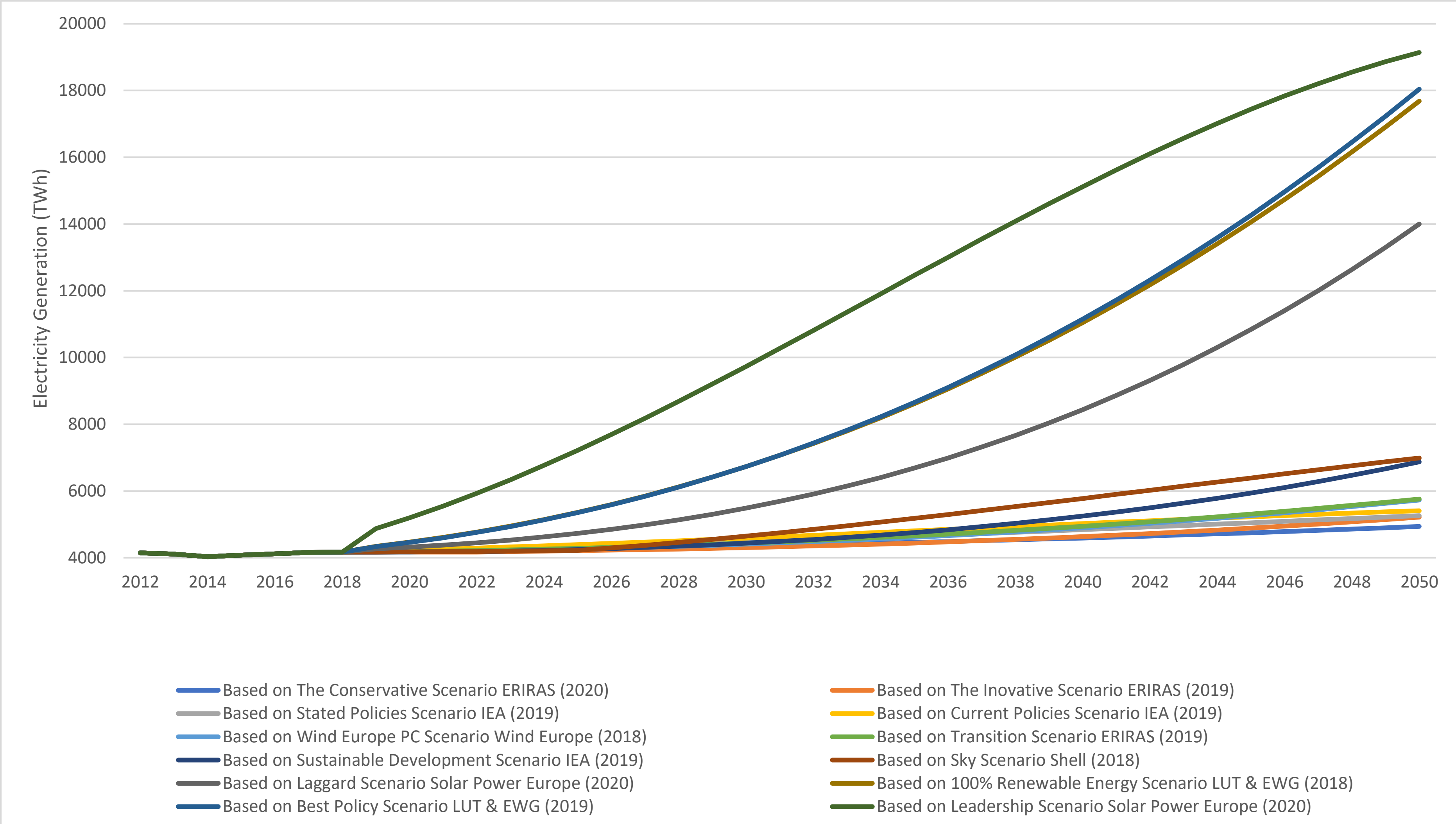


Figure 5.2.2 - Projections for the evolution of TAM in Europe until 2050.

Looking at Figure 5.2 and its different scenarios, the projections coming from the SolarPower Europe, Laggard and Leadership Scenarios [43], and the ones belonging to both LUT University [58] and Energy Watch Group's documents are clear standouts from the pack, with TAM projections between 14000 and 19000 TWh, stemming from a big focus on transforming the energy system in the continent, making it 100% reliant on renewable energies, with the LUT University's scenarios, in particular, having a strong component of energy storage and its impacts on the energy sector.

However, the vast number of scenarios are more conservative in their approaches, which translates in the values for electricity generation in 2050, with all remaining 8 scenarios being in the range of 5000 and 7000 TWh.

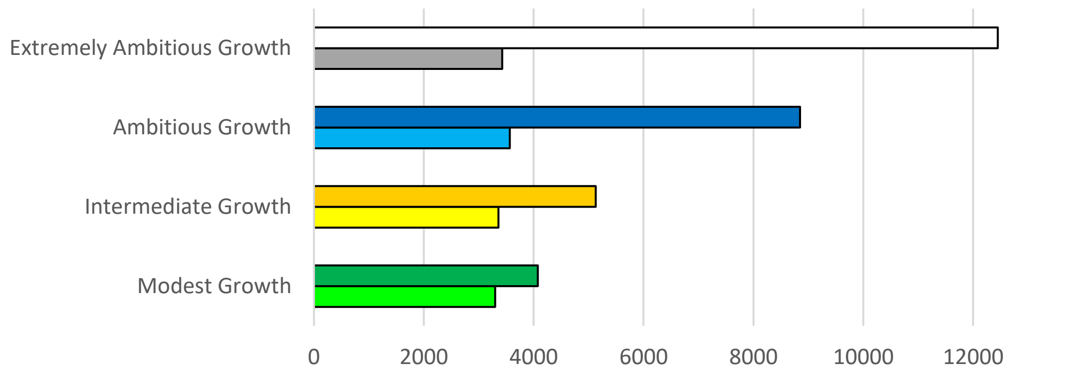
Comparing these with the European Union's numbers, there's an apparent discrepancy, with both the average and maximum values for TAM in 2050 being significantly higher in the case of the continent, around 17% and 32%, respectively. The most likely explanation for this difference is not only the higher number of countries considered in the definition of Europe that is being used but also the size of some of these countries, with the Ukraine, Turkey or Russian Federation being very large countries, with high population numbers and bigger energy needs.

This diversity of perspectives, when it comes to different sources and the variety within the same entities themselves, emphasizes the notion that these projections are not acting as forecasts for the evolution of the power sector in the region but are showing different pathways that can be taken in the development of the sector in the region, depending on the policies and targets that are established.

Additionally, Figures 5.3. and 5.4. show the average electricity generation in 2020 and 2050 for each of the four tiers of growth discussed earlier (Modest - green, Intermediate - yellow, Ambitious – blue, and Extremely Ambitious – grey and white).

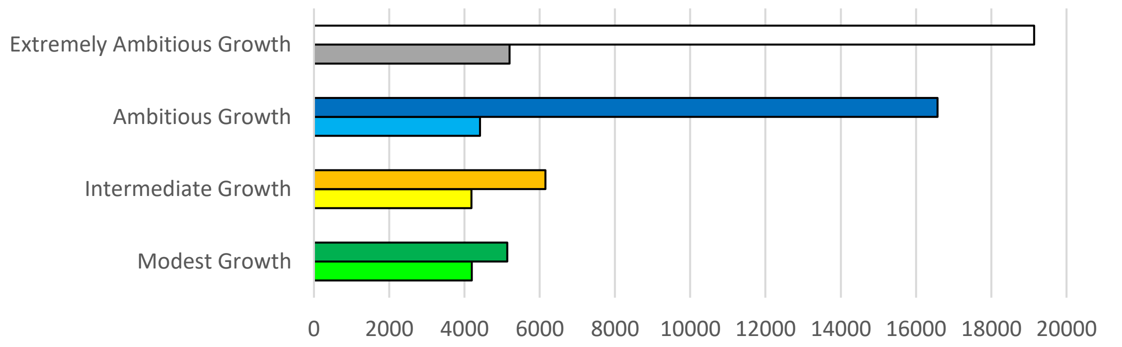
As opposed to the electricity generation values for 2050, in this case, the difference between the regions is minimal, with the biggest one coming in the Ambitious Growth tier, where scenarios regarding the European Union had an average growth of 60% concerning the 2020 data, while scenarios regarding Europe possessed an average increase of 73% for this tier.

With the continuous increase in population and standard of living in both regions (with much overlap between them), this similar growth is expected, with the Extremely Growth scenario projecting an increase in TAM for both regions of around 73%.



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050 TAM	4076	5130	8850	12450
2020 TAM	3299	3359	3566	3426

Figure 5.2.3 - Evolution of TAM between 2020 and 2050 in each Tier of growth for the EU-28.



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050 TAM	5138	6151	16573	19140
2020 TAM	4195	4186	4414	5196

Figure 5.2.4 - Evolution of TAM between 2020 and 2050 in each Tier of growth for Europe.

5.2.2. Interpolations of Large Hydro Adoption Data

Even though it isn't one of the original solutions for Project Drawdown, when it comes to projections for the evolution of the Adoption of hydropower technologies, Large Hydropower presented the easiest path to obtain these, with larger amounts of data available in reports.

For this particular technology, 58 interpolations were performed, stemming from largely the same publications as the TAM projections referred to earlier, since most of these presented not only evolution in terms of electricity generation but also the distribution of this generation amongst different technologies, large hydropower included. As opposed to the case of TAM, where the RRS model could only use up to 15 scenarios, for the Adoption projections, it can hold 16 scenarios, used for the European Union projections. At the same time, only 6 future pathways were gathered for values regarding Europe. These results can be seen in Figure 5.5. and 5.6.

In the case of Figure 5.5., three scenarios stand out from the majority. Much like with the projections for TAM, the European Commission's RES7_Near_Zero Scenario presents a high value of electricity generation, in this case from the Large Hydro technology, for many of the same reasons mentioned previously, along with the ECF Demand-Focus Scenario from ECF [56] both showing a projection of around 550 TWh of electricity generation, with the latter scenario presenting a more concentrated approach of reduction on the side of the demand from the electricity grid and not the production. Additionally, JRC's High Renewables Scenario [40] is another notable case, with its projection reaching around 500 TWh. As the scenario's name suggests, it stems from the high investment and focuses on renewable energy and its related technologies in this particular future pathway.

In contrast, as can be seen, the large majority of scenarios, however, present very different projections, taking into account the current hydropower trends mentioned before. The remaining 13 scenarios project the value for electricity generation by this technology in 2050 to be between 400 and 440 TWh, suggesting this short increase to be the most likely outcome and keeping up with the trends of the last 10 years for the technology (with a maximum variation of about 20% [48]), with scenarios such as IEEJ's Advanced Technologies projecting only around 25 TWh of growth for the technology in the 30 years.

Looking at Figure 5.6., with only six future pathways developed, there isn't a particular stand out amongst them.

SPE's Leadership Scenario and IEA's Sustainable Development Scenario present values of 900 and 920 TWh of generation, respectively, signaling a substantial growth in the Adoption of the technology, with the former suggesting stabilization of generation in the latter years of the 2040s, after the arrival of Europe at a 100% Renewable point, while the last presents a more sustained growth along the 30 years.

At a medium-range, the two remaining scenarios from IEA's World Energy Outlook 2019 are present, with around 830 TWh for Large Hydro Adoption in 2050, while the remaining SPE scenarios are more modest in terms of growth, reaching 700 TWh, with its Moderate Scenario, in particular, presents the same 100% Renewable target for Europe as the Leadership Scenario, but only in 2050.

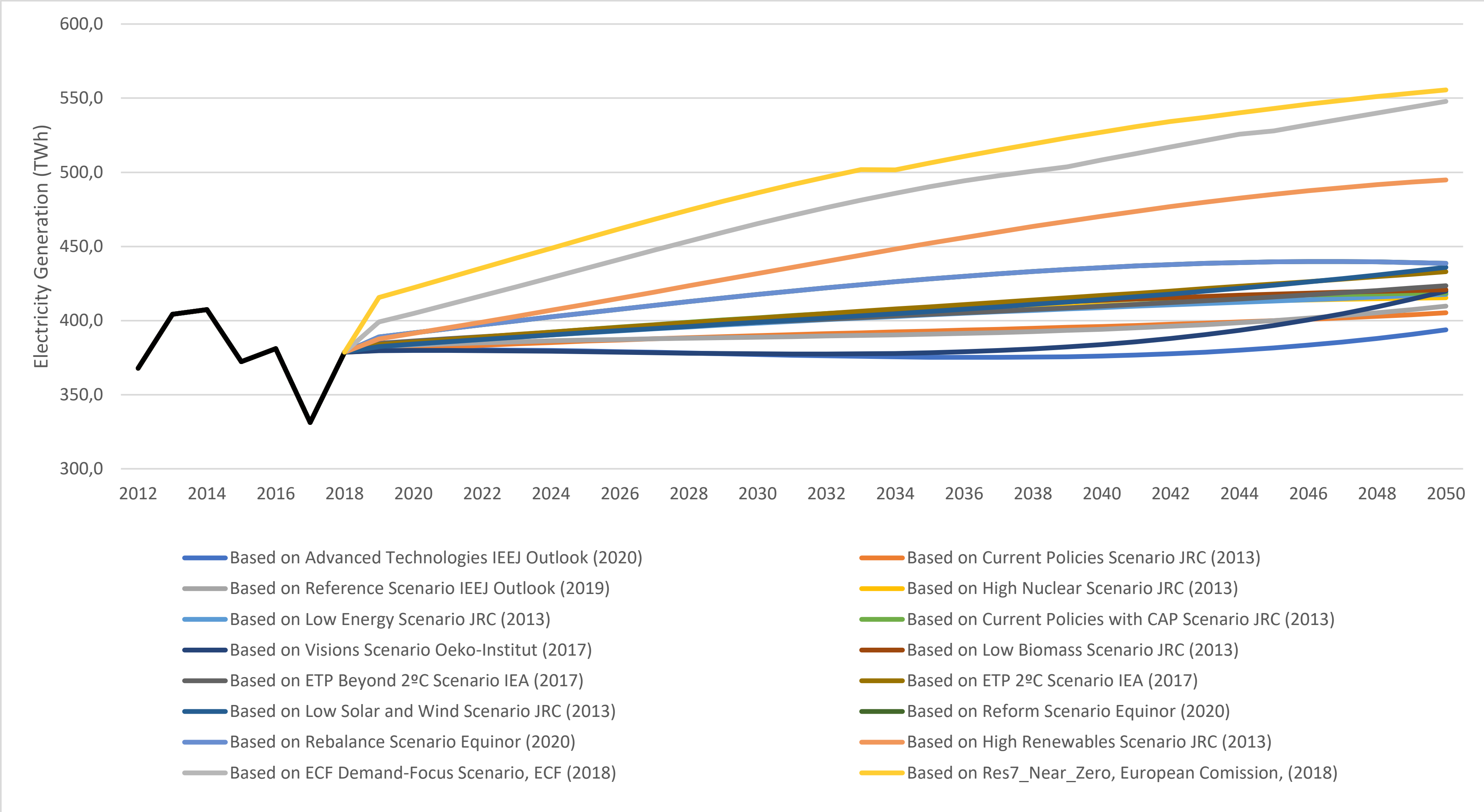


Figure 5.2.5 - Projections for the evolution of LH Adoption in the European Union until 2050.

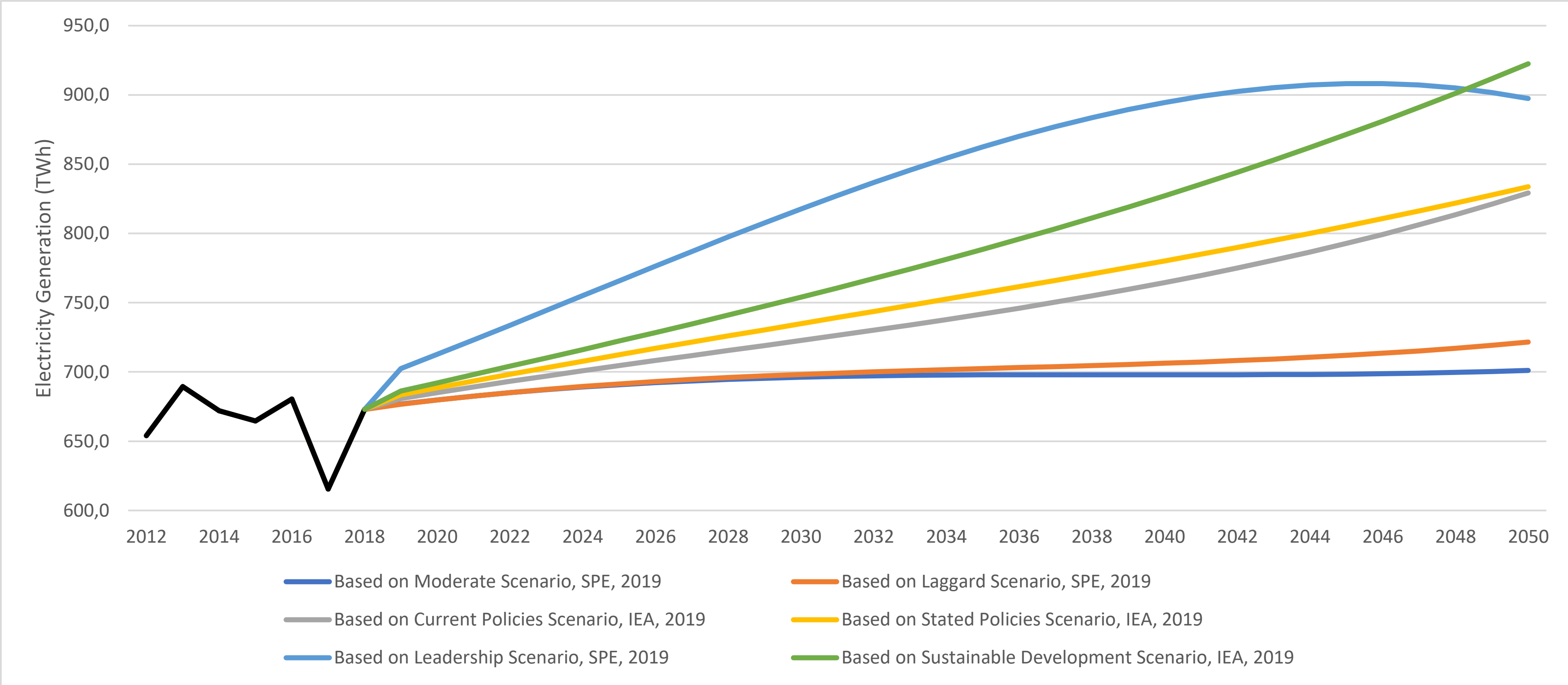
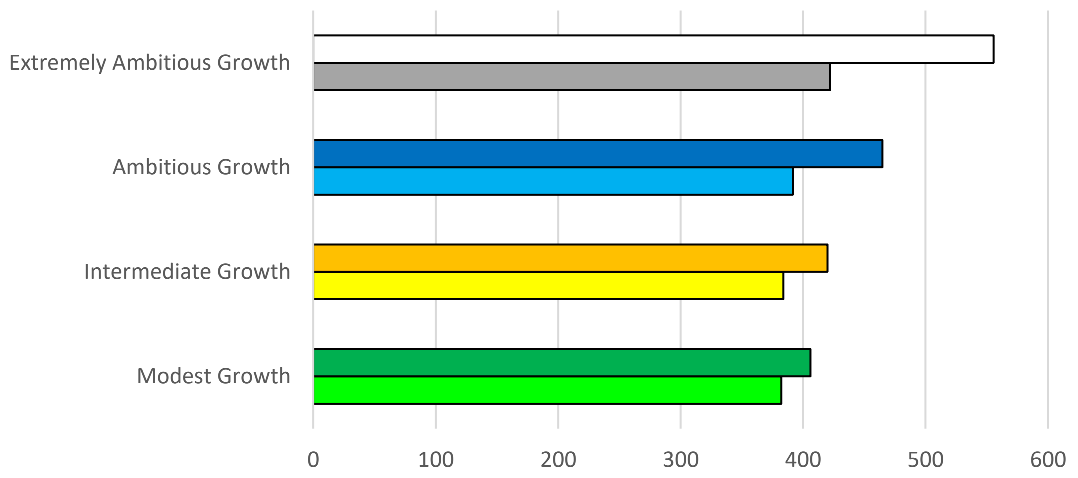


Figure 5.2.6 - Projections for the evolution of Large Hydro Adoption in Europe until 2050.

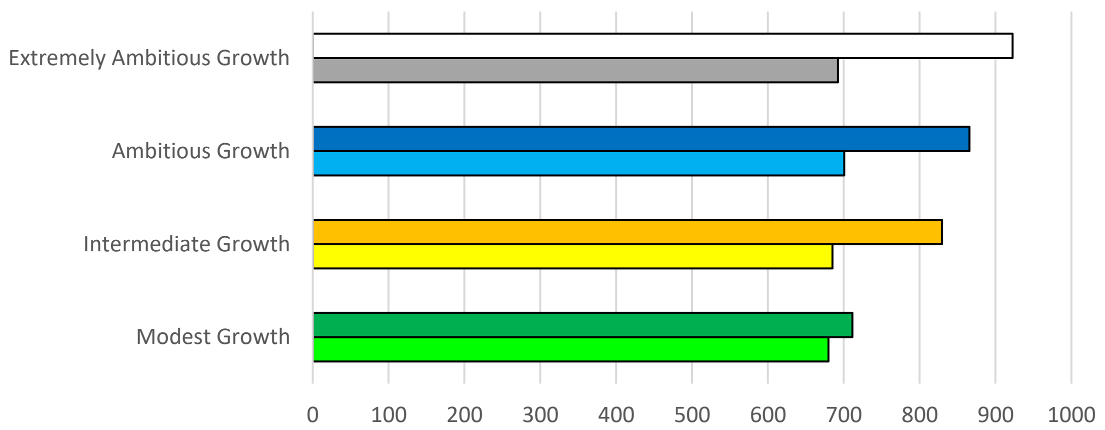
As is clear, much like it is the case for TAM, in terms of Large Hydro Adoption, it is once again expected that these values be considerably higher for Europe compared with the European Union for many of the same reasons.

Additionally, Figure 5.7. and 5.8. show the average of Adoption, both in 2020 and 2050 for each of the four tiers of growth discussed earlier (Modest - green, Intermediate - yellow, Ambitious – blue, and Extremely Ambitious – grey and white).



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050	406	420	465	556
2020	382	384	392	422

Figure 5.2.7 - Evolution of LH Adoption between 2020 and 2050 in each Tier of growth for EU-28.



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050	711	829	866	922
2020	680	685	701	692

Figure 5.2.8 - Evolution of LH Adoption between 2020 and 2050 in each Tier of growth for Europe.

Once again, as opposed to the Adoption values for 2050, in this case, the difference between the regions is minimal in terms of growth, with the biggest one coming in the Intermediate Growth tier, where scenarios regarding the European Union had an average growth of 9% in relation to the 2020 data, while scenarios regarding Europe possessed an average growth of 17% for this tier.

In contrast with the data for TAM, the expected growth for Large Hydropower is relatively small, with only the scenario in the Extremely Ambitious Growth tier showing an increase above 20%, with the Modest Growth tier for European data showing an average increase of only 4%. These numbers clearly show the expected stagnation of Large Hydropower. Many publications consider that the room for the technology to grow and the number of existing facilities to increase is quite small in the region.

5.3. Results from the Interpolation of Small Hydro Adoption Data

One of the first results regarding the analysis of Small Hydro technologies was its historical data. Since it was only available in IRENA's Renewable Energy Statistics until 2015 as opposed to TAM and LH, whose most recent available data pertained to 2018, it was necessary to use interpolations, and one data point from ESHA's Small Hydropower Roadmap in the case of EU-28 data and another from UNIDO's World Small Hydropower Development Report regarding Europe, this historical data that could serve as a base for future projections was built and can be seen in Table 5.2, with the underlined datapoints being the result of interpolation and the data points in italic coming from the two publications mentioned earlier.

Table 5.2 - Historical Electricity Generation Data for Small Hydro Technologies in EU-28 and Europe. [36][50]

	EU-28 Adoption (TWh)	Europe Adoption (TWh)
2012	41,6	52,3
2013	50,5	53,8
2014	52,1	54,8
2015	45,3	57,2
2016	50,1	58,0
2017	51,3	60,0
2018	52,7	61,8
2019	54,4	*63,8*
2020	*56,5*	66,0

With this data, it was then possible to obtain 14 scenarios for the EU-28 data and 6 scenarios for Europe through the methods explained in section 5.2.. The resulting projections are shown in Figure 5.9. and 5.10.

When it comes to the created scenarios for the European Union, on the upper end of scenarios, there's a clear standout, a pathway based on the hypothesis that the technology could grow at double the average growth rate of the historical data period, being close to reaching 400 TWh of generation from Small Hydro technologies. This, however, seems to be unlikely when comparing it with the current Adoption of LH, for example, being around that same value currently.

Except for the scenarios based on the World Energy Council publication [60], the majority of pathways based on the evolution of LH with SH being a percentage of this evolution are at the lower end of results, with the lowest being JRC's Current Policies with CAP Scenario at 58 TWh in 2050, while the rest of these kinds of scenarios never go past the 70 TWh mark. These scenarios, by nature, are very dependent on the initial LH scenario, so if this one only possesses a moderate growth for this technology, these will too.

Lastly, it is worth noting that these scenarios that were created with average, half the average, or double the average of growth rates gave a lower datapoint for 2050 when the scenario was based on the historical capacity of Small Hydropower when compared to the ones based on the historical electricity generation, being 37%, 25% and 55% lower, respectively.

Looking at Figure 5.10., every scenario was created from growth rates of historical values and, taking into account the way these future pathways were constructed, the resulting data points for Adoption in 2050 are what would be expected, with the scenarios projecting that the average growth rate would duplicate giving the highest values for 2050, at around 500 TWh for the pathway based on electricity generation and 330 TWh for the scenario based on the historical capacity of the technology. When looking at the other four scenarios in Figure 5.10., the trend that is present in the EU-28 scenarios also exists in this case, with the scenarios based on historical capacity projecting a lower Adoption of the technology than the ones based on historical generation, with 150 TWh for the former and 170 TWh for the latter in the average growth scenarios, for example.

These scenarios at the higher end of the spectrum, however, seem unlikely, when compared with the generation for Large Hydro technologies today for example, which has a much larger expression in both the EU-28 and Europe and has its most recent historical values between 400-500 TWh, seeming improbable that Small Hydropower reaches this level, even in a 30-year time period.

This method, in contrast with the one used for TAM and LH projections, is largely exploratory with the different scenarios being created for this work specifically and not stemming from data coming from different reports from nationally and internationally recognized institutions and is, therefore, quite susceptible to less likely results when it comes to the projections and a higher level of uncertainty when it comes to the final results of the Small Hydropower technologies overall.

Additionally, Figure 5.11. and 5.12. show the average of adoption in 2020, and 2050 for each of the four tiers of growth discussed earlier (Modest - green, Intermediate - yellow, Ambitious – blue, and Extremely Ambitious – grey and white).

The future pathways projected for the European Union data present a lower growth in all four tiers when compared to Europe's, with the most similar one being the Extremely Ambitious growth tier, with 86% and 87% growth respectively when in contrast with Europe's the 2020 historical data point.

As was mentioned before, at the lower range of scenarios for the EU-28, the pathways based on LH growth show very small increases in generation for 2050, presenting a growth of only 4% in the Moderate tier and about 27% in the Intermediate tier that contains two of these kinds of scenarios, much lower than the 60% increase in the case of Europe data.

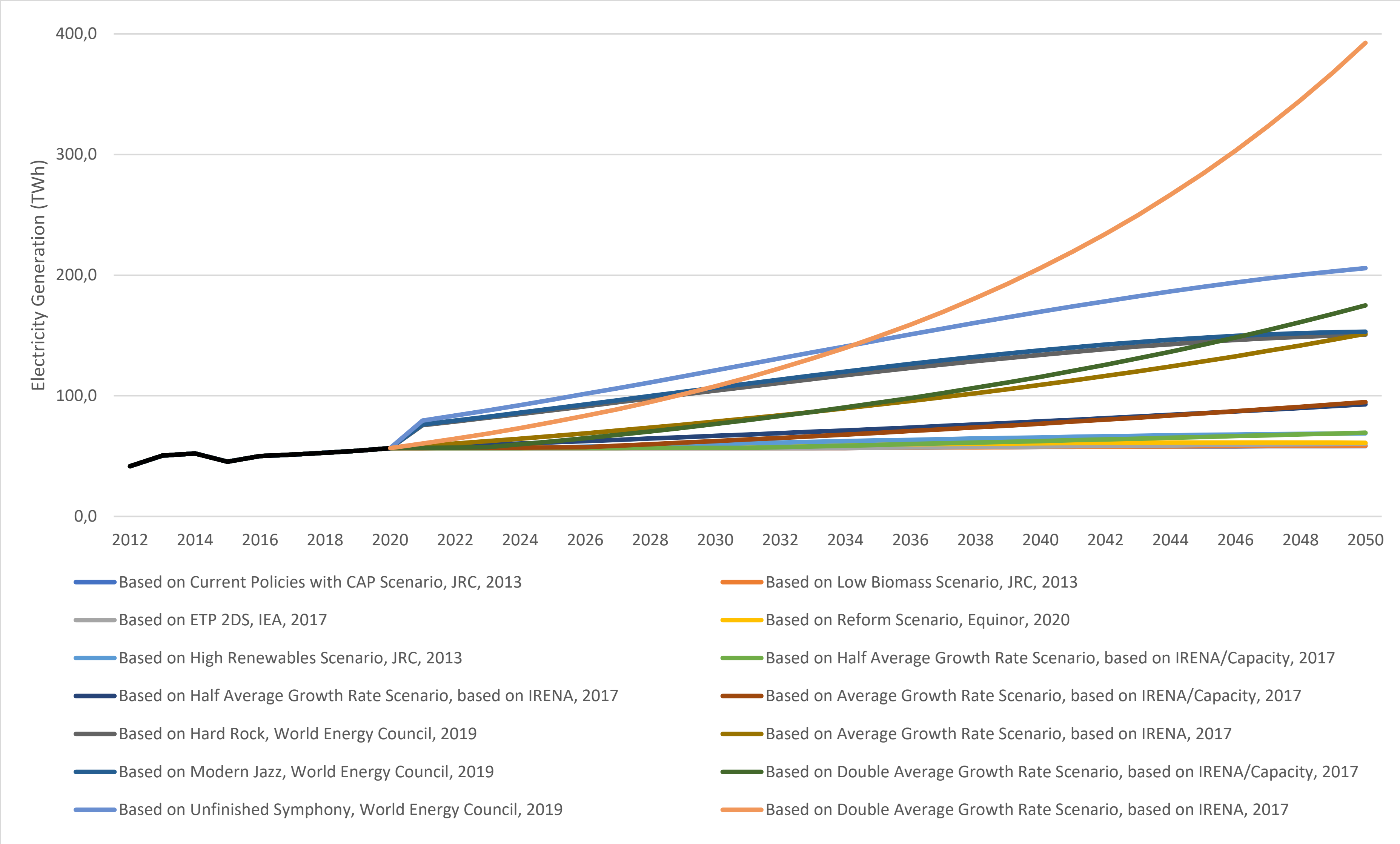


Figure 5.2.9 - Projections for the evolution of Small Hydro Adoption in the EU-28 until 2050.

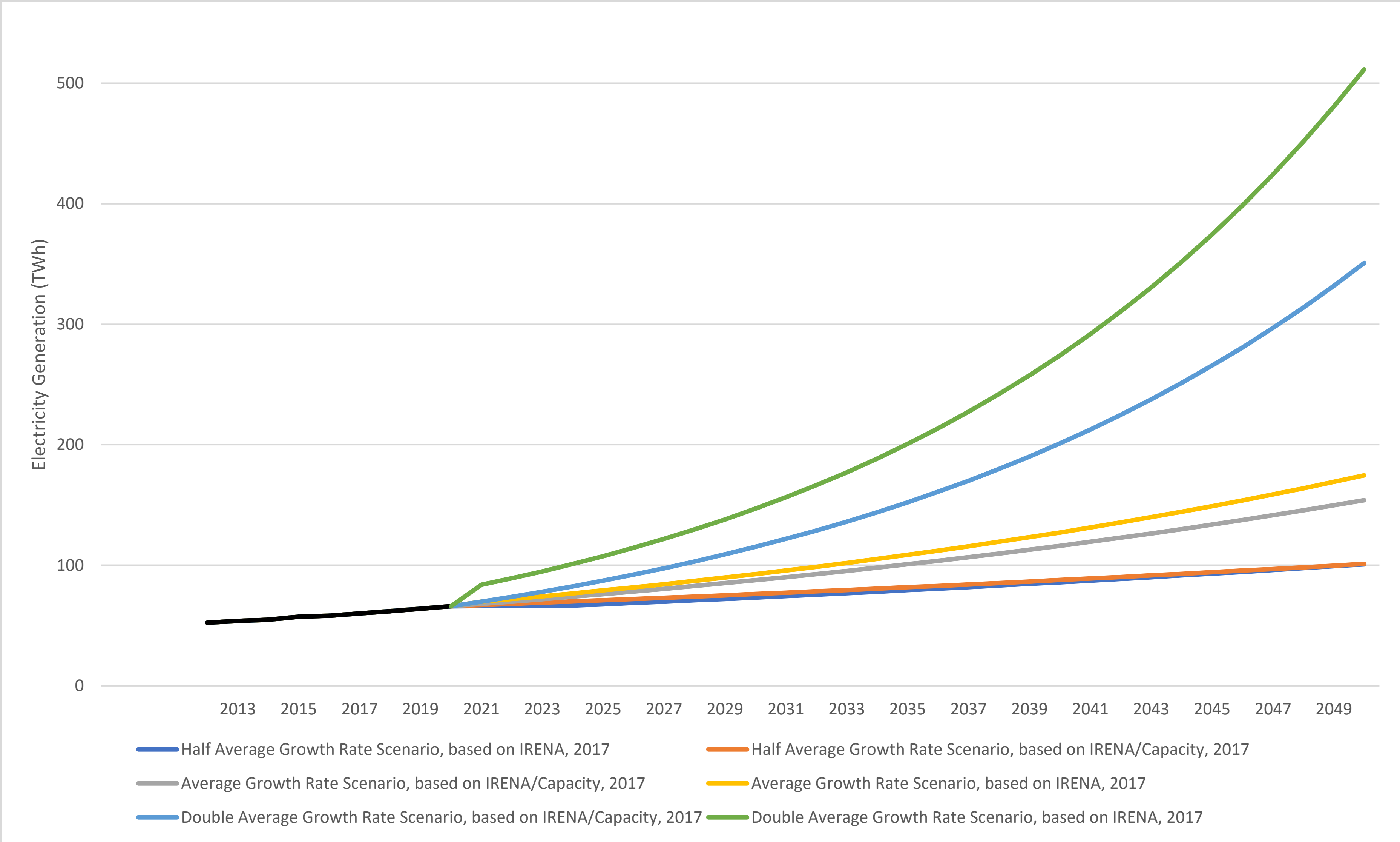
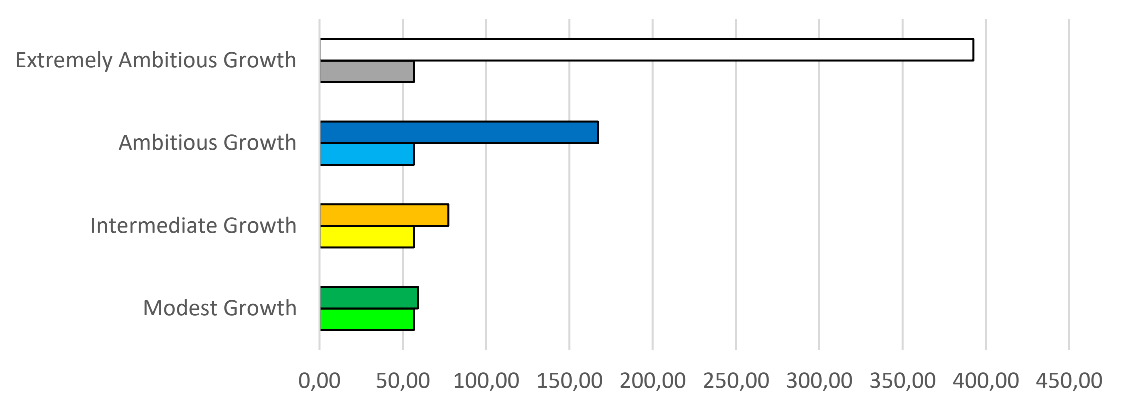
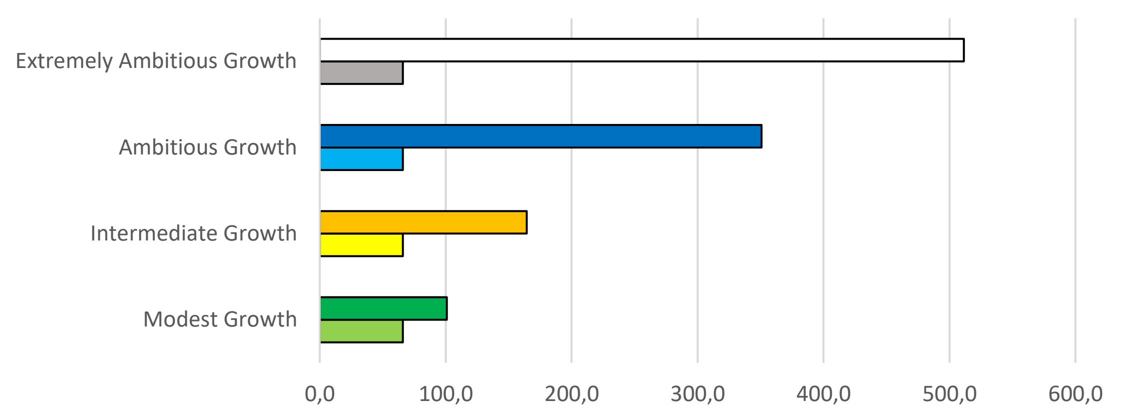


Figure 5.2.10 - Projections for the evolution of Small Hydro Adoption in Europe until 2050.



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050	59,1	77,4	167,2	392,6
2020	56,58	56,58	56,58	56,58

Figure 5.2.11 - Evolution of SH Adoption between 2020 and 2050 in each Tier of growth for the EU-28.



	Modest Growth	Intermediate Growth	Ambitious Growth	Extremely Ambitious Growth
2050	100,9	164,3	350,8	511,4
2020	66,0	66,0	66,0	66,0

Figure 5.2.12 - Evolution of SH Adoption between 2020 and 2050 in each Tier of growth for Europe.

5.4. Variable Meta-Analysis (VMA) Results

Following these results concerning the generation of electricity from the different technologies, as was mentioned in the Methodology chapter, extensive research through several types of reports and papers was done to obtain more technical, financial, environmental, and social data for the different technologies, with this data being compiled and shown in Tables 5.3., 5.4., and 5.5., these show the parameters, units, number of data points for said parameters and the mean value from those said data points, as well as the highest and lowest values collected. In the event of this value being zero, that particular cell of the table was left null. It is also worth pointing out that the distinction between Europe and the European Union in this phase of the work was not accounted for, as it was considered that this type of data could change significantly from continent to continent (which is the reasoning behind the exclusion of data outside of Europe that was explained in section 4.2.5) but this variation between the Europe and EU-28 with being lesser so.

Table 5.3 - Variable Meta-Analysis Input Data for Conventional Technologies

VMA Parameter	Unit	Data-points	Mean Value	High Value	Low Value
First Cost per Implementation Unit	€2020/kW	33	1468	2634	303
Lifetime Capacity	hours	29	153126	187278	118974
Average Annual Use	hours/year	26	4536	6358	2715
Variable Operating and Maintenance Cost (VOM)	€2020/kWh	17	0,003	0,003	0,003
Fixed Operating and Maintenance Cost (FOM)	€2020/kW	24	38,4	59,4	17,5
Fuel Costs	€2020/kWh	57	0,020	0,028	0,011

A particularity of the data for conventional technologies, seen in Table 5.3., is that since the term "conventional technologies" encompasses more than one technology (in this case being considered coal, natural gas, and oil), the data were subjected to weighting process where to each of these technologies, their current weight in the European power mix was assigned, factoring in the calculations made by the model that produce these final results.

Additionally, it is worth pointing out that the financial values (First Cost, VOM, and FOM) were all used in the RRS model with the model's standard units, US$2014 and were then converted for this work into €2020, which makes them more applicable to the region.

When it comes to Table 5.4. and 5.5. it was also gathered data regarding direct and indirect greenhouse gases emissions – as the aim is to evaluate the possibility of replacing the conventional technologies with hydropower to reduce these emissions – as well as the number of jobs that could be created and the number of specific materials that would be needed if the potential of hydropower was fulfilled in the region.

This type of data is, however, scarce. In the case of GHG emissions, there is some available, as seen by the number of data points for this parameter in Tables 5.4. and 5.5. but presents the difficulty of not always distinguishing between large and small hydropower, hence the reason for a low number of data points. In the case of potential jobs and use of materials from the explored sources, this distinction was never present. It was always presented as either "large hydropower" or "hydropower," which were all considered to be regarding this technology, explaining why Table 5.5. does not feature this kind of data.

Table 5.4 - Variable Meta-Analysis Input Data for Large Hydro Technologies.

VMA Parameter	Unit	Datapoints	Mean Value	High Value	Low Value
First Cost per Implementation Unit	€2020/kW	22	2905	4491	1318
Lifetime Capacity	hours	12	240709	270704	210715
Average Annual Use	hours/year	9	4156	6175	2138
Variable Operating and Maintenance Cost (VOM)	€2020/kWh	14	0,002	0,004	0,001
Fixed Operating and Maintenance Cost (FOM)	€2020/kW	19	24,5	45,3	3,7
Direct Emissions	t $CO_{2\text{-}eq}$/TWh	13	10431	21674	-
Indirect Emissions	t $CO_{2\text{-}eq}$/TWh	12	8568	16000	1137
Jobs	Jobs/MW	28	4,2	6,7	1,7
Water Use	dam^3/TWh	30	166861	718227	-
Iron Use	ton/TWh	3	2667	4423	911
Cement Use	ton/TWh	6	1183	1695	672
Copper Use	ton/TWh	1	500,0	-	-
Aluminum Use	ton/TWh	4	68	113	22

Table 5.5 - Variable Meta-Analysis Input Data for Small Hydro Technologies.

VMA Parameter	Unit	Data-points	Mean Value	High Value	Low Value
First Cost per Implementation Unit	€2020/kW	81	4126	6673	1578
Lifetime Capacity	hours	17	160401	224526	4586
Average Annual Use	hours/year	22	3171	96277	1756
Variable Operating and Maintenance Cost (VOM)	€2020/kWh	8	0,065	0,116	0,013
Fixed Operating and Maintenance Cost (FOM)	€2020/kW	38	183,2	387,0	-
Direct Emissions	t $CO_{2\text{-}eq}$ /TWh	10	13560	24579	2541
Indirect Emissions	t $CO_{2\text{-}eq}$ /TWh	31	21303	59360	-

From the data on these tables, only the mean values were used for the runs of the Drawdown model, which will be explained further on. In contrast, for the sensitivity analysis portion of this work, the mean values will be replaced by the high and low ones in order to assess how this change can impact the results.

In a brief analysis of these tables, it is clear that First Cost per Implementation Unit is the most common among the parameters, with the highest number of data points. At the same time, Variable Operating and Maintenance costs (VOM) have the lowest number of data points (except for the parameters exclusive to LH technologies).

5.5. Project Drawdown RRS Model Runs Results

The next set of results is the one obtained from running the Drawdown model for each of the scenarios inserted in it regarding the European Union data, as well as the average of each of the tiers of Adoption, for both technologies, with 19 runs from the Large Hydro model (16 from scenarios and 3 from the average of tiers) and 17 runs from the Small Hydro model (14 from scenarios and 3 from the average of tiers). The results presented in this section will focus on the Financial and Emissions indicators since the Adoption results were already mentioned previously.

5.5.1. Large Hydropower Solution

As shown in Figure 5.13., the cumulative emissions reduction for the three-decade-period throughout the various scenarios of LH Adoption is below 2,5 Gt of CO_2eq in the majority of cases, with only the two most ambitious scenarios as well as the average of the Ambitious and Extremely Ambitious tiers surpassing this mark, the total range and variability of these results being presented in Figure 5.15. with the first being 1,6-3,7 Gt of CO_2eq and showing an average value of 2,2 Gt of CO_2eq.

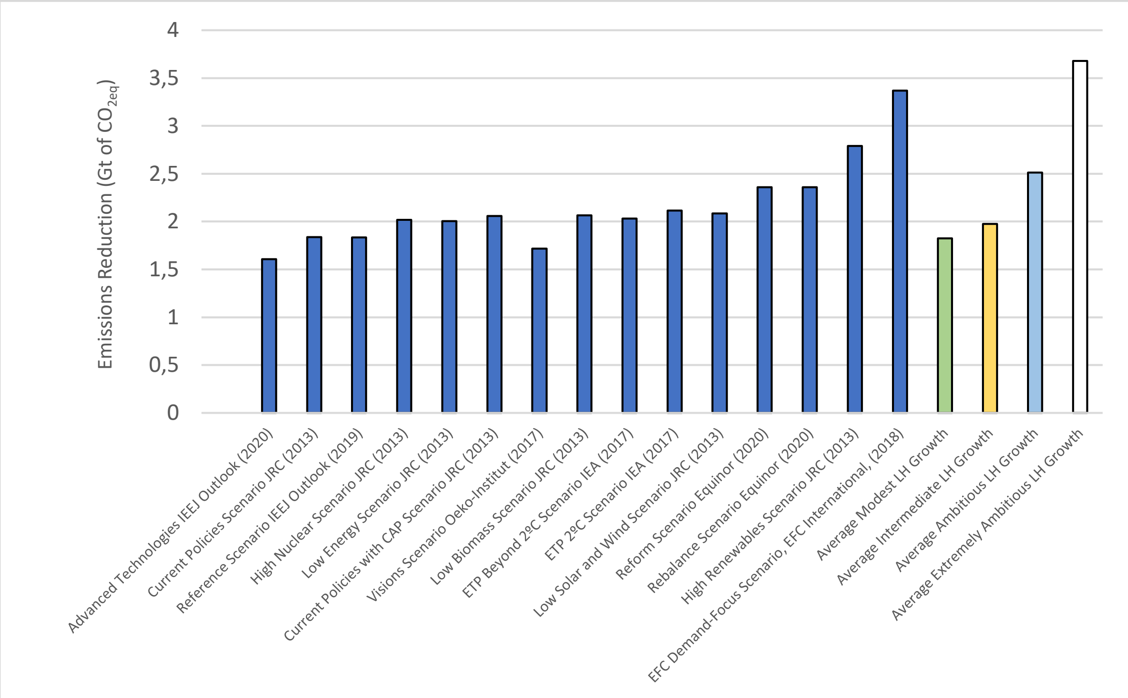


Figure 5.5.1 - Total Emissions Reduction by 2050 via LH (Gt of CO2eq).

On the economic side of things, as per Figure 5.14., the savings during the lifetime of the hydropower plants are projected to be, in the majority of scenarios, around 250 billion € over the 30 years in study, with this number reaching close to 400 billion € in the Extremely Ambitious Scenario. Once again, as can be seen in Figure 5.15., the average of savings for these scenarios is close to 200 billion €. In comparison, the range is between 200-380 billion €, with JRC's High Renewables Scenario, EFC's Demand-Focus Scenario, and the Extremely Ambitious Scenario being considerable outliers as per the rest of the results, as well as with the Total Emissions Reduction when it comes to the two latter scenarios.

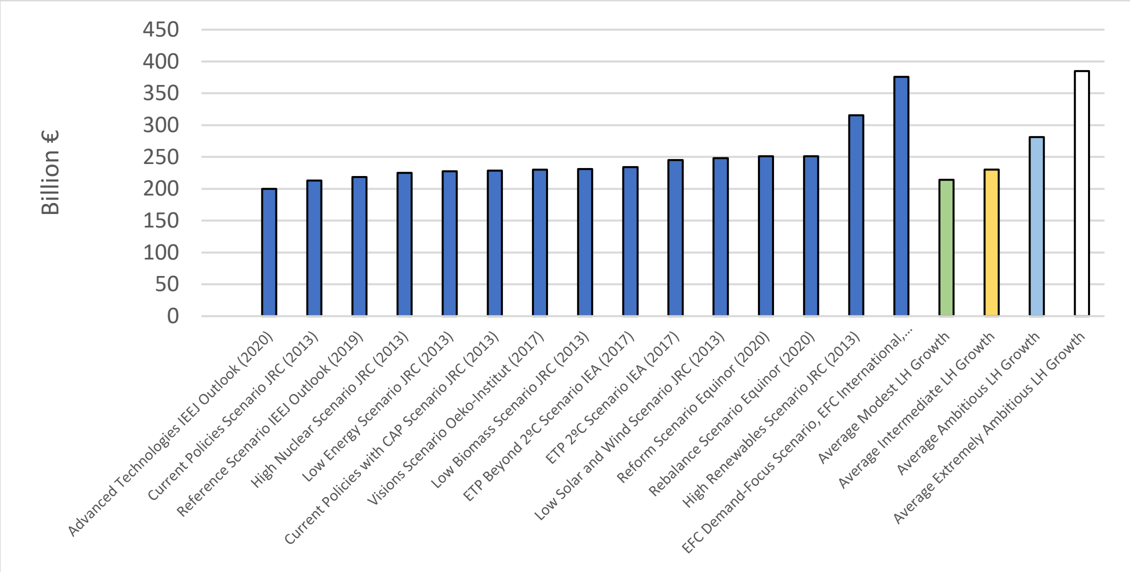


Figure 5.5.2 - Lifetime Operating Savings via LH (Gt CO2eq).

These scenarios existing as outliers could be prevented by selecting more ambitious pathways for the 16 chosen scenarios that feature in the model. However, this aspect stems from the methodology itself, with selecting conservative and ambitious scenarios from various publications to ensure a lack of bias in these pathways. Therefore, the presence of these outliers is an inevitable consequence and will feature in most cases.

In figure 5.15. other results for the LH technology are shown, such as Average Abatement Cost and Cumulative First Cost for these exact scenarios. This first indicator represents the cost of reducing environmental negatives, bridging the gap between financial and environmental results, being a useful tool to assess the potential for a possibly environmental-friendly technology in economic terms. The latter can be seen as a level of investment needed for the technology to keep up with the projected Adoptions in each scenario.

When it comes to Abatement Cost, the projected numbers for the technology in the EU-28 are all negative, with an average of around 7,5 USD/t of CO_2eq, representing an average net saving and showing the possibility of earning money while reducing the emissions through Large Hydropower projects.

Regarding Cumulative First Cost, the results show an average of about 82 Billion € which, compared with the projected investments for solar technologies, for instance [16] is quite a low number and illustrates once again the trends of projected low investment and evolution in the technology.

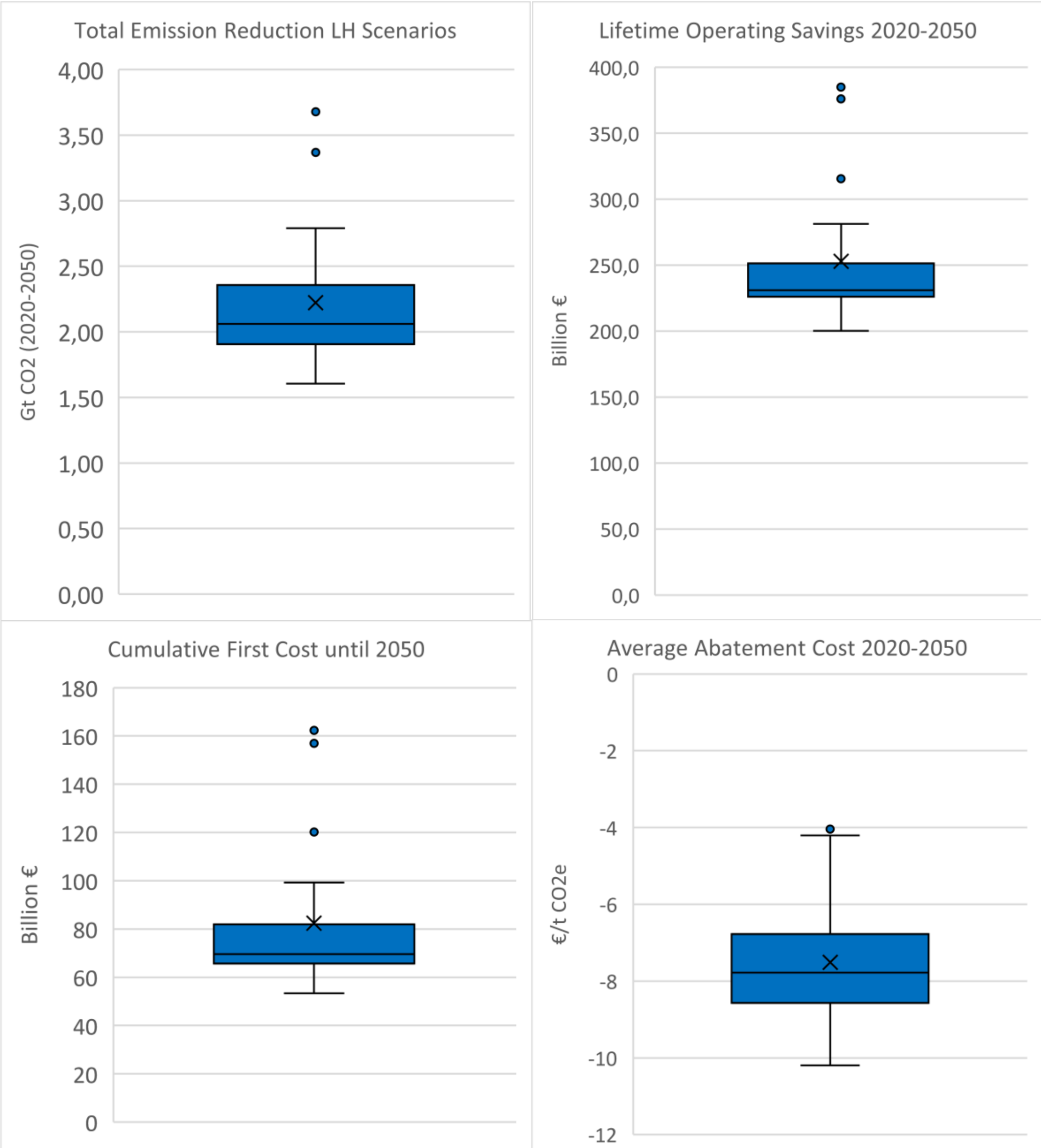


Figure 5.5.3 - LH range of Financial and Emission results in detail.

5.5.2. Small Hydropower Solution

In Figure 5.16., the results for emission reductions of the Small Hydropower technology are shown. These results show several differences when compared with the LH ones.

Firstly, the less ambitious scenario does not project a reduction of emissions, but instead a growth in GHG emissions, although a number very close to zero, about 0,3 Mt of CO_2eq, something that does not happen in any scenario for the other technology analyzed.

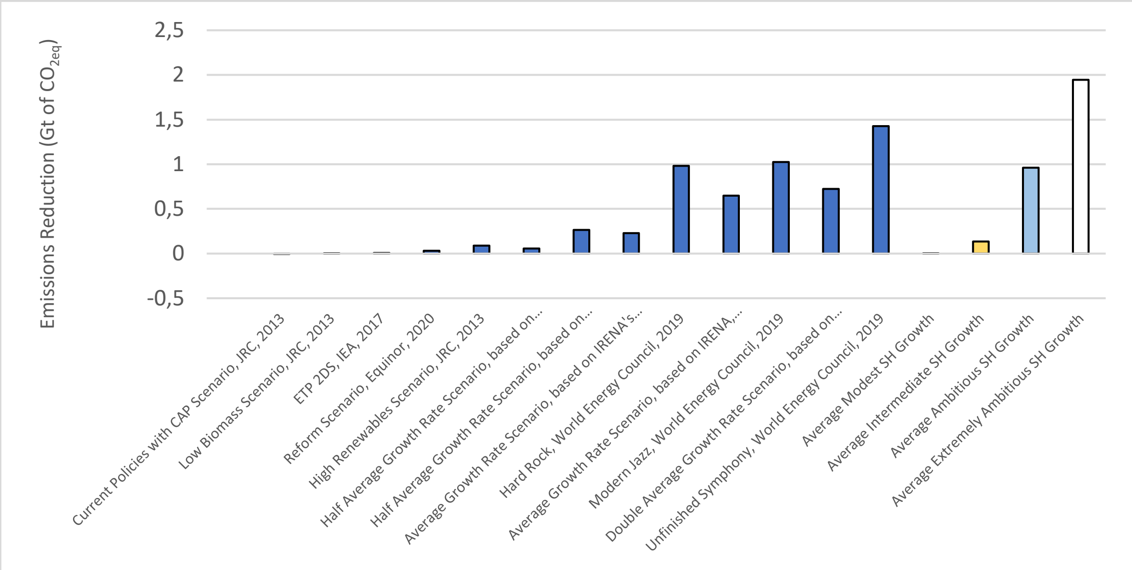


Figure 5.5.4 - Total Emissions Reduction by 2050 via SH (Gt CO2eq).

Secondly, most scenarios present an amount of emission reduction under 1 Gt of CO_2eq, with an average of 0,5 Gt of CO_2eq and a range of 0-1,9 Gt of CO_2eq, as can be seen in more detail in Figure 5.18.

Lastly, it is worth pointing out that even the most ambitious of scenarios, the pathway in the Extremely Ambitious Scenario tier, presents reductions that are inferior to LH's, with a maximum of reduction just shy of 2 Gt of CO_2eq for the Small Hydropower technology, with three of the 17 scenarios hovering around the 1 Gt of CO_2eq mark.

On the financial side of things, as can be seen in Figure 5.17. as opposed to the situation in the LH technology, the Lifetime Operating Savings via Small Hydropower

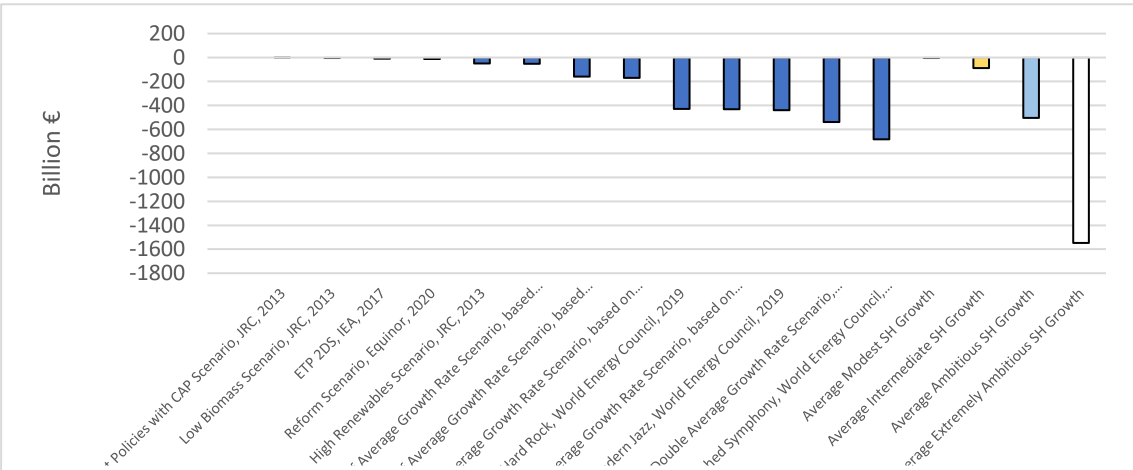


Figure 5.5.5 - Lifetime Operating Savings via SH (Gt of CO2eq).

present, in fact, negative values for this parameter, with the majority of scenarios representing a net cost under 200 billion €, with a considerable number of scenarios showing an, even more, severe cost, stemming undoubtedly from the investment and maintenance costs of the technology, as seen Table 5.5. earlier.

Figure 5.17. shows the average of this parameter to be a net cost just shy of 240 billion €, while in Figure 5.18. it can be seen that the Extremely Ambitious Growth Scenario presents itself as an outlier, placing itself very far off the range of the rest of the obtained results.

Staying with Figure 5.18, the format remains, and two other indicators are shown for this technology, Average Abatement Cost and Cumulative First Cost of SH, in the 30-year-period and until 2050, respectively.

In the first case, as opposed to LH, once again, this parameter averages a value of 34 €/t of CO_2eq, representing an average net cost and a net cost in every scenario, since even the lowest outlier of the data shows a number of 13 €/t of CO_2eq, meaning that the reduction of emissions through Small Hydropower projects will need a considerable amount of investment.

Secondly, the Cumulative First Cost results show an average of about 92 billion €, suggesting a need for bigger investment to make this technology viable, especially when in comparison with the LH technology, have a much shorter range of 53-162 billion, a stark contrast with the much larger range for SH at around 16-390 billion €. These numbers all result from the assumptions stated earlier and the comparison with indicators shown earlier for conventional technologies, such as fuel or first costs.

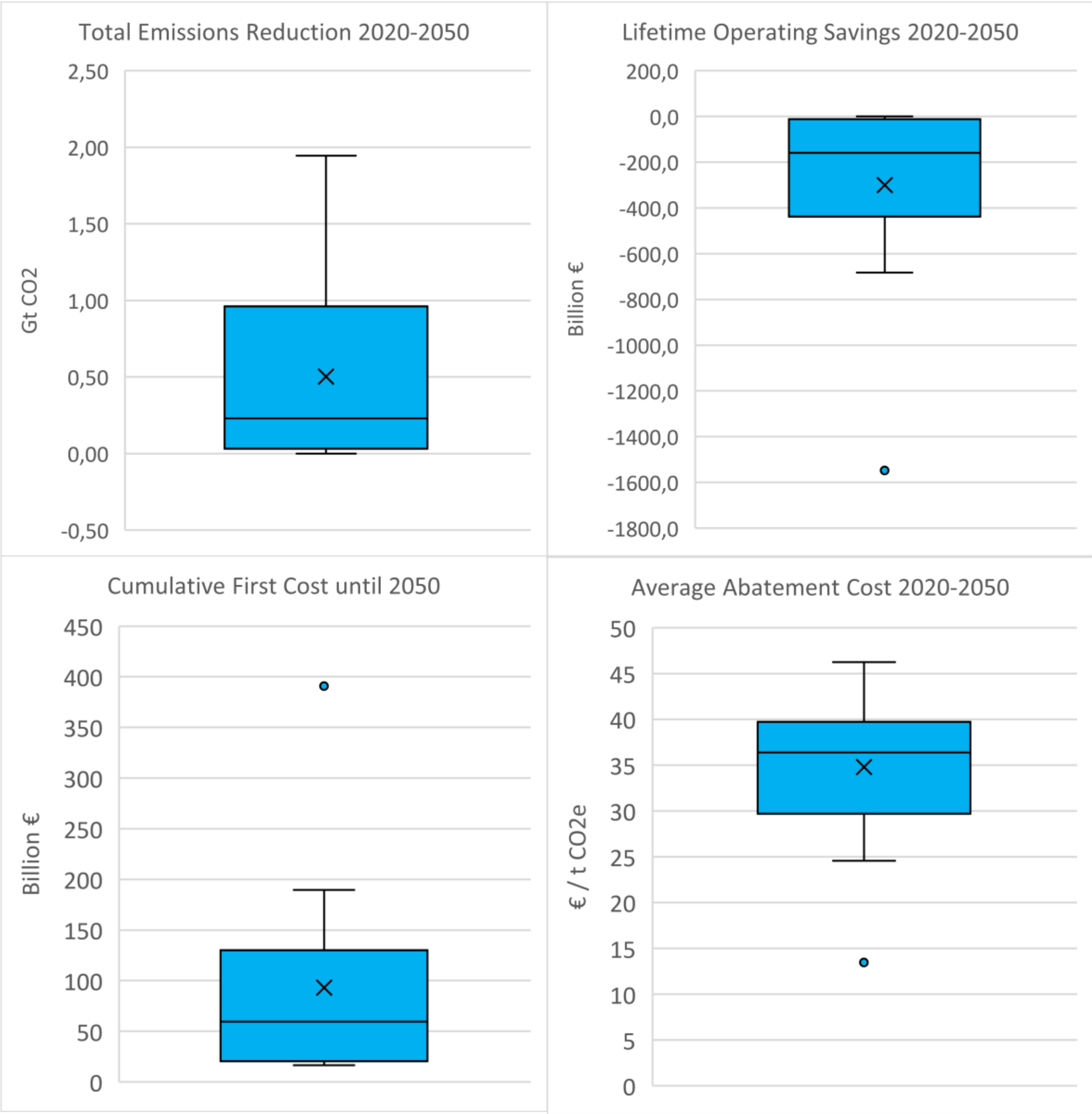


Figure 5.5.6 - SH range of Financial and Emission results in detail.

5.6. Sensitivity Analysis Results

In this section of the work, the results from the Sensitivity Analysis will be presented. In the previous section, the results shown stemmed from the main runs of the Drawdown model, where the parameters of VMA were used with their mean values in every situation. In this section, this will be changed with each of the parameters being altered one at a time (i.e., ceteris paribus) to its high and low values to assess the impact that the change of each parameter, in particular, has on the final financial, environmental and social (in the case of jobs created) results.

For this phase of analysis, not every scenario will be used, but instead, the average of Adoption of the Modest and Ambitious tiers will be in place, also referred here as AMT (Average Modest Tier) and AAT (Average Ambitious Tier), as these are considered the most realistic scenarios for the future

The parameters that feature in this analysis are the following: First Cost per Implementation Unit, Lifetime Capacity, Fixed Operating Cost (FOM), Direct Emissions, Indirect Emissions, Jobs Created, Water Use, and in the specific case of LH, Iron, Cement, Copper, and Aluminium Use. It is worth noting that the Variable Operating Cost (VOM) and Average Annual Use parameters were not analyzed as they are not independent indicators, usually depending on FOM or First Cost and Lifetime Capacity, respectively. All these parameters are featured in Tables 5.3., 5.4. and 5.5.

Before presenting these results, it is worth highlighting one shortcoming of this method. Even though it is methodologically sound, it produces some combinations that may be unlikely in practice, such as a low value for First Cost per Implementation Unit with a Moderate Adoption of technology.

These results are divided amongst Figure 5.19., Table 5.5., Figure 5.20. and Table 5.6, with the first three referring to LH and the latter one referring to SH. Figures 5.19. and 5.20. follow the same formatting, with the first column showing the Run that is being performed (AMT Runs using Average Modest Tier of Adoption and AAT using Average Ambitious Tier of Adoption, as explained previously), followed by a description of that particular run. For example, "AMT Run 5" simply means that the Adoption chosen for this run of the model was the Average of Modest Tier EU Scenarios and the parameter that is being altered.

In contrast, all others remain the same is "FOM MAX", meaning that the chosen data for the Fixed Operating Cost was its maximum value. The remaining columns show the four indicators analyzed previously: Total Emissions Reduction, Lifetime Operating Savings, Cumulative First Cost, and Average Abatement Cost, each one with its particular variation after the one change when compared to the same scenario with every parameter at an average value. In these tables, the variation is highlighted in green if positive and red if negative.

Additionally, Tables 5.6.1 and 5.6.2 show the impact of changing the value from average to high or low, but for the VMA parameters exclusively studied for the LH technologies, such as Jobs Created and Water and Materials used. The first column shows the parameter being altered, followed by its average, high and low values. The third column presents the capacity of Large Hydropower added in this Modest Scenario (necessary for the final jobs created calculation). The fourth features the Electricity Generation added from this technology along these 30 years being studied (necessary for the final material use calculation). In contrast, the last two columns show the projected numbers for these parameters and their respective units.

Looking at Figures 5.19. and 5.20., for Total Emissions Reduction, it is clear that the only variations that cause a change on this result are the ones in the Direct and Indirect Emissions parameters, with the maximum and minimum values causing symmetrical variations in the result, except for SH's "AAT Run 10". However, this change causes slight variations in the final result, with the maximum being a variation of +7% and a minimum of -7% in SH's "AMT Run 9" and "AMT Run 10".

In the case of Lifetime Operating Savings, the most significant changes happen will the Lifetime and FOM parameters are altered, with the latter causing a symmetrical variation of 25% in the numbers for Large Hydropower and 68% when it comes to Small Hydropower, with the Lifetime parameter causing lesser variations, but still considerable, especially in the case of SH with a 40% variation.

As could be expected, Cumulative First Cost is impacted mainly by the changes in the First Cost per Implementation Unit parameter, with the variations being around 55% and 62% for each technology.

The case of Average Abatement Cost stands out from the remaining parameters; with it being used as a bridge between the Financial and Environmental spheres of the problem, it is affected by changes in every parameter in, at least, one of the runs. The parameters that show the biggest variation, however, are First Cost and FOM, with a maximum percent change of 41% in LH's "AAT Run 1" and "AAT Run 2" and SH's "AMT Run 1" and "AMT Run 2" with 56%.

When it comes to Tables 5.6.1, and 5.6.2., one can see that the biggest change when choosing an Average of Ambitious Scenarios instead of Moderate ones if felt in the Jobs Created parameter, with the final number more than doubling in the case of using the average, lowest or highest level of the parameter, going up to a maximum of a possible 118 thousand Jobs and a minimum of 11 thousand.

Large Hydropower		Gt CO2 (2020-2050)	%	Billion USD	%	Billion USD	%	USD/t CO2eq	%
Sensitivity Analysis Round	Round Description	Total Emissions Reduction	Total Emissions Reduction Variation	Lifetime Operating Savings 2020-2050 (Billion l)	Lifetime Operating Savings 2020-2050 Variation	Cumulative First Cost until 2050 (Billion l)	Cumulative First Cost until 2050 Variation	Average Abatement Cost 2020-2050 (l / t	Average Abatement Cost
AMT Run	AMT Run	1,824	0%	214,162	0%	58,362	0%	-9,126	0%
AMT Run 1	First Cost MAX	1,824	0%	214,162	0%	90,248	55%	-8,189	-10%
AMT Run 2	First Cost MIN	1,824	0%	214,162	0%	26,475	-55%	-10,063	10%
AMT Run 3	Lifetime MAX	1,824	0%	240,849	12%	58,362	0%	-9,126	0%
AMT Run 4	Lifetime MIN	1,824	0%	187,476	-12%	58,362	0%	-9,126	0%
AMT Run 5	FOM MAX	1,824	0%	159,732	-25%	58,362	0%	-7,959	-13%
AMT Run 6	FOM MIN	1,824	0%	268,592	25%	58,362	0%	-10,292	13%
AMT Run 7	Direct Emissions MAX	1,787	-2%	214,162	0%	58,362	0%	-9,316	2%
AMT Run 8	Direct Emissions MIN	1,862	2%	214,162	0%	58,362	0%	-8,943	-2%
AMT Run 9	Indirect Emissions MAX	1,800	-1%	214,162	0%	58,362	0%	-9,251	1%
AMT Run 10	Indirect Emissions MIN	1,849	1%	214,162	0%	58,362	0%	-9,004	-1%
AAT Run	AMT Run	2,512	0%	281,277	0%	99,304	0%	-6,060	0%
AAT Run 1	First Cost MAX	2,512	0%	281,277	0%	153,559	55%	-3,430	-43%
AAT Run 2	First Cost MIN	2,512	0%	281,277	0%	45,049	-55%	-8,690	43%
AAT Run 3	Lifetime MAX	2,512	0%	316,326	12%	99,304	0%	-6,060	0%
AAT Run 4	Lifetime MIN	2,512	0%	246,228	-12%	99,304	0%	-6,060	0%
AAT Run 5	FOM MAX	2,512	0%	209,789	-25%	99,304	0%	-4,871	-20%
AAT Run 6	FOM MIN	2,512	0%	352,764	25%	99,304	0%	-7,250	20%
AAT Run 7	Direct Emissions MAX	2,461	-2%	281,277	0%	99,304	0%	-6,187	2%
AAT Run 8	Direct Emissions MIN	2,564	2%	281,277	0%	99,304	0%	-5,939	-2%
AAT Run 9	Indirect Emissions MAX	2,478	-1%	281,277	0%	99,304	0%	-6,143	1%
AAT Run 10	Indirect Emissions MIN	2,546	1%	281,277	0%	99,304	0%	-5,979	-1%

Figure 5.6.1 - Results of Sensitivity Analysis rounds for LH. Reference for comparison are Average Moderate Tier and Average Ambitious Tier. Each round had only one single parameter changed.

Table 5.6.1 - Results of Sensitivity Analysis rounds for LH and its Jobs Created and Materials Use parameters using an Average of Modest Tier of Adoption.

LH EU Model						
Input	Level		Capacity added 2018-2050 (TW)	Electricity Generation added 2018-2050 (TWh)	Total Amount of Input	Final Units
Jobs (Jobs/MW)	Mean	4	0,007	-	27	Thousand Jobs
	High	7			44	
	Low	2			11	
Water Use (dam^3/TWh)	Mean	166862	-	12918	2156	km^3
	High	718228			9278	
	Low	170			2	
Iron Use (ton/TWh)	Mean	2667	-	12918	34450	kton
	High	4423			57134	
	Low	911			11765	
Cement Use (ton/TWh)	Mean	1183	-	12918	15287	kton
	High	1695			21895	
	Low	672			8679	
Copper Use (ton/TWh)	Mean	500	-	12918	6459	kton
Aluminum Use (ton/TWh)	Mean	68	-	12918	872	kton
	High	113			1463	
	Low	22			281	

Table 5.6.2 - Results of Sensitivity Analysis rounds for LH and its Jobs Created and Materials Use parameters using an Average of Ambitious Tier of Adoption.

LH EU Model						
Input	**Level**		**Capacity added 2018-2050 (TW)**	**Electricity Generation added 2018-2050 (TWh)**	**Total Amount of Input**	**Final Units**
Jobs (Jobs/MW)	Mean	4	0,02	-	74	Thousand Jobs
	High	7			118	
	Low	2			30	
Water Use (dam^3/TWh)	Mean	166861	-	14176	2365	km^3
	High	718228			10181	
	Low	170			2	
Iron Use (ton/TWh)	Mean	2667	-	14176	37803	kton
	High	4423			62696	
	Low	911			12910	
Cement Use (ton/TWh)	Mean	1183	-	14176	16775	kton
	High	1695			24027	
	Low	672			9523	
Copper Use (ton/TWh)	Mean	500	-	14176	7088	kton
Aluminum Use (ton/TWh)	Mean	678	-	14176	956	kton
	High	113			1605	
	Low	22			308	

Small Hydropower		Gt CO2 (2020-2050)	%	Billion USD	%	Billion USD	%	USD/t CO2eq	%
Sensitivity Analysis Round	Round Description	Total Emissions Reduction	Total Emissions Reduction Variation	Lifetime Operating Savings 2020-2050 (Billion I)	Lifetime Operating Savings 2020-2050 Variation	Cumulative First Cost until 2050 (Billion I)	Cumulative First Cost until 2050 Variation	Average Abatement Cost 2020-2050 (I / t	Average Abatement Cost
AMT Run	AMT Run	0,002	0%	-2,958	0%	17,578	0%	24,550	0%
AMT Run 1	First Cost MAX	0,002	0%	-2,958	0%	28,431	62%	38,398	56%
AMT Run 2	First Cost MIN	0,002	0%	-2,958	0%	6,725	-62%	10,702	-56%
AMT Run 3	Lifetime MAX	0,002	0%	-4,141	40%	17,578	0%	24,550	0%
AMT Run 4	Lifetime MIN	0,002	0%	-1,776	-40%	29,109	66%	24,362	-1%
AMT Run 5	FOM MAX	0,002	0%	-4,972	68%	17,578	0%	30,797	25%
AMT Run 6	FOM MIN	0,002	0%	-0,945	-68%	17,578	0%	18,303	-25%
AMT Run 7	Direct Emissions MAX	0,002	-2%	-2,958	0%	17,578	0%	25,071	2%
AMT Run 8	Direct Emissions MIN	0,002	2%	-2,958	0%	17,578	0%	24,050	-2%
AMT Run 9	Indirect Emissions MAX	0,002	-7%	-2,958	0%	17,578	0%	26,449	8%
AMT Run 10	Indirect Emissions MIN	0,002	7%	-2,958	0%	17,578	0%	22,905	-7%
AAT Run	AMT Run	1,030	0%	-519,570	0%	146,314	0%	39,800	0%
AAT Run 1	First Cost MAX	1,030	0%	-519,570	0%	236,655	62%	60,476	52%
AAT Run 2	First Cost MIN	1,030	0%	-519,570	0%	55,974	-62%	24,804	-38%
AAT Run 3	Lifetime MAX	1,030	0%	-727,281	40%	146,314	0%	42,640	7%
AAT Run 4	Lifetime MIN	1,030	0%	-311,859	-40%	156,750	7%	42,590	7%
AAT Run 5	FOM MAX	1,030	0%	-873,210	68%	146,314	0%	57,223	44%
AAT Run 6	FOM MIN	1,030	0%	-165,930	-68%	146,314	0%	28,056	-30%
AAT Run 7	Direct Emissions MAX	1,010	-2%	-519,570	0%	146,314	0%	43,539	9%
AAT Run 8	Direct Emissions MIN	1,050	2%	-519,570	0%	146,314	0%	41,777	5%
AAT Run 9	Indirect Emissions MAX	0,893	-13%	-519,570	0%	146,314	0%	45,916	15%
AAT Run 10	Indirect Emissions MIN	1,030	0%	-519,570	0%	146,314	0%	39,800	0%

Figure 5.6.2 - Results of Sensitivity Analysis rounds for SH. Reference for comparison are Average Moderate Tier and Average Ambitious Tier. Each round had only one single parameter changed.

6. DISCUSSION

In this section of the work, the results that were shown will be discussed along with their benchmarking in the hopes of presenting an enriched interpretation of what they could mean, leading to meaningful conclusions in the last chapter of this thesis.

6.1 Contrasting Results Between Technologies

In the Results chapter of this work, the individual results for each of the two hydropower technologies were shown, along with findings regarding TAM and the Financial and Environmental aspects of this analysis. These are certainly valuable, but it is important to note that these technologies are not only competing in the current European market to replace conventional technologies, but they are also challenging other renewable sources of energy like photovoltaic or wind, along with competing amongst themselves for their own spot in the EU's power mix currently and in the future. With this in mind, the discussion concerning these results should be led not only individually but with a broader approach, comparing the two technologies with each other and other renewable energy sources that may have been studied in the same configuration.

This comparison between technologies will then be made in this subsection. For clarity, the color scheme that has been used throughout the work will continue in this phase, with the data referring to LH featuring in dark blue while SH data will be shown in a lighter blue color.

Firstly, as shown in Figure 6.1., the comparison in terms of the electricity generation from each technology in 2050 is shown in two boxplot charts. The most immediate observation that can be made is that the projected generation from LH is, even in its most modest scenario, consistently above the projected generation for SH, even in its most ambitious scenario that, has been discussed previously, seems unlikely.

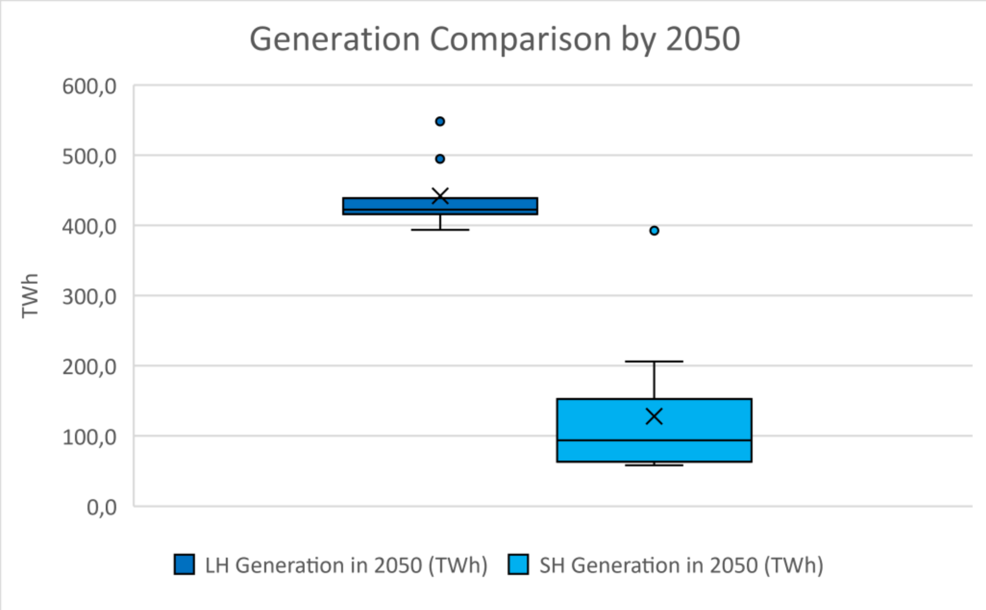


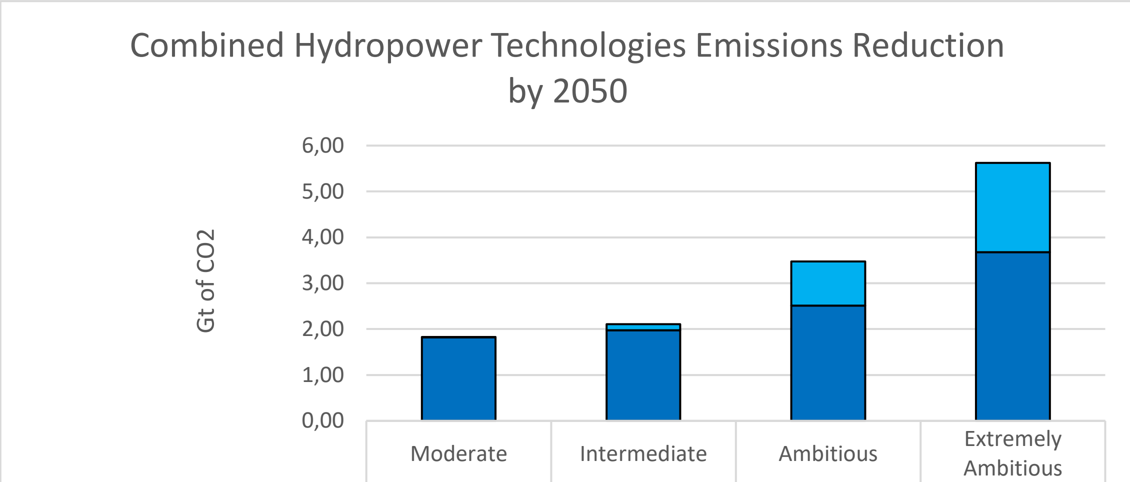
Figure 6.1.1 - Comparison of ranges of projected Generation for LH and SH technologies in 2050.

Additionally, still looking at this Extremely Ambitious Scenario for SH electricity generation (being the clear outlier in this case), it presents a data point of close to 400 TWh of generation, which is higher than the historical 2018 value for electricity generation from LH, showing that for this future pathway to be taken, a considerable amount of investment in the technology would have to be made.

Looking at the range of the projected generation for the two technologies, there is once again a clear difference, with a range of about 100 TWh for Small Hydro data and a range of under 25 TWh for the Large Hydro data set, suggesting once again the unpredictability and uncertainty of the future of Small hydropower, stemming mainly from the lower amount of data available to use for future projections, and a pretty clear pathway for LH.

Figure 6.3. shows the comparison of Emission results for both technologies. On the left-hand side, a similar pattern to generation is presented, with LH featuring a smaller range of numbers for Gt of CO_2eq avoided, being superior in most cases to the emissions reduction of SH (except for the latter's most ambitious scenarios) and SH a larger dispersion in terms of data points. On the right-hand side, however, the boxplot chart shows a slightly different picture. In this case, SH presents a larger range of values once again. Still, these are superior to the ones from LH, with averages of -7,5 €/t of CO_2eq and 34 €/t of CO_2eq respectively, showing once again that Small Hydropower can be able to reduce environmental negatives it needs larger investment. This factor stems from three main reasons: a larger variability of costs, lesser emissions reduction, and a higher cumulative first cost compared to LH. These numbers align with the current estimates for abatement cost in the literature [61] that show a number averaging around -8 €/ t of CO_2eq.

The impact of the combined generation from the two hydropower technologies on the Total Emissions Reduction by 2050 can be seen in Figure 6.2. Once again, the contribution from LH in this aspect is considerable, especially in the case of the Moderate and Intermediate Growth tiers, where SH's contributions are quite minor, only becoming significant in the Ambitious and Extremely Ambitious tiers of Adoption.



	Moderate	Intermediate	Ambitious	Extremely Ambitious
SH Total Emission Reductions	0,002	0,135	0,961	1,945
LH Total Emission Reductions	1,824	1,975	2,512	3,679

Figure 6.1.2 - Combined Hydro Technologies Total Emissions Reduction in Gt CO2eq by 2050 and by Tier of Adoption Projections.

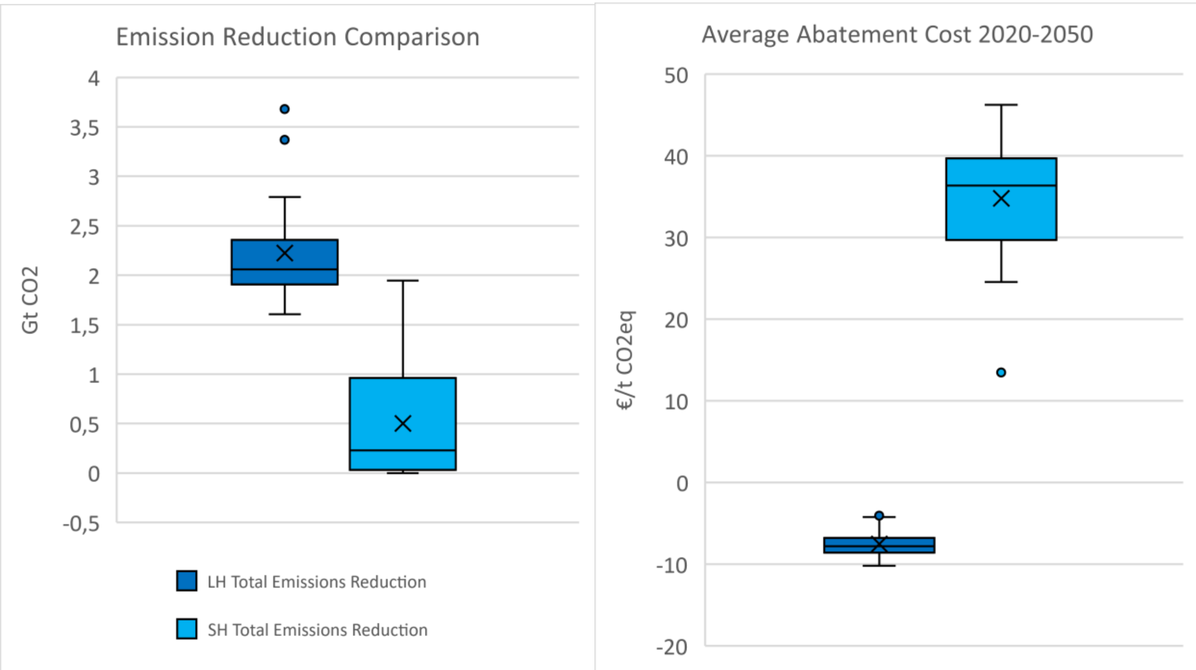


Figure 6.1.3 - Comparison of ranges of projected Emissions Reduction in Gt of CO2eq for LH and SH (left hand side) and respective ranges of Abatement Cost for these technologies (right-hand side) in 2050.

When it comes to the financial side of results, presented in Figure 6.4, the difference between the technologies is considerable in terms of Cumulative First Costs. Small Hydro features a much more comprehensive range of data points even though it presents smaller Adoption values at around 170 billion € while Large Hydro's is at about 100 billion €, with a higher average value for Small Hydropower, as could be expected Table 5.5. On the right-hand side of the boxplot chart, Lifetime Operating Savings are displayed, and there is once again a clear distinction between the technologies, with net savings until 2050 for Large Hydropower and an average net cost of just shy of 300 billion € for Small Hydropower, making LH the only possible profitable technology between the two.

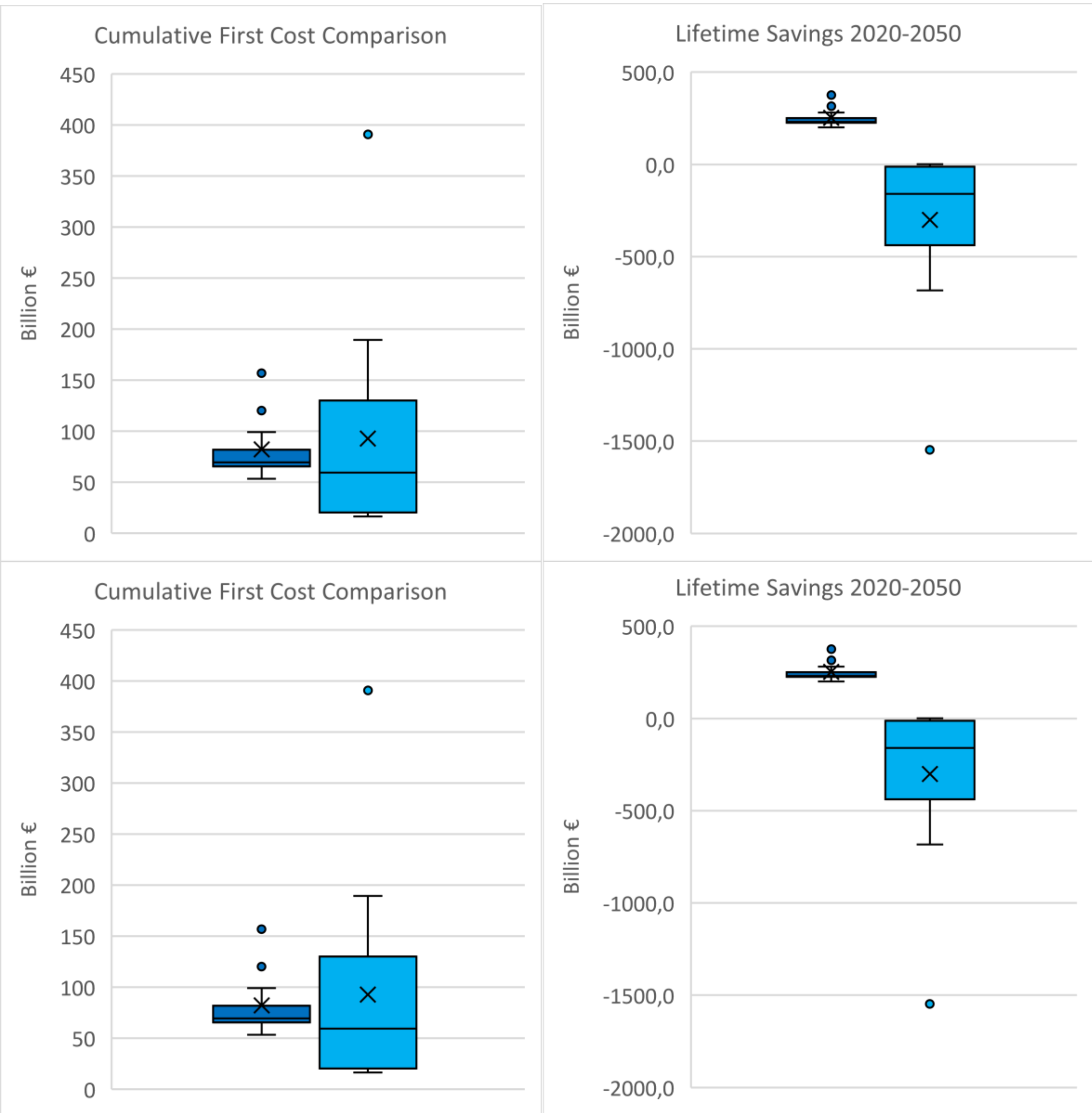


Figure 6.1.4 - Comparison of ranges of projected Cumulative First Cost for LH and SH (left-hand side) and respective ranges of Lifetime Savings for these technologies (right-hand side) in 2050, in billion €.

It is, however, important to point out that, as was mentioned previously, the current efforts point to the repowering and refurbishing hydropower facilities and these results are all regarding the construction of new facilities and infrastructure and therefore the values from these results are high estimates of the associated costs of these technologies.

6.2 Comparison with Project Drawdown 2020 Review

Beyond the comparisons between the results of the two technologies, taking into account that this work is being done as part of the regionalization efforts of Project Drawdown, it can also be worth it to compare these findings with the results from the 2020 Review of Project Drawdown.

Firstly, it is important to note that these Project Drawdown results referred to a global scale for the solutions. Therefore, this comparison is being made with the aim of assessing the weight that the solutions in Europe can have globally. This aspect is especially relevant when considering that some reports, like IEA's World Energy Outlook 2019, project a decline in the share of the global power sector representation of Europe, with the 2018 value of 16% being predicted to decrease to 12% in 2040 and 10% in 2050, due to a low average annual growth.

Additionally, the sources used to study these solutions on a global scale are not necessarily the same, with this factor having a significant impact, especially on the results for the various parameters in VMA.

Lastly, as was pointed out at the beginning of this work, only one of the two mentioned technologies studied herein, is a solution depicted on Project Drawdown analysis - Small Hydropower. Therefore, no results from the 2020 Review exist for the Large Hydropower solution and cannot be shown. The comparison of results for SH can be seen in Table 6.2.1. In this table, the two different results for each indicator stem from the Average Moderate tier and Ambitious tier of Small Hydro Adoption, respectively.

Table 6.2.1 - SH Results Comparison. The ranges shown here are the results of Average Modest SH Growth and Average Ambitious SH Growth.

Small Hydro			
	Total Emissions Reduction (Gt of CO_2eq) 2020-2050	Lifetime Operating Savings (Billion USD) 2020-2050	Projected Electricity Generation in 2050 (TWh)
Project Drawdown 2020 Review [15]	1,69 to 3,28	315,1 to 543,6	994 to 1136
Results	0,002 to 0,96	-656 to -3,7	59 to 167

When it comes to reducing total emissions, the Ambitious growth tier shows quite an interesting result. While it is inferior to the upper and lower ranges of the results from the 2020 Review, this was to be expected since the scale is much smaller. This data point is, however, significantly above 50% of the lower range of the global result, which takes into account the conservative nature of the RRS model assumptions, is quite a high and noteworthy result.

In terms of Electricity Generation, the Drawdown Review projects a considerable global growth for the electricity generation from the technology, with pathways that count with electricity generation that surpass the current Adoption of LH technologies in Europe. Taking a look at the lower end of results from the Drawdown Review shows an immense difference to this works' findings, even taking into consideration the conservative nature of the Drawdown model once again, as well as the low growth in the scenarios included in the Moderate Growth tier for SH, with the global data point being over 16 times larger than the results for the EU-28. Glancing at the results of this work, it projects a growth of 4-66% for the technology in the region. Comparatively, according to data from UNIDO's WSHDR 2019 and assuming an average capacity factor of 45% (the average found in the literature and included in the VMA portion of this work), globally, the SH solution is currently generating about 307 TWh of electricity. When opposing this with the projected values from the 2020 Review, it shows a growth of 69-73% for each growth tier, which, at the upper end of results, is closely in line with the findings from this work, suggesting that these might be a likely scenario.

Lastly, the picture changes quite drastically regarding the Financial indicator shown in the table, Lifetime Operating Savings. The Project Drawdown Review 2020 findings show savings between 315-543 Billion USD, while the results from this work not only do not show the same level of savings from the growth of the technology but present a net cost with the projected Adoptions from the two growth tiers mentioned above, most likely due to the average high First, Variable and Fixed Operating Costs.

7. CONCLUSIONS

With this work being framed under the Project Drawdown research framework, its findings progress the solutions oriented approach and regionalization efforts at the European scale. Being projections and considering the large scope of results obtained, it is not likely that these findings can be used to drive changes in public policy. Still, they can be utilized to assess the current state of hydropower, how it is expected to evolve in the decades to come, and the possible and likely middle grounds that can be adopted.

Furthermore, with Drawdown being a crucial point in time that must be achieved as soon as possible, this work, along with every other that is conducted under the Project Drawdown scope of action, as well as its regional groups such as DERA, is a pivotal piece of the puzzle when it comes to finding solutions for climate change. This is a global problem with global consequences and must be assessed with a holistic approach such as the Project's. Still, the solutions for this global problem must be applied at a local level, taking into account each region's or country's specificities, to reap the best results possible in each place without damaging the environment and negatively impacting local communities.

The conclusions that can be gathered from these findings of Hydropower technological solutions and its future, confirm its current role and remind the potential that these technologies can have. The results for LH confirm the current expectations of the technology, projecting either a decrease or moderate growth of its Adoption in the majority of scenarios. This future for hydropower is not news, with the considerable increase in Adoption of solar photovoltaic and wind power, allied with the growing environmental concerns of large undertakings such as the building of a hydropower plant, the hurdles for this, at this point, a centuries-old tool for the fight against climate change are vast. However, as shown by the results in this work, there is still some life left in this technology. With lower costs and emissions of GHG when compared to the conventional electricity-generating technologies, Large Hydropower still has economically and environmentally advantages, with potential considerable net savings and emissions reductions, being primed to be a reliable replacement for these conventional, fossil-fuel-based technologies through the much-needed overhauling of the power sector that is currently in place.

Additionally, as shown by the existing plethora of solutions in Project Drawdown, the climate change problem does not have a "silver bullet"; it cannot be fixed through a single solution. Therefore, united with solar PV, wind, and other less-established renewable energy technologies such as tidal, Large Hydro can be used together and a reliable backup through the times of change and establishment of these technologies.

When it comes to SH, however, the findings present some different conclusions. The less extensive nature of the literature regarding this technology presented some challenges and made the analysis considerably more exploratory. The results show a solution that, in its current form, presents a future potential reduction of emissions that lacks the scale that is needed for the current climate problem, with only the most ambitious projected scenarios featuring any kind of considerable reduction. In conjunction with its poor performance in financial terms stemming from its high investment and maintenance costs, with projected net costs for the technology through its lifetime, it should be expected that in the European Union, its place will continue to be among the less significant electricity generating technologies in place, as opposed to regions like Asia where Small Hydropower has a significantly larger expression. [51] With more advancement in the technical aspects of the solution driving down investment and maintenance costs and support from local policies, the technology can serve as an essential part of electricity generation in the European Union if there is a conscious decision to decentralize this generation, being suited for more isolated areas due to its small scale.

For future research that can result from this work, it can be two-fold. On the one hand, the continuation of the regionalization efforts of the project, analyzing each sector solution's potential in Europe. On the other hand, investigation on how hydropower's potential (as seen by this work) can be implemented in practice at every level, delineating regional and local policies, for example.

Lastly, it is also essential to point out some shortcomings of this work, the tools it used, and its methodology. Firstly, this works' main results are projections of TAM and Adoption and the impact that this projected evolution in electricity generation has on the financial and environmental aspects of the two technologies. Being only expected outcomes and not certain ones, the data used always possesses a certain level of uncertainty carried by the lack of ability of the reports' authors to know exactly what will happen to these technologies in the future. This uncertainty is enhanced by the growing effects of climate change, with changes in weather patterns on which the hydropower solutions are heavily reliant. Particularly, unexpected dry years that may come can have a big impact on these projections.

This first shortcoming brings about another important point about the methodology of this work. This analysis was made using data regarding electricity generation of the solutions since is the functional unit of the RRS Model and not data about installed capacity. Considering that the electricity generated by hydropower facilities is so dependent on the amount of precipitation, as mentioned before, a similar analysis conducted taking account current and predicted installed capacity could bring forth pertinent results.

Secondly, as seen in the methodology chapter, the RRS Model only allows for 15 scenarios to be considered for TAM and 16 for Adoption. As was explained, the number of scenarios found in the literature was significantly higher than this, and a selection process had to be undertaken. This aspect limits the number of future pathways that can be analyzed and compared in the model and, with this necessary selection process, makes it so with the same quantity of original data and depending on the selection criteria; the final results could be vastly different.

Finally, the scenarios that had to be created to obtain projections for the Small Hydro technology were largely exploratory, as mentioned previously, and could be made differently with many assumptions, differing drastically from the three growth rates used to project the evolution of the solution.

In conclusion, the electricity that we generate through hydropower technologies will undoubtedly remain an important pillar of the power sector until 2050, playing an essential role as an enabler for evolving and new technologies, helping bring the needed revolution to the power sector to mitigation GHG emissions and fight against climate change.

REFERENCES

[1] V. Smil, *Energy in World History*, 1st ed. Routledge, 1994.

[2] R. Brownstein, "The Rage Unifying Boomers and Gen Z," *The Atlantic*, 2020.

[3] A. P. J. Mol and G. Spaargaren, "Environment, Modernity and the Risk-society: the Apocalyptic Horizon of Environmental Reform," *Int. Sociol.*, vol. 8, no. 4, pp. 431–459, 1993, doi: https://doi.org/10.1177/026858093008004003.

[4] D. Jones, "Global Electricity Review 2021" 2021. [Online]. Available: https://ember-climate.org/project/global-electricity-review-2021/.

[5] IPCC, "Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change," *Ipcc - Sr15*, vol. 2, no. October, pp. 17–20, 2018, [Online]. Available: www.environmentalgraphiti.org.

[6] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, "Early decarbonisation of the European energy system pays off," *Nat. Commun.*, vol. 11, no. 1, pp. 1–9, 2020, doi: 10.1038/s41467-020-20015-4.

[7] P. D'Aprile *et al.*, "Net-Zero Europe Decarbonization pathways and socioeconomic implications," 2020. [Online]. Available: https://www.mckinsey.com/business-functions/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost#.

[8] P. Hawken, *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*, First. Penguin Books, 2017.

[9] I. Renewable Energy Agency, *Renewable Energy Statistics 2020*. 2020.

[10] IEA, "Technology Roadmap - Hydropower," Paris, 2012. doi: 10.1007/1-4020-0612-8_961.

[11] DERA, "Drawdown Europe Research Association," 2021. https://www.drawdowneurope.org/ (accessed Aug. 27, 2021).

[12] M. A. Brown *et al.*, "A framework for localizing global climate solutions and their carbon reduction potential," *Proc. Natl. Acad. Sci.*, vol. 118, no. 31, p. e2100008118, 2021, doi: 10.1073/pnas.2100008118.

[13] "About Project Drawdown," 2019. https://drawdown.org/about (accessed Aug. 10, 2021).

[14] "About Us," 2020. https://www.drawdowneurope.org/about/ (accessed Aug. 10, 2021).

[15] K. Wilkinson, "Drawdown Review," p. 104, 2020, [Online]. Available: https://drawdown.org/drawdown-framework/drawdown-review-2020%0Ahttps://drawdown.org/sites/default/files/pdfs/TheDrawdownReview–2020–

Download.pdf.
[16] L. Fernando, "European Potential of Solar Technologies for Electricity Generation under Project Drawdown Framework," no. December, 2020.
[17] P. Drawdown, "Small Hydropower," 2019. https://www.drawdown.org/solutions/small-hydropower (accessed Oct. 25, 2021).
[18] F. Carrasco, *Introduction to Hydropower*, First. The English Press, 2011.
[19] S. Currie, *Hydropower-Energy and the Environment*. 2011.
[20] D. Clark, "How will climate change affect rainfall?," *The Guardian*, 2011.
[21] R. A. R. Jeffrey T. Brack, Jack J. Kraushaar, *Energy and the Environment*. Wiley; 3rd edition (December 14, 2015), 2015.
[22] R. Lacal-Arantegui and M. Vellei, *ETRI 2014*. 2014.
[23] H. RAMOS and and A. B. de ALMEIDA, "Small Hydropower Schemes as an Important Renewable Energy Source," 1999.
[24] M. Geiger, S. Hamlen, and M. Vogel, "Micro-hydropower for the Home, Farm, or Ranch," no. May, pp. 29–32, 2013.
[25] P. Durand, "Private Minihydropower Development Study: The Case of Ecuador," 1992.
[26] IEA, "Hydropower Special Market Report - Analysis and forecast to 2030," 2021. [Online]. Available: www.iea.org.
[27] A. M. Bagher, M. Vahid, M. Mohsen, and D. Parvin, "Hydroelectric Energy Advantages and Disadvantages," *Am. J. Energy Sci.*, vol. 2, no. 2, pp. 17–20, 2015.
[28] IRENA & ETSAP, "Hydropower Technology Brief," no. February, pp. 1–18, 2015.
[29] S.-L. Wee, "Thousands being moved from China's Three Gorges - again," *Reuters*, 2012.
[30] IEA, "World Energy Outlook 2019," 2019. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2019%0Ahttps://www.iea.org/reports/world-energy-outlook-2019%0Ahttps://webstore.iea.org/download/summary/2467?fileName=Japanese-Summary-WEO2019.pdf.
[31] IEA, "Energy Technology Perspectives 2017," *Int. Energy Agency Publ.*, p. 371, 2017, [Online]. Available: https://webstore.iea.org/download/summary/237?fileName=English-ETP-2017-ES.pdf.
[32] Greenpeace, "Energy [r]evolution," 2015. [Online]. Available: https://www.greenpeace.org/canada/en/publication/1572/energy-revolution-2015-the-latest-documentation-2/.
[33] ERI RAS and M. S. of M. SKOLKOVO, *Global and Russian Energy Outlook to 2019*. 2019.
[34] BP Outlook, "BP Energy Outlook 2019 edition The Energy Outlook explores the forces shaping the global energy transition out to 2040 and the key uncertainties surrounding that," *BP Energy Outlook 2019*, 2019, [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf.
[35] S. Teske, *Achieving the paris climate agreement goals: Global and regional 100% renewable energy scenarios with non-energy GHG pathways for +1.5°C and +2°C*. 2019.
[36] Equinor, "Energy Perspectives 2018 Long-term macro and energy outlook," p. 60, 2018, [Online]. Available: https://www.equinor.com/content/dam/statoil/documents/energy-perspectives/energy-perspectives-2018.pdf.
[37] International Renewable Energy Agency(2017), "Renewable Energy Statistics 2017," 2017.

[38] The Institute of Energy Economics Japan(IEEJ), "IEEJ Outlook 2019: Energy transition and a thorny path for 3E challenges," 2018. [Online]. Available: https://eneken.ieej.or.jp/data/8122.pdf.
[39] The Institute of Energy Economics Japan(IEEJ), "IEEJ Outlook 2020. Coping with the increasingly challenging energy trilemma (3Es)," 2020.
[40] S. Simoes *et al.*, *The JRC-EU-TIMES model. Assessing the long-term role of the SET Plan Energy technologies*, no. EUR 26292 EN. 2013.
[41] Energy watch group, "Global energy system based on 100% renewable energy," 2018. [Online]. Available: http://dx.doi.org/10.1016/j.cirp.2016.06.001%0Ahttp://dx.doi.org/10.1016/j.powtec.2016.12.055%0Ahttps://doi.org/10.1016/j.ijfatigue.2019.02.006%0Ahttps://doi.org/10.1016/j.matlet.2019.04.024%0Ahttps://doi.org/10.1016/j.matlet.2019.127252%0Ahttp://dx.doi.o.
[42] Project Drawdown, "Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide," 2019.
[43] SolarPower Europe and LUT University, "100% Renewable Europe How To Make Europe's Energy System Climate-Neutral Before 2050," 2020. [Online]. Available: https://www.solarpowereurope.org/european-market-outlook-for-solar-power-2020-2024/.
[44] European Small Hydropower Association, "Small Hydropower Roadmap. Condensed research data for EU-27," pp. 18–19, 2012.
[45] IRENA, *Renewable Energy Statistics 2016 Statistiques D ' Énergie Renouvelable 2016 Estadísticas De Energía*. 2016.
[46] WindEurope, "Breaking new ground - Wind Energy and the Electrification of Europe's Energy System," *WindEurope*, vol. September, 2018.
[47] Eurelectric, "Decarbonisation pathways: Full study results," p. 89, 2018, [Online]. Available: https://cdn.eurelectric.org/media/3558/decarbonisation-pathways-all-slideslinks-29112018-h-4484BB0C.pdf.
[48] IEA, "Electricity Information 2020," 2020. [Online]. Available: https://www.iea.org/subscribe-to-data-services/electricity-statistics.
[49] IRENA, "Renewable Energy Prospects for the European Union," 2018. doi: 10.1055/s-2001-10028.
[50] Olivier Lavagne d'Ortigue, A. Whiteman, and S. Elsayed, "Renewable Energy Capacity Statistics 2015,International Renewable Energy Agency(IRENA)," p. 44, 2015, [Online]. Available: http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2015.pdf.
[51] UNIDO, "World Small Hydropower Development Report 2019," *World Small Hydropower Dev. Rep.*, p. 24, 2019, [Online]. Available: https://www.unido.org/sites/default/files/files/2020-05/Africa Book.pdf.
[52] F. C. Matthes, H. Hermann, and W. Zimmer, "The Vision Scenario for the European Union 2011 Update for the EU-27," vol. 49, no. 0, p. 65, 2011.
[53] IRENA, *Global Renewables Outlook: Energy transformation 2050*. 2020.
[54] EU, "EU Reference Scenario 2016," *EU Ref. Scenar. 2016*, p. 27, 2016, [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf [accessed on 25 August 2017].
[55] JRC, *Deployment Scenarios for Low Carbon Energy Technologies*. 2018.

[56] European Climate Foundation (ECF), "Net Zero by 2050: From Whether to How," no. September, 2018, [Online]. Available: www.lindsayynobledesign.com.

[57] Navigant, "2020 Gas Decarbonisation Pathways study - Gas for Climate 2050," 2020. [Online]. Available: https://gasforclimate2050.eu/sdm_downloads/2020-gas-decarbonisation-pathways-study/.

[58] M. Ram *et al.*, "Energy Transition in Europe Across Power , Heat , Transport and Desalination Sectors," 2018.

[59] Ioannis Tsiropoulos, Dalius Tarvydas, and Andreas Zucker, *Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 edition*. 2018.

[60] World Energy Council, "World Energy Scenarios 2019," *WEC Publ.*, pp. 1–152, 2019, [Online]. Available: https://www.worldenergy.org/assets/downloads/2019_Scenarios_Full_Report.pdf.

[61] K. Gillingham and J. H. Stock, "The cost of reducing greenhouse gas emissions," *J. Econ. Perspect.*, vol. 32, no. 4, pp. 53–72, 2018, doi: 10.1257/jep.32.4.53.

[62] F. Vieira and J. P. Gouveia, "7th Meeting on Energy and Environmental Economics 7th May 2021 DEGEIT , Universidade de Aveiro , Online Exploring the Potential of Hydropower Technologies for European Electricity Generation Project Drawdown and its Framework for Climate Solutions," no. May, 2021.

REFERENCES FOR DATA IN PROJECT DRAWDOWN'S REDUCTION AND REPLACEMENT MODEL

[1] Carbon Tracker Initiative, *Expect the Unnexpected*. 2017.

[2] Advanced System Studies for Energy Transition, *Technology Pathways in Decarbonisation Scenarios*. 2018

[3] SVEN TESKE, *Achieving Paris Agreement Goals.* 2019

[4] International Energy Agency, *Projected Costs of Generating Eletricity*. 2020

[5] International Renewable Energy Agency, *Renewable Power Generation Costs*. 2019

[6] International Energy Agency, *Monthly Oil Price Statistics*. 2020

[7] International Energy Agency, *Energy Prices*. 2019

[8] International Renewable Energy Agency, *Renewable Energy Benefits: Measuring the Economics*. 2016

[9] International Renewable Energy Agency, *Renewable Energy and Jobs*. 2020

[10] Agência Portuguesa do Ambiente (APA), Fundo Ambiental, *Roteiro para a Neutralidade Carbónica 2050. Estratégia de longo prazo para a neutralidade carbónica da economia portuguesa em 2050 (Roadmap for Carbon Neutrality 2050. Long-term strategy for carbon neutrality of the Portuguese economy in 2050).* 2019

[11] K. Bódis, F.Monforti, S.Szabó (2014), Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data

[12] Schmidt T. S., R. Born, and M. Schneider (2012). Assessing the costs of photovoltaic and wind power in six developing countries. Nature Climate Change 2, 548 – 553. doi: 10.1038 / nclimate1490

[13] R. Turconi, A. Boldrin, T. Astrup (2013) Life cycle assessment(LCA) of electricity generation technologies: Overview,comparability and limitations

[14] NETL, Role of Alternative Energy Sources: Hydropower Technology Assessment (2012)

[15] E. Rubin, I. Azevedo, P. Jaramillo, S.Yeh (2015), A review of learning rates for electricity supply technologies

[16] S. V. Ratner and R. M. Nizhegorodtsev (2016), Analysis of Renewable Energy Projects' Implementation in Russia

[17] Tor Haakon Bakken, Ånund Killingtveit, and Knut Alfredsen, The Water Footprint of Hydropower Production—State of the Art and Methodological Challenges (2017)

[18] PNAS, Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies (2013)

[19] Garcia Gusano (2016) Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway

[20] Pang et al. (2014): Environmental life cycle assessment of a small hydropower plant in China

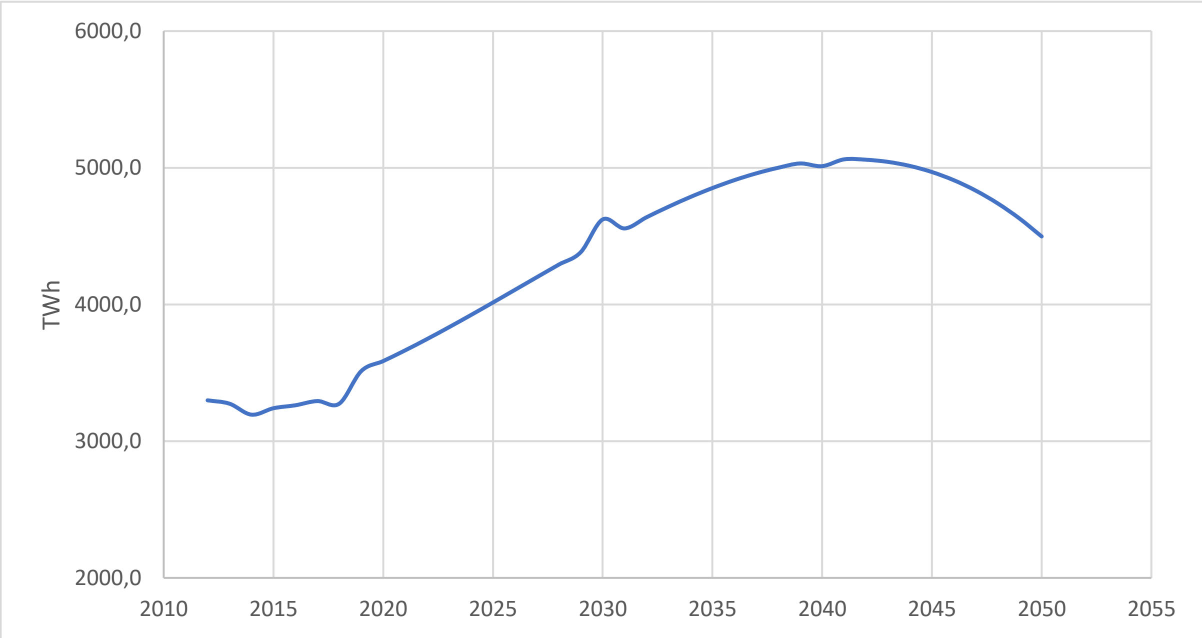
[21] Hanafi (2015). CO2 emissions from an SHP plant of Indonesia. Hanafi, J. & Riman, A. (2015). Life Cycle Assessment of a Mini Hydro Power Plant in Indonesia: A Case Study in Karai River. The 22nd CIRP conference on Life Cycle Engineering, 29, pp. 444-449. Section 4. doi: 10.1016/j.procir.2015.02.160

[22] Vougioukli (2017). CO2 emissions from LCA analysis of a small hydro project from

Greece.Vougioukli, A.Z., Eleni, D. & Dimitrios, G. (2017). Financial Appraisal of Small Hydro-Power Considering the Cradle-to-Grave Environmental Cost: A Case from Greece. (I. Nicolae, Ed.) Energies, 10(4). Table 6. doi:doi:10.3390/en10040430

[23] Steinhurst et al. - Steinhurst, W., Knight, P., Schultz, M. (2012). Hydropower Greehouse Gas Emissions - Stae of the Research. Synapes Energy. Economics, Inc.

A. ANNEX: Interpolation Results Using Raw Data



Annex A - Interpolation results If Raw Data were to be used.

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7th May 2021
DEGEIT, Universidade de Aveiro, Online

EXPLORING THE POTENTIAL OF HYDROPOWER TECHNOLOGIES FOR EUROPEAN ELECTRICITY GENERATION

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Abstract

Climate change is an undeniable problem, and the solutions available to fight it need to be deeply understood. Along with other institutions, Project Drawdown is one of the leading fronts in research and resources about climate solutions. Its global analysis in 2017 and 2020, followed by regionalization efforts in the US and Europe are critical pieces of this understanding and contextualization of climate change solutions in multiple sectors. This study aims to understand the contribution that hydropower solutions, both large and small, scale can have in climate change mitigation efforts in Europe, specifically in reducing greenhouse gas (GHG) emissions, associated costs and its role in future developments of the electricity generation industry, one of the GHG biggest emitters.

The methodology is supported on an extensive data collection of future electricity generation projections (TWh) and key characteristics of the hydropower technologies. The preliminary results show that the electricity generated in Europe will grow in every scenario that was studied. However, the extent of this growth varies a lot along the different scenarios from the various publications due to different models used, main socio-economic assumptions and technological availability. When it comes to the portion of that generation that is accomplished by hydro technologies, the results seem to show a trend of stabilization or slight growth in some scenarios. These results might suggest that with its maturity, the future of these technology may be laying essentially in repowering and improvements in existing powerplants and not in the building of new ones, an opposed trend when compared with solar or wind-based electricity generation technologies.

Keywords: *Project Drawdown, Electricity Generation, Climate Solutions, Hydropower*

⟨2021⟩

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Analysis of the Future of Hydropower Technologies in the European Union under Project Drawdown Framework

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