Blue energy potential assessment and their impact on the electricity system of the Republic of Croatia

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UNIVERSITY OF ZAGREB
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MASTER'S THESIS

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Zagreb, 2021.

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Zagreb, 2021.

I hereby declare that this thesis is entirely the result of my work except where otherwise cited. I have fully cited all used sources and I have only used the ones given in the list of references.

This work was done within the Interreg MED project “Blue Deal – Blue Energy Deployment Alliance”, project number 5MED18_1.1_M23_072.

I would like to thank Professor Neven Duić for giving me the opportunity to write this thesis.

I would like to express my deepest gratitude to Dr. Sc. Hrvoje Mikulčić for availability, willingness to help and unwavering support. I am also extremely grateful to the assistants Hrvoje Stančin and Filip Jurić for their insightful suggestions and help. They all improved the quality of this thesis and I thank them for excellent cooperation and patience.

I very much appreciate the valuable advice and help from assistant Antun Pfeifer.

Special thanks to my friends and colleagues for their support and encouragement, especially to those with whom I have spent a lot of time studying and in discussion.

And finally, the biggest thank you to my family for their continued and unconditional support. You have been with me through all the challenges this study has brought. Without you, my whole study and this thesis would be an incomparably harder and bigger undertaking.

Lea Leopoldović

SVEUČILIŠTE U ZAGREBU
FAKULTET STROJARSTVA I BRODOGRADNJE
Središnje povjerenstvo za završne i diplomske ispite
Povjerenstvo za diplomske ispite studija strojarstva za smjerove:
procesno-energetski, konstrukcijski, brodostrojarski i inženjersko modeliranje i računalne simulacije

University of Zagreb Faculty of Mechanical Engineering and Naval Architecture	
Date:	Appendix:
Class: **602 - 04 / 21 - 6 / 1**	
Reg. No.: **15 - 1703 - 20 -**	

MASTER THESIS

Student: **Lea Leopoldović** St. No.: 0035203012

Title of thesis in Croatian: **Procjena potencijala plave energije i njihov utjecaj na elektroenergetski sustav Republike Hrvatske**

Title of thesis in English: **Blue energy potential assessment and their impact on the electricity system of the Republic of Croatia**

Task description:

The energy transition requires the integration of various renewable energy sources using conventional and new technologies. Blue Energy (BE) represents a huge potential that remains untapped due to technological and legislative constraints. Despite this, the development of offshore wind farms has almost reached a commercial stage of profitability and is one of the most promising sources of BE. Furthermore, wave energy and other forms of BE have limited potential and require the development of special technologies for closed seas in order to enable the economically viable possibility of exploiting their potential. In order to provide a better insight into the potential of BE for the Adriatic Sea and conduct an analysis of their impact on the electricity system of the Republic of Croatia, it is necessary to model the existing situation and include the assumed capacities of BE technologies taking into account their level of development.

As part of the thesis it is necessary to make the following:

1. Identify all blue energy technologies with the current stage of development and the possibilities of their use in the Adriatic Sea.
2. Model the reference scenario of the electricity system of the Republic of Croatia based on the Proposal of the Energy Development Strategy of the Republic of Croatia until 2030 with a view to 2050 and include technically feasible capacities for the considered blue energy technologies.
3. Carry out an analysis of the potential for offshore wind farms and wave energy converters and analyze their impact on the stability of the electricity system
4. Conduct a techno-economic analysis for selected blue energy technologies. Make an estimate of the necessary costs for the installation of the proposed technologies (€). Calculate potential savings in fossil fuel consumption (MWh), reduction of CO_2 emissions (t) and state the costs of emission reduction (€ / t CO_2).

The necessary information can be obtained from the mentor. It is necessary to state the used literature and possible received help in the paper.

Thesis assigned:	Thesis submission date:	Thesis defence date:
November 12, 2020.	January 14, 2021.	January 18– 22, 2021.
Supervisor:	co-Supervisor:	Committee Chair:
Prof.dr.sc. Neven Duić	dr.sc. Hrvoje Mikulčić	Prof. dr. sc. Tanja Jurčević Lulić

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NOMENCLATURE

Nomenclature	**Unit**	**Description**
E_P	J	the potential energy
ρ	$\frac{kg}{m^3}$	density of seawater
A	m^2	the area of the basin
g	$\frac{m}{s^2}$	the acceleration due to gravity
R	m	the tide height above sea level

LIST OF ABBREVIATIONS (ACRONYMS)

Nomenclature	**Description**
AEM	Anion exchange membrane (s)
BE	Blue Energy
CEEP	Critical excess electricity production
CEM	Cation exchange membrane (s)
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CSP	Concentrating solar thermal power
DH	District Heating
EEZ	Exclusive Economic Zone
HC	High concentration
HP	Heat pump
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LC	Low concentration
LCOE	Levelized Cost of Energy
MRE	Marine Renewable Energies
NTC	Net Transfer Capacity
OTEC	Ocean Thermal Energy Conversion
PRO	Pressure Retarded Osmosis
PV	Photovoltaic
RED	Reversed Electrodialysis
RES	Renewable energy sources
ROI	Return on investment
rpm	revolutions per minute

SUMMARY

Nowadays, the whole world, including the European Union and Croatia, is turning to the use of renewable energy sources. From the Industrial Revolution, fossil-based technologies which contribute to CO_2 emissions have been primarily used for energy production, and therefore many countries are working intensely on the energy transition. The Adriatic Sea shows the potential for future use of marine energy technologies. In this thesis, the potential of Blue Energy technologies in Croatia will be analysed. The observed technologies will include offshore wind farms, wave power plants and seawater heat pumps.

The introduction deals with an overview of global, European and Croatian renewable energy sources. The next section describes Blue Energy technologies with regard to available parameters and their current state, as well as future potential. After that, the input data which was put into program EnergyPLAN was shown. This data is required for obtaining results that are related to the consumption, production, CO_2 emissions and others. Data for 2018 which served as the starting point was presented, and then the forecasts for 2030 and 2050 were processed. Also, the relevant parameters for BE technologies were analysed. It was important to assess the possibility of their exploitation along the Adriatic coast of Croatia because the obtained capacities were put in EnergyPLAN. An analysis of production and the impact on CO_2 emissions from these technologies was shown. Finally, a techno-economic analysis was carried out according to available data and forecasts for 2030 and 2050.

Keywords: renewable energy sources, Blue Energy technologies, offshore wind farms, wave energy, seawater heat pumps, EnergyPLAN, the Adriatic Sea

SAŽETAK

Danas se cijeli svijet, pa tako i Europska unija i Hrvatska, sve više okreću korištenju obnovljivih izvora energije. Od doba industrijske revolucije su se u najvećoj mjeri koristile konvencionalne tehnologije koje emitiraju ugljični dioksid (CO_2), te stoga mnoge države intenzivno rade na energetskoj tranziciji. Jadransko more ima potencijal koji bi se u budućnosti mogao iskoristiti tehnologijama za iskorištavanje energije mora. U ovom radu analizirat će se potencijali Plave energije. Odabrane tehnologije su pučinske vjetroelektrane, elektrane na valove i dizalice topline s morskom vodom.

Uvod obrađuje pregled obnovljivih izvora energije u svijetu, Europi i Hrvatskoj. Sljedeće poglavlje opisuje tehnologije Plave energije te njihovo sadašnje stanje i potencijalnu buduću primjenjivost s obzirom na postojeće parametre. Nakon toga, prikazani su podaci koji su se unosili u program EnergyPLAN radi dobivanja rezultata vezanih za potrošnju, proizvodnju, emisije CO_2, i ostalo. Obrađeni su podaci za 2018. godinu koja je poslužila kao referentna polazna točka, a zatim su obrađena predviđanja za 2030. i 2050. Posebno su analizirani parametri relevantni za Plave tehnologije i procjenu mogućnosti postavljanja njihovih kapaciteta duž hrvatske obale Jadranskog mora. Uslijedila je analiza proizvodnje i potrošnje iz tih tehnologija te utjecaj na emisije CO_2. Na kraju je provedena tehnoekonomska analiza prema dostupnim podacima i predviđanjima za 2030. i 2050.

Ključne riječi: obnovljivi izvori energije, Plava energija, pučinske vjetroelektrane, elektrane na valove, dizalice topline s morskom vodom, EnergyPLAN, Jadransko more

1. INTRODUCTION

Temperatures on Earth have always varied, but since the industrial revolution, they have been steadily rising and have never been higher. The consequences can be catastrophic for air quality, biodiversity, human health, agriculture, ecosystems, water resources, and many others [1]. This is not a problem that only affects countries that continue to resist integrating renewable energy sources (RES), it is a problem that affects all. Thus, the involvement of all countries is needed to reduce the risk of the negative consequences of climate change. Although 70% of total greenhouse gas emissions come from fossil fuels, the policy of many countries continues to focus on extracting energy primarily from fossil fuels [2]. This tendency towards fossil fuels is particularly evident in countries in transition. They exploit their deposits since conventional resources are economically more viable for them [2]. There is a need for an energy transition to transform the energy sector from fossil fuels to renewables, which will be possible only through cooperation. This will be achieved by transforming the market, specifically by providing affordable clean energy technologies to all citizens to ensure social equality [3]. It is necessary to work on improving energy efficiency, reducing demand in terms of energy savings and the transition from centralized to distributed systems [4]. Furthermore, the change in legislation will have to be pushed forward to ensure faster energy transition [4].

1.1. **Agreements aimed at emission reduction**

In November 2016 an agreement within the United Nations Framework Convention on Climate Change (UNFCCC), dealing with greenhouse-gas-emissions mitigation, adaptation and the funding of the process, the so-called Paris Agreement was signed [5]. It is a continuation of the Kyoto Protocol from 1998, which advocated for the reduction of emissions of six greenhouse gases and has some similarities with it. Within the Agreement, two scenarios were analysed. The first one is that the temperature rise by the end of this century remains below 2°C above the pre-industrial levels. To achieve that, it would be necessary to reduce emissions by at least 25% by 2030, and to achieve zero emissions by 2075 [2]. A more ambitious plan is to maintain the temperature rise to a maximum of 1.5°C. This will be possible if CO_2 emissions are reduced by 40 – 60% by 2030 and zero emissions are reached by 2050 [2]. According to Pablo-Romero et al. [2], to achieve the target of a maximum 2°C increase in temperature, CO_2 emissions should not exceed the total amount of 1 178 Gt CO_2, while in the case of 1.5°C the same should not exceed 420 Gt CO_2. Each country needs to assess how it will achieve its goals. To ensure that all this does not remain only on paper, every 5 years it will be necessary to show progress as well as the planned future actions [5].

European Union (EU) in December 2019 went a step further when the European Commission presented the European Green Plan [6] whose goal is to make Europe the first climate-neutral continent by 2050. It consists of eight thematic areas and two horizontal areas. To realize the plans of the European Green Deal, it is necessary to reduce emissions in transport, which is responsible for a quarter of GHG emissions. This will be possible if transport emissions are reduced by 90% by 2050. This includes an increase in the production of alternative fuels and the number of refuelling points, automated and connected multimodal mobility, and advancement of public transport in urban areas. It is estimated that it takes 25 years to change the industrial sector, so the decisions regarding the integration of RES should be made in the next 5 years so that they can be implemented by 2050. Moreover, it is necessary to develop digital progress, which will consequently have a positive impact on the implementation of RES. All of the above will be possible with the participation of all Member States and policies to achieve the set goals. In the document, the potential of maritime resources is acknowledged. It plans to investigate options and propose measures to exploit the maritime area, with offshore wind leading the way. In addition to proposing measures for improving the climate, there are also solutions for the protection of biodiversity, soil, air and water. The need for power demand is constantly rising and that demand has to be met, so the alternative to burning fossil fuels is generating power from renewable energy sources. RES includes solar energy, hydro energy, wind power, biomass, geothermal energy, wave energy, tidal energy, the temperature difference of the ocean, and salinity difference between saltwater and freshwater.

1.2. Renewable energy sources globally

RES are on the steady and continuous rise. Solar photovoltaic systems (PV) and wind energy are the ones that developed most notably. In Figure 1 the increase in installed capacity globally can be seen. Even for a short period of 6 years, it can be seen that RES installed capacities more than doubled. From a little over 100 GW of newly installed RES capacities in 2013 to more than 200 GW of newly installed RES capacities in 2019. In 2013 about 40% of the total annual installed capacities were RES, while in 2019 this percentage was 75%. In total, renewable power generating capacities were at 2 588 GW globally. The leader was solar PV with about 115 GW, followed by wind with 60 GW and hydropower with 16 GW of newly installed capacities. The last 5% consists of bioenergy, geothermal energy, concentrating solar thermal power (CSP) and ocean energy. The leading countries are China with 789 GW, USA with 282 GW, Brazil with 137 GW, and Germany with 124 GW of installed capacities [7].

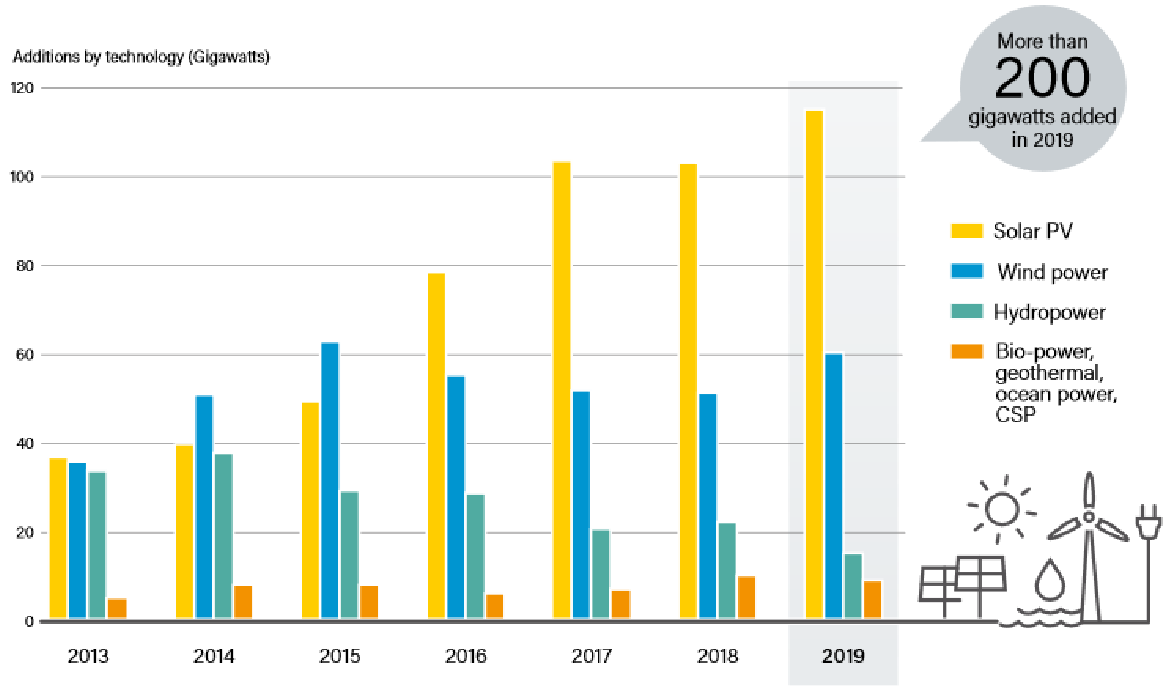


Figure 1. Annual additions of RES installed capacity by technology between 2013 and 2019 [7]

Renewable technology prices have long been one of the main reasons against greater utilization. However, experts' predictions regarding their price have proven to be accurate due to the constant improvement of their competitiveness. This can be seen when the global trends of Levelized Cost of Energy (LCOE) - a ratio between the total lifetime cost of an investment and the cumulated generated energy by investment, are analysed [8]. As can be seen from Figure 2, LCOE of RES technologies has continually decreased over the years, in such an amount that some of RES technologies already outperform conventional sources. LCOE of solar PV plants declined by an impressive 82% between 2010 and 2019, which makes it the largest decrease in LCOE in that period for any renewable technology. LCOE of CSP also had a significant decrease of 47% while biomass has had a more modest decline of 13%. Both geothermal and hydropower recorded an increase of 49% and 27% in LCOE. It would be good to note that prices related to bioenergy, geothermal and hydro energy depend on each project, and therefore prices may fluctuate each year. For example, hydropower had delayed projects in 2019 that had higher costs than expected, which may not be repeated in the next years. For onshore wind, LCOE decreased by 39%, and with the price of 0.053 USD/kWh has surpassed most fossil-based plants, with the exception of coal which has LCOE of around 0.05 USD/kWh. Offshore wind turbines are not far behind, with a 29% decrease in LCOE. Some forecasts show that by

2035, offshore wind technologies will be cheaper than onshore ones [9]. This is due to stronger and stable offshore winds. For this reason, the scenarios that will be analysed include substantial offshore wind capacities and even offshore floating structures in 2050. Therefore, the path to greater offshore wind integration has been carved out.

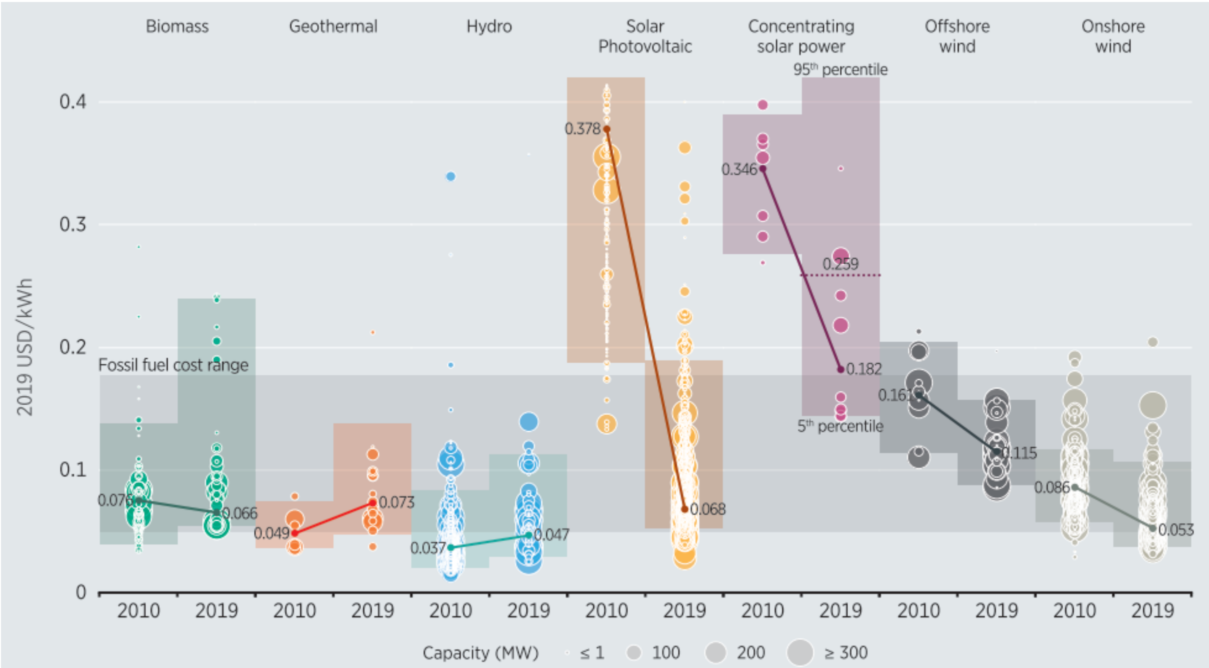


Figure 2. Global LCOE from newly commissioned technologies between 2010 and 2019 [8]

In Figure 3 the forecasts for installed power generation capacity up to 2040 are shown [10]. It is evident that solar PV is expected to have the biggest increase in installed capacities and that wind energy installations will grow steadily as well. The shares of installed hydro and nuclear capacities are also significant. One of the disadvantages of RES is their intermittency and that problem is being offset with different energy storage technologies, of which battery storage is projected to reduce prices by 40% until 2040. As can be seen, overall growth is expected, for some RES more visible than others. Figure 3 also predicts a decline in fossil fuel capacity production in most cases, except for gas.

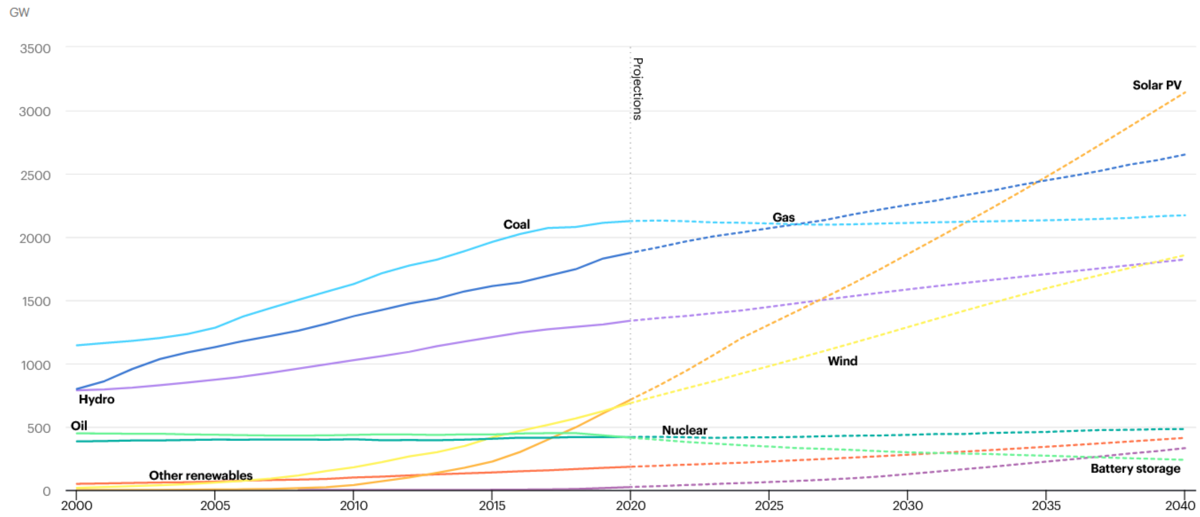


Figure 3. Installed power generation capacity by source 2000 – 2040 [10]

1.3. Renewable energy sources in the European Union

EU has proven to be a leader towards a greener and more sustainable future, funding research and innovation projects under the Horizon 2020 project with 1 billion euros [11]. The European Green Deal set a plan that by 2030 EU greenhouse gas (GHG) emissions need to be reduced by at least 50%, although it recommends as much as 55% compared to 1990 [12].

Wind energy has greatly helped in the implementation of RES. The onshore wind energy still prevails, but the offshore wind has also recorded rapid growth in the EU, as seen in Figure 4. In 2019, the countries that contributed the most to this increase were United Kingdom (UK) with 629 MW onshore and a high 1.8 GW of offshore wind, Spain with 2.3 GW of onshore wind, Germany with 1.1 GW of onshore and 1.1 GW offshore wind, and Sweden with 1.6 GW onshore wind [13]. Undoubtedly, one of the factors is the decrease in costs which has made them more competitive on the market. Despite its challenges, offshore wind has remained an attractive option for power generation and has reached a satisfactory level of maturity to compete on the market. One of the biggest increase in wind farm construction is expected in Europe, especially in the UK and Germany which have already invested significant funds, around 60 billion euros, representing 81% of total EU investment in this sector [14]. Further growth is expected in the North Sea, following the trend that has been present for years. The prognosis for 2030 is 45 GW in the North Sea, and 8 GW in the Baltic Sea [14].

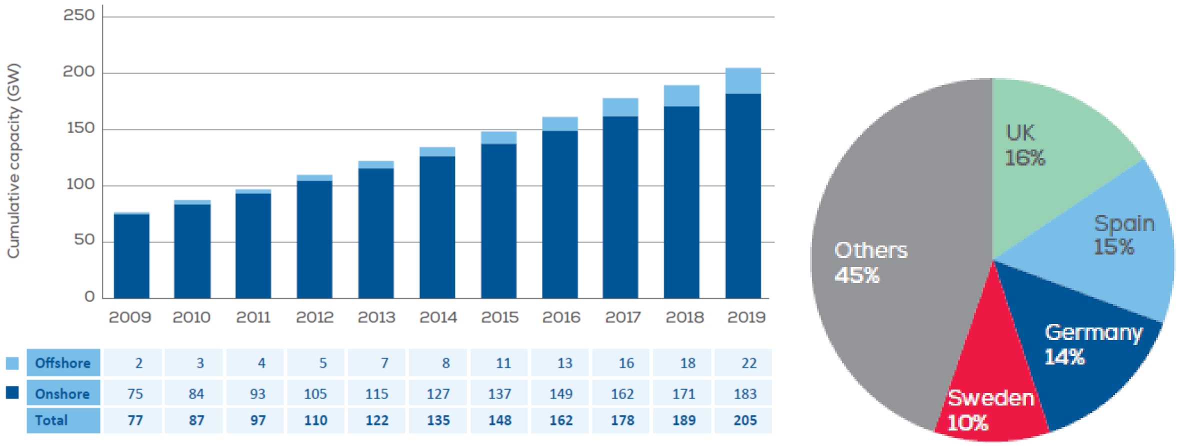


Figure 4. Cumulative wind power capacity in Europe (on the left) and percentage of newly installed wind capacities by country in 2019 (on the right) [13]

The European Commission (EC) forecasts that offshore renewable energy could have a major role in achieving climate neutrality. According to EC [15], the plan is to install 60 GW of offshore wind capacities by 2030 and 300 GW by 2050. For ocean energy, it predicts 1 GW by 2030 and 40 GW by 2050. Between 2007 and 2019, EC invested 3.84 billion euros in the development of ocean wave and tidal energy, but that amount will be increased by approximately 800 billion euros to achieve the mentioned goals [15]. These investments promote offshore technologies, which can encourage other countries to start exploring the potential in their marine areas.

In Figure 5 are shown the predictions for the EU power sector until 2050. Renewable capacities prevail, and conventional power generating capacities are in decline, with the exception of gas [16]. The reason why gas power plants continue to grow is because of lower pollution compared to coal and oil power plants [10].

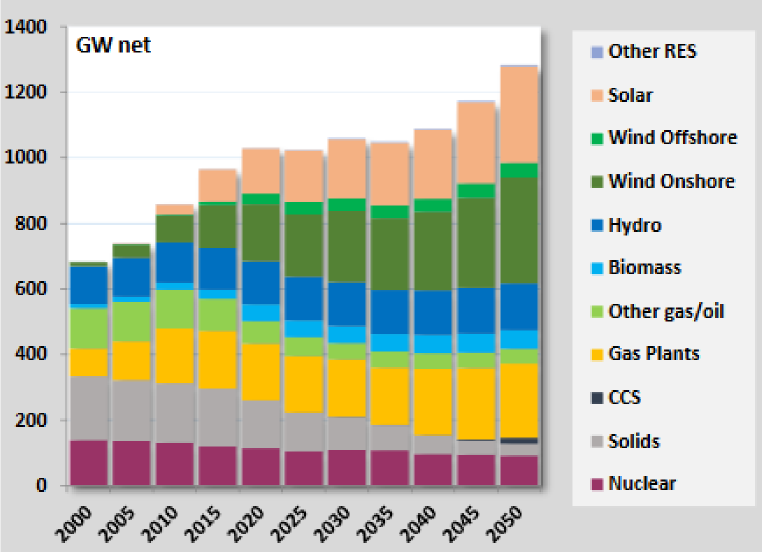


Figure 5. Operating power capacities in EU (GW) [16]

It should be noted that due to the crisis caused by COVID-19, some forecasts predicted a decline in production and investment in renewables. Forecasts for RES were pessimistic since the activity is reduced in most areas, the cost of projects is rising and investment decisions are put on hold because the banks are hesitant to approve loans. However, according to the International Energy Agency's (IEA) *Renewable Energy Report* from November 2020 [10], RES proved to be much less susceptible to the economic crisis than the fossil fuel industry. In May 2020, the IEA published an analysis of the impact of COVID-19 on the development of renewable energy, which showed that it did not decline, but was stagnated. The report from November pointed out that power from RES will increase by about 7% in 2020. Although there was a decline in bioenergy use in industry and biofuels in transport, the increase in demand for RES will be about 1% in 2020. The IEA reported that from January to October 2020, the auctioned renewable capacity was highest to date. Compared to the same period last year, it was 15% higher. Installed capacities will increase by 4% in 2020, which is almost 200 GW of newly installed RES. The US and China will lead the way. Each of these countries will record a 30% increase in wind and solar PV additions. In 2021, a record 10% increase in RES installations is expected, with India and Europe leading the way.

1.4. Croatia’s renewable energy sources

At the end of 2018, the total capacity of all power plants in Croatia was 5 010 MW [17]. Figure 6 shows the share of each technology in electricity generation at the end of 2019. For years, hydropower has been the leading RES, however, it is estimated that it is presently at its peak, as most dammed hydro potential resources have been built [18].

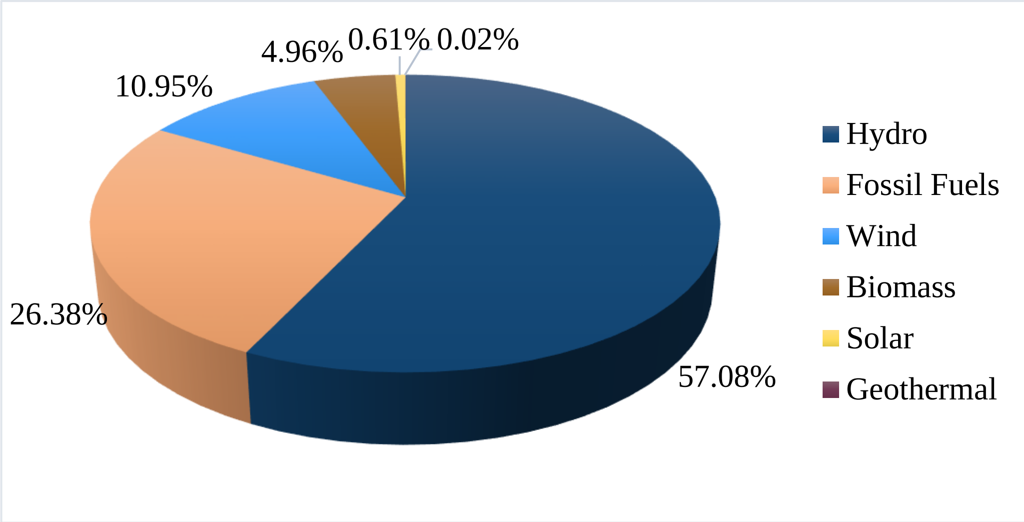


Figure 6. Generated electricity of power plants in Croatia at the end of 2019 [17]

Therefore, Croatia has turned to other RES resources such as onshore wind energy, biomass and biogas plants, solar photovoltaics (PV), and geothermal energy. In 2018, RES in Croatia accounted for 7.3% of primary energy production, not including hydropower which accounted for 30.3% [19]. Of those mentioned, onshore wind energy has developed the most significantly in the last decade. This development can be seen in Figure 7. Consequently, the potential for other forms of renewable energy that could be carried out is being explored and one of the possibilities is integrating marine renewable energy resources.

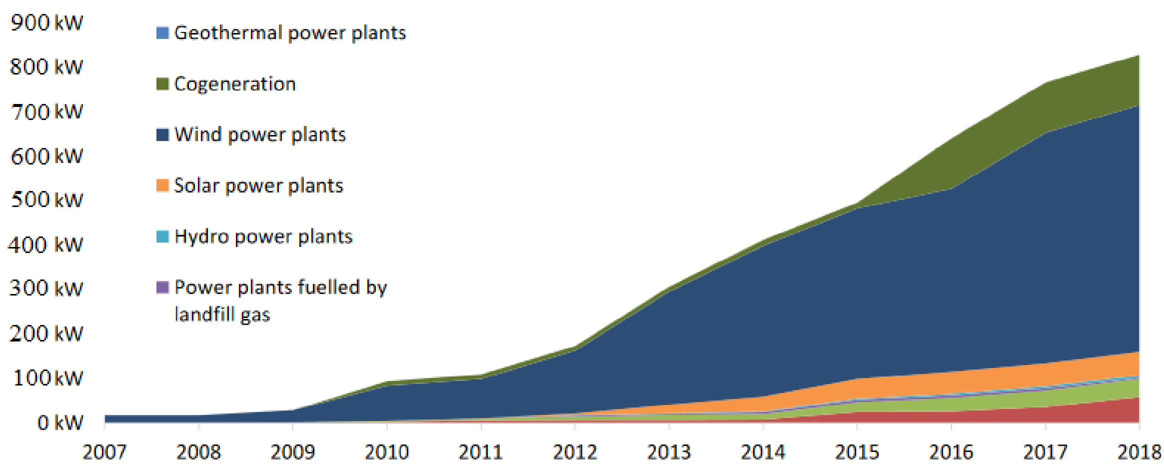


Figure 7. Installed capacities of RES technologies between 2007 and 2018 [17]

When compared to the other EU Member States, Croatia is currently above the EU average in achieving the goals of integrating renewable energy sources into gross final energy consumption, as well as CO_2 emissions per capita. In 2019, official statistical data regarding energy development until 2030, and the forecast for 2050 has been released. The data [20] showed that in 2017 the Republic of Croatia achieved a RES share of 27.3% in gross final energy consumption, while the EU average was 17.5%. Furthermore, the statistical data showed that Croatia has already achieved its target for 2020, which was set at 20% of the share of RES in gross final energy consumption. The same applies to CO_2 emissions, with 5.8 t CO_2 per capita in 2016, while the EU average was 8.44 t CO_2 per capita.

Croatia's future energy plans are presented in the Energy development strategy [20], where three possible scenarios are described. Scenario S0 is a continuation of the current measures, Scenario S1 is a plan to significantly improve energy efficiency, and Scenario S2 is similar to the previous one, but with the slower energy transition with regards to cost savings. As expected, Scenario S1 shows the potential for the greatest reduction in emissions, especially in 2050. The highlighted goals would be to work on increasing the efficiency of all systems, to invest in the insulation of buildings and to incorporate more hybrid and electric vehicles into transportation. In this thesis, the data according to Scenario S2 will be used for years 2030 and 2050.

In Scenarios S1 and S2, similar growth and decline are predicted, with the rise of some capacities being greater in Scenario 1 [21]. Given the current market competitiveness, it is assumed that the biggest number of new RES power plants will be solar and wind power. Slower but steady growth can be recorded for hydropower and gas. For hydropower plants, most dammed hydropower potential has been exploited, so the mentioned growth will be due to capacities from run-of-river hydropower and small hydropower plants. As for biomass and geothermal power plants, they will grow as well, but more slowly. The production of electricity from thermal power plants is expected to decline. Oil-fired facilities should be shut down by 2030, and coal-fired ones by 2040. Of course, this is very beneficial for the further exploitation of RES. While the Krško Nuclear Power Plant is planned to be out of operation by 2043 [22], there are ongoing tests to obtain a license to extend its operation even after that year [20]. Electricity generation has a similar trend to that of the installed capacities described above. That means that more electricity will be produced from RES, while most conventional power plants will slowly go out of operation, with the exception of gas power plants.

This thesis will analyse the Blue Energy potential in Croatia, with a focus on offshore wind power and other marine renewable energy technologies that apply to the Adriatic Sea. First, the data for 2018 according to [19] will be introduced. Then, estimates for 2030 and 2050 according to [23] will be presented. The data for RES in those years will be determined according to [20]. Finally, the impact of the selected marine RES on the Croatian national energy system will be observed in the years 2030 and 2050. In the end, their cost-effectiveness and contribution to decarbonisation will be observed.

2. BLUE ENERGY

Blue Energy (BE) is a name for the energy sector that exploits marine renewable energy (MRE) [24]. According to Castelos et al. [25], MREs are all the resources which are exploited in the marine environment. This refers to ocean energy, offshore wind, energy derived from marine geothermal resources, and bioenergy derived from marine algae. Ocean energy is further divided into five categories: wave energy, tidal current (stream), tidal range, thermal gradient (Ocean Thermal Energy Conversion - OTEC), and salinity gradient. All these technologies have potential in different parts of the world which has been known for years. However, due to the faster industrial and commercial growth of onshore wind energy, solar power and biomass, their development has been delayed [26]. Other obstacles are technology costs. Owing to the fact that most of these technologies are expensive, there is a risk that they will never be implemented [24]. It should be noted though that in the last few decades, combining different BE technologies has become common. Use of offshore wind and wave is already widespread. The benefits include cost reductions [27], better exploitation of marine space [28], smaller environmental impact, and others. To further foster the deployment of BE technologies it is important to interconnect legislation with the implementation of the new and emerging RES technologies in the Mediterranean area, including Croatia. Especially since Croatia has certain advantages over other Mediterranean countries. These include shallow bathymetry in the Adriatic Sea compared to rest of the Mediterranean Sea. This is suitable for offshore wind projects similar to those in the Northern Sea, wave energy converters, and the use of sea thermal energy for heating and cooling purposes in coastal areas. There are already commercial and prototype examples of these technologies in Croatia. They include seawater heat pumps across Croatia's coastline located in Dubrovnik, Makarska, Petrčane, Split and Novi Vinodolski. There is also a prototype of wave energy converter in Rijeka called Wave Breaker. In the following paragraphs will be given the description of marine renewable energy technologies.

2.1. Offshore wind energy

The idea of offshore wind turbines has been a step forward in the use of wind energy due to many advantages over onshore wind turbines. The main advantage of offshore wind turbines is that the wind speed offshore is higher. This is because there are no land obstacles, which means that they can generate more power. Also, the available terrain is larger so it is common to build wind farms. Since they are further away from populated areas, there are fewer complaints concerning noise and appearance. For the local communities, it also means more job opportunities. [29]

Disadvantages include problems with bringing parts to the location which brings up the costs. Also, it is more time consuming to fix the problems offshore [30]. Harsh sea conditions can damage the turbine and other parts. This is another reason why maintenance costs are high [31]. Furthermore, the big problem are capital costs which include the platforms on which they will be built on, interconnection, underwater cables, and other factors that increase the price in comparison to onshore wind [29]. On the other hand, an average onshore wind turbine is operating 2 000 – 2 500 hours per year, while offshore can operate up to 4 000 hours annually [32]. Therefore, even though it will take more time for return on investment (ROI), offshore wind turbines produce more power so in the long term they are more sustainable. Another cost indicator is Levelized Cost of Energy (LCOE). In 2019, for offshore wind it amounted to 0.115 USD/kWh and for onshore 0.053 USD/kWh, but these prices are continuously decreasing [8].

The scheme of the energy transmission system from the offshore wind farm is shown in Figure 8 [33]. The rotor blades convert wind energy into low-speed rotational energy of around 6 – 30 rpm, which is converted via a gearbox to about 1 500 rpm. The generator, connected to the turbine shaft with said gearbox, produces electricity of 400 – 1 000 V. Additionally, it must be transformed to the required local voltage before distribution. To export the power to shore, the turbines have to be connected to a transformer station. That is achieved with the external sea cable. Finally, a cable transmission station is a place where the offshore and onshore cables are connected.

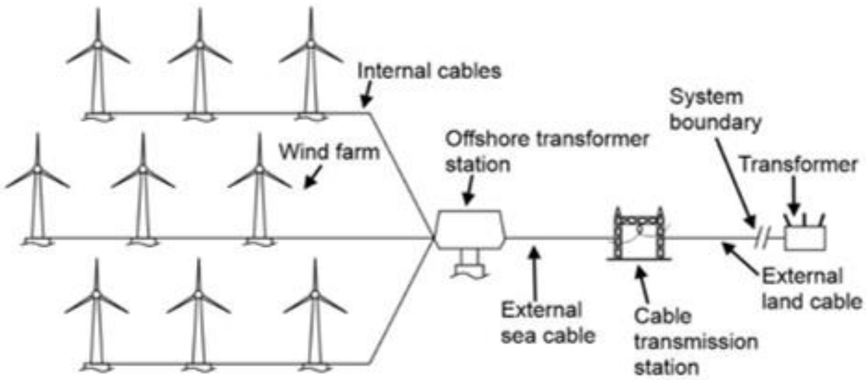


Figure 8. System boundary for an offshore wind farm [33]

Offshore wind turbine foundations are being extensively researched. The foundations are studied based on the wind conditions, turbine size, sea depth, waves, currents, geology and ice [33]. Increased interest for floating offshore turbines is particularly visible since they can be used in deeper water, for depths greater than 80 meters. In Figure 9 [34], three different types of offshore wind turbine foundations are shown. The first ones are monopole, and they are the most common, accounting for about 81% [35] of all offshore wind foundations in Europe. The second one is the jacket, which is the second most common with 8.9% [35] share in Europe. The remaining three types are offshore wind floating structures for higher depths – TLP, Semi-sub and Spar.

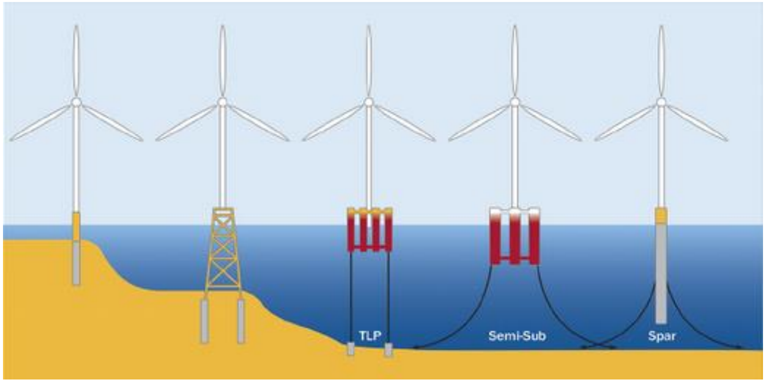


Figure 9. Type of offshore wind foundation [34]

There are indirect emissions related to wind energy. They are considerably smaller than for fossil-based resources and occur during construction of the system. Table 1 shows the approximate time it takes to recover the amount of emissions generated from onshore and offshore wind energy. That parameter is called energy payback time, and in the table, we can see that it amounts more for offshore than onshore wind. That is because transporting and mounting the offshore system is more energy and financially consuming than for the onshore system.

Table 1. Energy payback time in months for wind energy [36]

Wind energy	Turbine (MW – rotor diameter)	g CO_2/kWh	Energy payback time
Onshore	2.3 – 108	6	6.2 months
	3.2 – 113	5	5.2 months
Offshore	4 – 130	10.9	11.1 months
	6 – 154	7.8	10 months

When comparing BE technologies, offshore wind is the most developed and has the best prospects. In the last decade, the yearly average of newly installed offshore wind turbine capacities has risen by around 167%, from 3 to 8 MW. The average size of commercial offshore wind farms has grown approximately 200%, from 200 MW to 600 MW [35]. In 2019, new wind installations in Europe were 15.4 GW [13]. Out of those, 3.6 GW were offshore, which is a record amount of installed offshore capacity in one year [13]. Still, it is only 24% of all installed wind power. More than half of those installations were in the UK with 1.8 GW of installed capacity, in Germany with 1.1 GW, in Spain and Sweden [13].

According to a study published in 2019 [37], it is estimated that the theoretical maximum annual offshore wind production for the whole Mediterranean area is about 742 TWh annually. There were 92 wind farms installed in 11 European countries with fixed foundations mounted at depths below 50 meters. Wind speed needs to be between at least 7.5 – 8 meters to be cost-effective [38].

The total estimated technical wind energy potential in Croatia, which includes both built and unbuilt projects, is 7 000 – 9 000 MW [20]. Croatia has covered 8% of its power demand with wind energy in 2019, however, that was all from onshore installations, since it does not have any installed offshore wind farms [13]. The Adriatic Sea can be exploited for wind power, although with wind speeds of around 5 m/s [37]. Speed is the highest in the areas below the mountain ranges of Velebit and Dinara. The most promising areas for offshore wind are near the islands of Krk and Cres and near the city of Senj [39].

The research in one study [37] showed the potential for building offshore wind turbines in the Mediterranean. From Table 2 can be seen theoretically possible production for three depth categories. The second category, 50 to 250 meters deep, has proven to be by far the most promising. There is also the potential for deployment in the more shallow sections with depths of up to 50 meters.

The study showed that Croatia is one of the countries with the greatest potential in the Mediterranean.

Table 2. Theoretical maximum annual wind offshore production for Croatia [37]

I. Category: Annual offshore wind production 0 – 50 m (TWh/year)	8.2
II. Category: Annual offshore wind production 50 – 250 m (TWh/year)	53.8
III. Category: Annual offshore wind production 250 – 500 m (TWh/year)	0.9
Total annual offshore wind production (TWh/year)	62.8
Area (km^2)	46.5
Areal density of production (TWh/year)/km^2	0.001

2.2. Ocean energy

2.2.1. Wave energy

Wave energy generates power from the movement of waves. Wave energy converters are devices used to achieve that goal. They can be positioned near-shore, offshore, or submerged below the surface [40]. Medium to high latitude, from 40° to 60° [41], are the best conditions for the use of wave energy. Deep waters over 40 meters are favourable as well. The power density there is about 60 – 70 kW/m [42]. LCOE of wave energy is around 325 €/MWh which is one of the highest among RES resources [24].

There are various benefits and disadvantages of wave energy [41]. It is easily accessible, reliable and easy to predict. Its power density is 2 – 3 kW/m^2, which is more than wind's 0.4 – 0.6 kW/m^2 and solar's 0.1 – 0.2 kW/m^2. Furthermore, it can produce power 90% of the time, compared to 20 – 30% for wind and solar. Moreover, it can travel long distances with little energy loss. That can be observed by following the storms that travel from the western side of the Atlantic Ocean to the western coast of Europe. There are many different wave energy converters. However, because of the amount of research that still needs to be done and that involves investment, this can be considered both an advantage and a disadvantage. The devices have to be constructed so that they can withstand the harsh conditions that exist offshore. Also, converters have to be able to align with the direction, which is harder to predict offshore because it changes rapidly. Besides, it is difficult to maintain converters which operate further away from the shore and are submerged.

In the following is a brief description of the technologies, which are shown in Figure 10:

a) Attenuators – a sequence of connected tubes that move along the sea surface, following the movement of waves [41]. A representative example is the Pelamis snake which produces 750 kW of power. It is a joint steel tube 140 meters long, has a diameter of 3.5 meters, and a weight of 350 tons before ballasting [27].

b) Point absorbers – these are smaller devices where the rotational or fluctuating movement generates electricity [41]. The benefits are that they do not depend on the direction of the waves [41], they do not have to be fixed to the seabed which results in less impact on the marine environment [27], and can be either floating or submerged [43]. One of many examples is Ocean Power Technology's Powerbuoy (150 kW) [41].

c) Oscillating wave surge – converters that oscillate back and forth, and are positioned perpendicular to the wave direction [44]. They are usually fixed to the seabed and primarily installed nearshore [43]. Some examples include WaveRoller, Wavepiston, Aquamarine Power Oyster (800 kW) [43] etc.

d) Oscillating water column – the main components of these converters are the Wells turbine and air-water chamber. As the waves move, the air is compressed or expanded, driving the Wells turbine. The Wells turbine is independent of the airflow direction and thus ideal for this type of converter [44]. Although it has lower efficiency [41], it is still a useful way of generating power. They are usually installed near shore and have a power production between 300 kW and 1 MW [43]. One example is the Wavegen Limpet in Western Scotland (500 kW).

e) Overtopping devices [43] – the water tank is filled with water from the top, which then passes over the barrier and powers the turbine. Afterwards, the water returns to the ocean. One example is Wave Dragon with an output power between 4 and 11 MW, depending on wave power.

f) Submerged pressure differential devices – devices that are fixed to the seabed. First, the upper part is above the surface until the wave pressure pushes it downwards. It moves upwards when the pressure drops again [44]. While the advantage is that it is underwater and cannot be seen, the maintenance of it is problematic. These converters are usually located near the shore, and one example of this technology is the 250 kW Archimedes Wave Swing [41].

g) Bulge wave technology [45] – the rubber tube floats and is filled with water. When a wave passes, an air pocket is created. It passes through the tube and grows, gaining energy. That drives the turbine which is located at the end of the tube.

h) SEAREV wave energy converter [45] – a floating device with a weight or a gyroscope in it. The movement of that weight powers an electric generator inside the device which produces power.

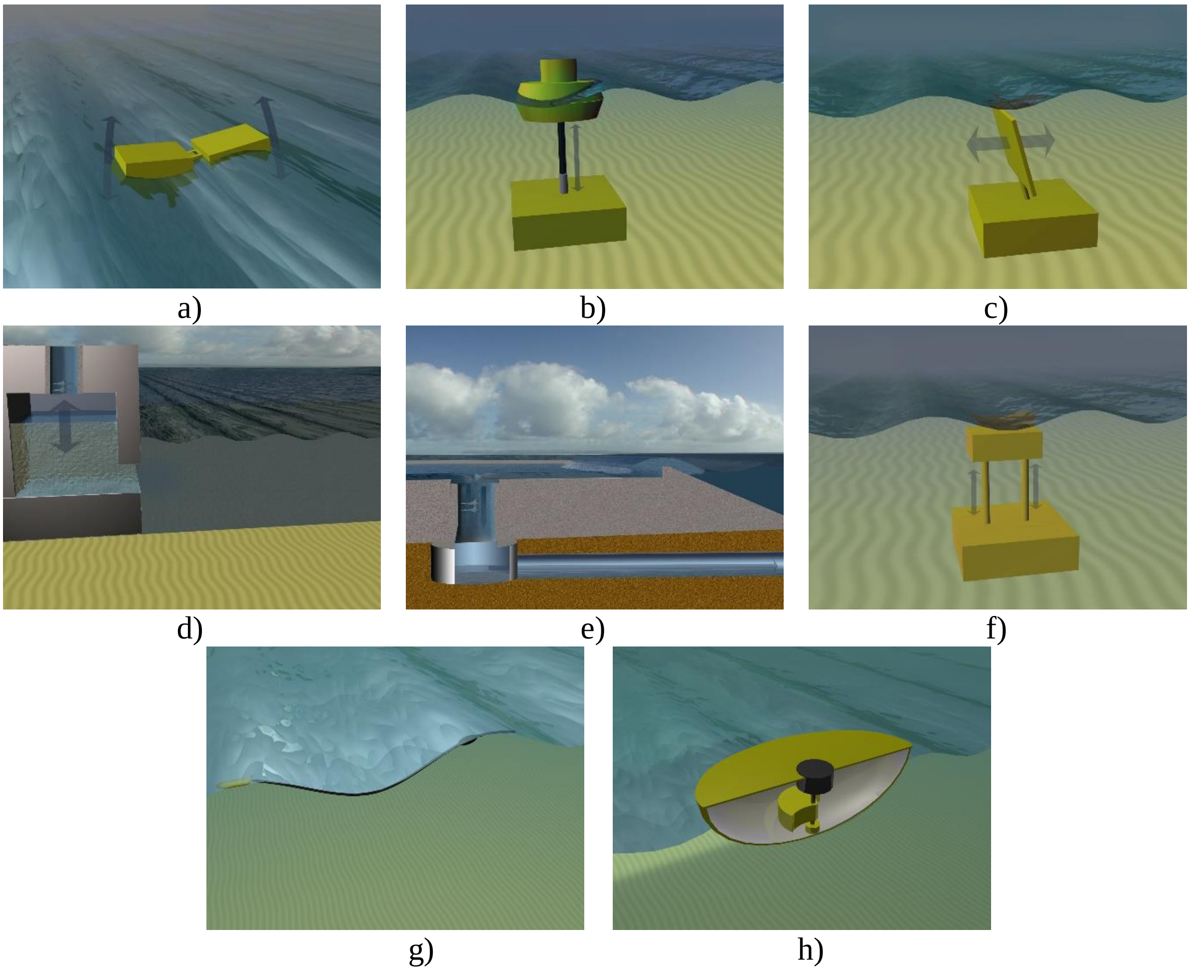


Figure 10. Types of wave energy converters [45]

According to López et al. [41], the most potential have the areas within 40° – 60° of latitude, both in the Northern and Southern Hemisphere. However, bigger potential has Southern Hemisphere because of the highest mean annual wave power, especially in the South – Indian Ocean with 120 kW/m of annual average power. Those areas include nearshore Australia, New Zealand, South Africa, Chile and the offshore area around 1 400 km east of Kerguelen Island. In the Northern Hemisphere, the most potential is in the North of the Atlantic Ocean, 50 – 60 meters deep, with 80 and 90 kW/m on the west coast of the British Isles, Iceland, and Greenland. Europe in general has very high potential, with already a lot of installed power and prototypes in the UK, Ireland, France, Spain, Sweden, Denmark etc. Furthermore, in the Mediterranean Sea, the region with the most potential is next to the northwest of the island of Sardinia, with an annual power range of 8.9 – 10.3 kW/m. As can be seen in Figure 11, the Adriatic Sea does not have a big potential for exploitation and is not economically viable. The Adriatic Sea is semi-enclosed and therefore the wave height is quite low [18]. Implementing it with other BE technologies, such as offshore wind, would be a good way to use wave energy.

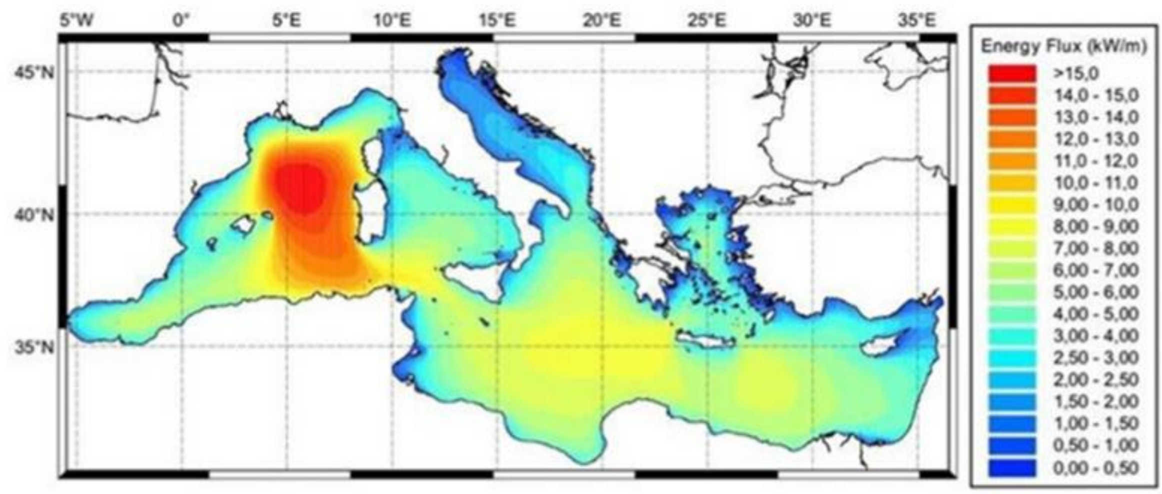


Figure 11. Wave energy potential in the Mediterranean Sea [46]

There is an innovative wave energy prototype in Croatia. It is called the Wave breaker [47]. It is a tube 5 – 20 meters in length and 1 – 10 meters in diameter. The inventors saw the destructive force of waves caused by storms in Adriatic. That is why this device was primarily developed as a shield for coastal areas from destructive waves. It collects kinetic energy and converts it to power. It also collects waste, which makes is a multifunctional device.

2.2.2. Tidal energy

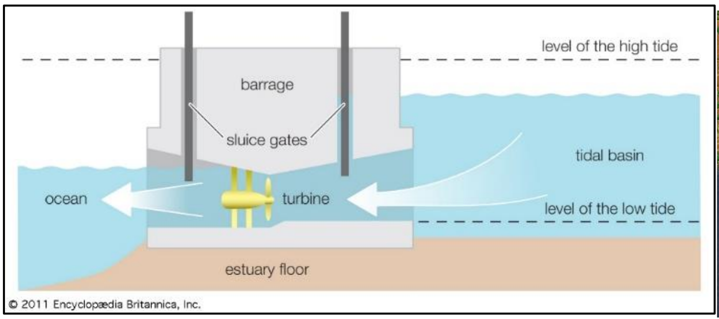
Tidal energy uses the rise and fall of the tides to produce power. Estimates have been made about the potential of tidal technologies. According to [27] data, it could generate as much as 1.2 million MWh per year, about 7.5% of all the world energy. Tides are created due to the gravitational forces between the Moon and the Sun [48]. The major benefit is that because tides arise at expected times, they are fairly predictable. That is why it cannot run out. It also has a high energy density [43]. On the other hand, it is still underdeveloped due to the high price, with LCOE of 190 €/MWh [24]. According to some studies, if the development of these technologies continues, tidal stream energy could be price competitive in 2050 [43]. Tidal energy can be classified into two categories: tidal current (stream) and tidal range.

2.2.2.1. Tidal range

The tidal range uses the difference in water height and that potential energy [49] is calculated as follows:

$$E_P = \rho \cdot g \cdot \int_{h=0}^{h=R} h \cdot A \cdot dh, \tag{1}$$

where ρ is the density of seawater (kg/m^3), A is the area of the basin, g is the gravitational acceleration (m/s^2) and R is the tide height above sea level (m). There are two types of tidal range systems: barrages and lagoons. Tidal barrages [50] emerged in the 1960s, the first one being in France. It is La Rance Barrage power plant built in 1966 with 240 MW of installed capacity and the mean tidal range of 8.5 meters [43]. The Sihwa Lake Tidal Power Station in South Korea is another famous example. It was built in 2011 with a record installed capacity of 254 MW. Tidal barrages allow water to flow through a turbine, similar to dams. These facilities are built across estuaries, as can be seen in Figure 12. This means that in the areas where there is a risk of flooding, it is especially useful as it can hold back or release water as needed [51].



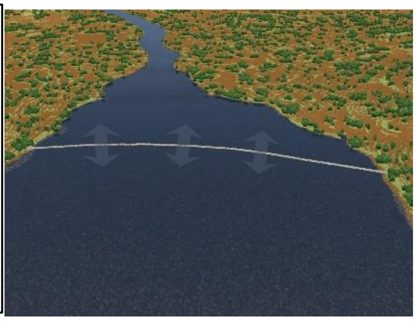


Figure 12. Tidal Barrage [52] [45]

Tidal lagoons are similar to tidal barrages. However, they do not fully close the estuary, only partly. They can also be built offshore. In Figure 13 are shown variations of tidal lagoon systems. The first one is similar to the tidal barrage but does not affect the flow of the entire estuary. The last two images show different types of construction for offshore tidal lagoons [53].

Figure 13. Tidal lagoon (left), single basin offshore tidal lagoon (middle) and multiple basin offshore tidal lagoon (right) [45]

2.2.2.2. Tidal stream or tidal current

For this type of tidal technology, no reservoirs are required. They usually use turbines or other mechanical devices to produce power. This is considered a great benefit because of less environmental impact [54]. One of the most common forms is a horizontal axis turbine which works similarly as the horizontal axis wind turbine, but the medium is water. Water has around 830 times higher density [52], depending on the depth, which means that more energy can be generated. Such environment also affects the performance and durability of components.

The turbine can be vertical, horizontal or ducted, but the following examples also include other types of devices used to harness the power of tidal currents. Tidal current technologies can be classified into six groups [45], with accompanying pictures in Figure 14:

a) Horizontal axis turbine [50] – the principle is the same as with wind turbine, but as it works in a denser fluid, the blades are smaller and their rotational speed is lower.

b) Vertical axis turbine – the blades are rotated around the vertical axis. It is commonly used because it runs independently of the direction of the current [54]. As with horizontal turbine, the blades are smaller with lower rotational speed compared to vertical axis turbines operating in the air. That construction is due to the higher density of water [55].

c) Oscillating hydrofoil – the tidal stream flows on either side of the hydrofoil, thus creating lift force. This motion is then used to drive a hydraulic system – a pump that increases the pressure on a fluid, which then starts a hydraulic motor [54].

d) Enclosed turbine [45] – this is the mechanism in which the horizontal axis turbine is placed in a Venturi tube. This implies that the flow of water is concentrated through the narrowing tube. As the cross-section narrows, velocity increases while the pressure decreases. This increased speed powers the turbine.

e) Tidal kite [45] – the aim of this system is similar to the previous one, which is to increase the velocity of the tidal stream. The turbine itself lies just below the kite. The kite moves in the shape of the number eight, which is the predetermined direction, and that is how the velocity is increased.

f) Archimedes screw [45] – a mechanism in which the water moves up the spiral which then produces power.

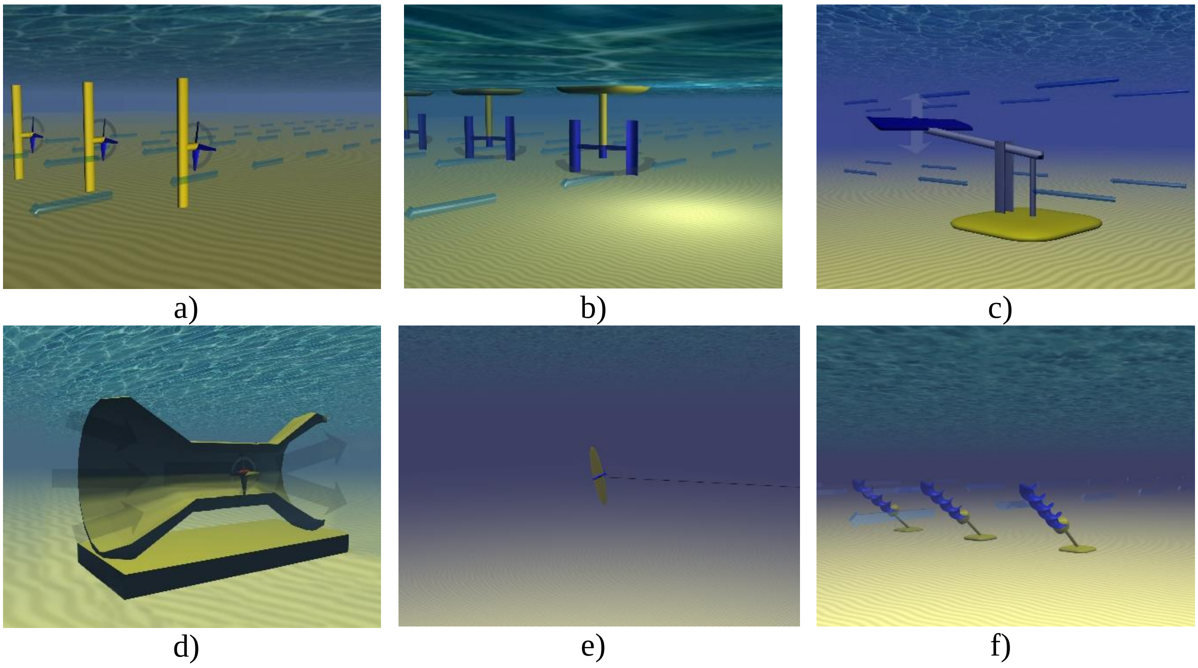


Figure 14. Types of tidal stream energy converters [45]

South Korea has the most capacities, but a large number of projects and planned prototypes are also in Europe. The north of Europe is widely known for its great potential and they have decided to explore it. However, other countries with potential have also committed themselves to developing this technology. Tidal technology capacities are mostly installed in the following countries: the UK, Ireland, France, Germany, Norway, Sweden, Denmark, Netherlands, Spain, Italy, South Korea, the USA, and Australia [43]. Of the countries in the Mediterranean area, regions in Greece (Evoia, Kea, Samos, Kithnos, Mytilene) and Messina Straits, Italy, have great potential [39]. In the Adriatic Sea, the most potential is in the Northern part. Within [38] was investigated the case of Limska draga bay, close to the city of Rovinj. It was concluded that to power a small town of fewer than 10 000 people, there would need to be a thousand large turbines to satisfy their power demand. From that example, it can be concluded that tidal energy is not suitable for development in Croatia.

2.2.3. Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) uses the temperature gradient between the warm surface and cold seawater at 800 – 1 000 meters in depth, with an average temperature difference of 20°C [56]. The bigger the temperature gradient, the more power can be produced [57]. OTEC technologies can be land-based, sea-based, or on floating platforms. Some challenges come with their integration such as environmental impact, issues with construction and material maintenance. Financial challenges include high capital costs and the current prices per kWh which are not competitive with other energy technologies.

According to a report published by the International Renewable Energy Agency (IRENA) [57], OTEC technologies are classified based on the working fluid that drives the turbine. Open (Claude) Cycle OTEC uses seawater, in which warm seawater passes through an evaporator, creating vapour pressure that drives the turbine. The cold seawater brought up from depth is then used to condense the vapour into a liquid state. That same water can then be used in an air-conditioning system, as well as for aquaculture because it is rich in nutrients. Closed (Rankine) Cycle OTEC uses ammonia as the working fluid which is especially convenient because it means a reduction in the size of turbines and pipes, thus lowering the price of the technology. Warm seawater brings ammonia to a vaporized state in the evaporator which then powers the turbine and finally is cooled down in condenser with cold seawater. Ammonia, warm and cold seawater never mix, hence closed cycle. Kalina cycle is a type of closed cycle OTEC where a mixture of ammonia and water is used as a working fluid, which has proven to have higher efficiency [58]. OTEC systems can also be hybrid meaning that they combine characteristics of open and closed cycles. Described technologies are shown in Figure 15.

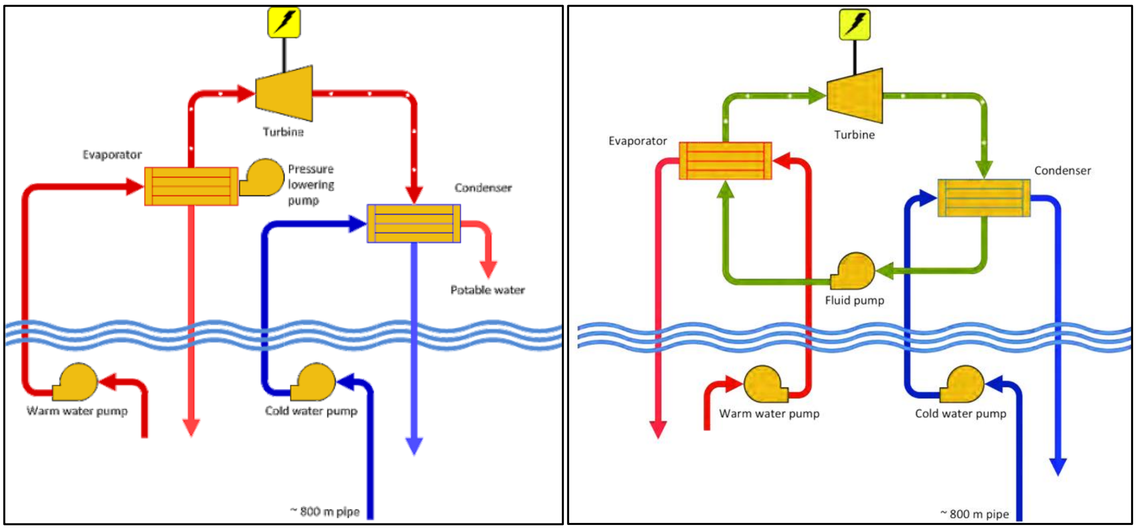


Figure 15. Open Cycle OTEC (on the left) and Closed Cycle OTEC (on the right) [59]

OTEC technologies are generally very beneficial for tropical area islands where their effects can be combined for freshwater production and air conditioning. The tropical west and southeast coast of America, a large number of islands in the Pacific, the Caribbean islands, the African and Indian coastlines are all areas that have a sea surface temperature of 25 – 30°C [56]. Those areas are marked in shades of orange on the map in Figure 16, which also shows the current operational plants as well as planned projects. Mediterranean Sea is generally warm, with a temperature of 10 – 12°C in the deep sea, which means that the temperature gradient is not high enough for sustainable energy development of OTEC plants for that region, and the map in Figure 16 shows the same results [27].

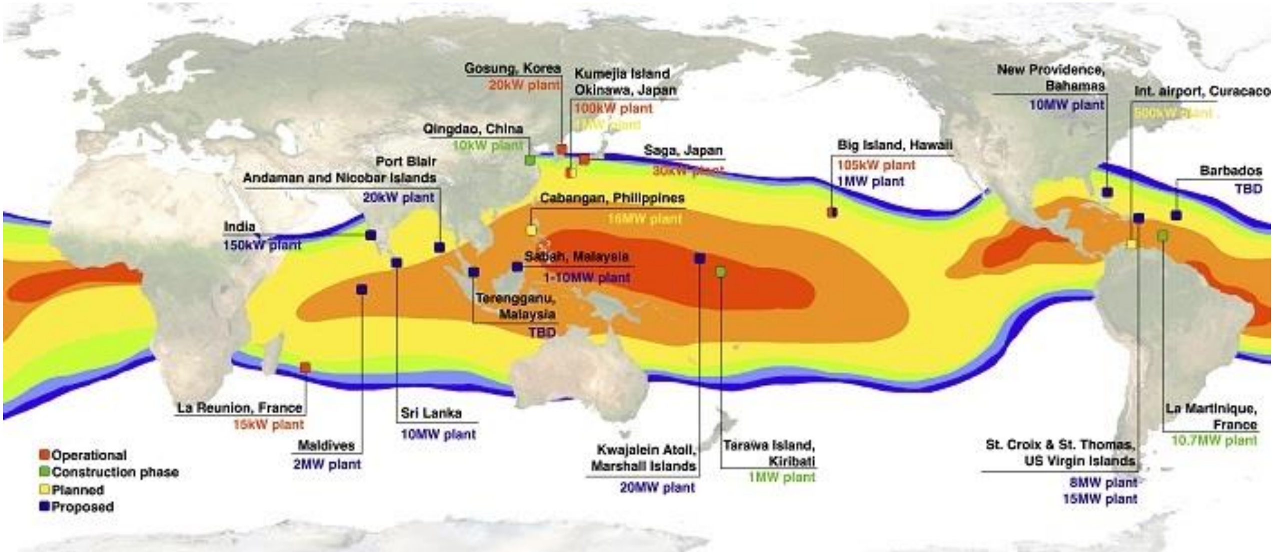


Figure 16. The regions suitable for the exploitation of OTEC technologies and existing or planned plants [60]

Adriatic sea is a very shallow sea with an average depth in the northern part of about 35 meters, in the central part 130 –150 meters, and in the southern part 450 meters [61]. The maximum depth is 1 233 meters in the south of the central part of the sea. Figure 17 [62] shows the vertical distribution of temperature along the south part, the Bari – Dubrovnik section. As can be seen, the temperature in the Adriatic sea even in the deepest parts is not lower than approximately 13°C and therefore is not suitable for integration of OTEC plants.

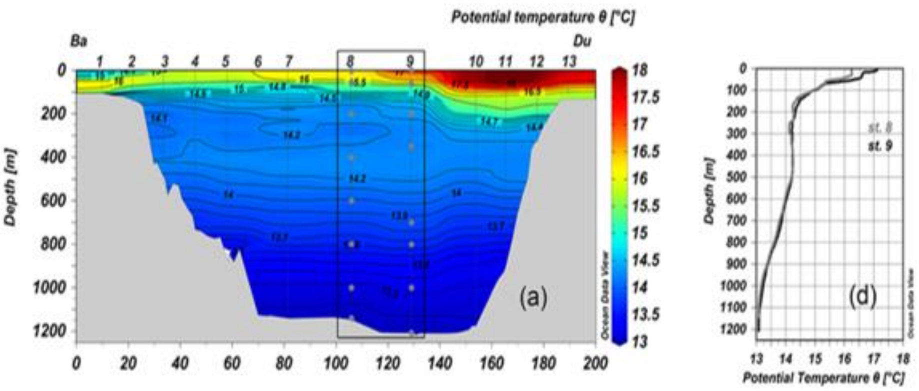


Figure 17. Vertical distribution of potential temperature along the Bari – Dubrovnik section of Adriatic Sea [62]

That being said, smaller systems in the form of seawater heat pumps are highly efficient, with high COP. They can be used for residential, commercial, and industrial purposes [63]. These heat pumps are used for heating, cooling, and preparation of domestic water, while the seawater intake can be as deep as 15 meters. There are eight built projects in Croatia. Those are mostly hotels located in Dubrovnik, Makarska, Petrčane and Split. There are also two seawater heat pump systems installed in two residential buildings in Split and Novi Vinodolski [64]. Because of their high coefficient of performance, they can contribute to savings in primary energy consumption and reduction of CO_2 emissions.

2.2.4. Salinity gradient

Salinity gradient power uses the salinity difference between seawater and fresh water at deltas and fjords [57]. When they mix, a difference in chemical potential occurs which has the potential to produce energy [65]. Economically, the membrane is the most challenging component because it makes up 50 – 80% of overall capital costs [66]. Another problem occurs in the case of natural estuaries because in these areas the difference between fresh and saltwater is too small [67]. A system that divides seawater and freshwater needs to be installed in these areas. Such structure includes for example dams or pipes, which will harm the ecosystem, as well as the land itself. The most investigated technologies are Pressure Retarded Osmosis (PRO) and Reversed Electrodialysis (RED).

In Pressure Retarded Osmosis (PRO) [68], water flows through a semi-permeable membrane. The membrane separates feed solution (low concentration solution) and draw solution (high concentration solution). Osmotic pressure develops due to the difference in salinity and the water molecules transfer from feed to draw solution. Consequently, there is a higher flow through the draw solution. A high-pressure pump is in that circuit and it drives the turbine. The membrane has a significant impact since the greater the flow of water means more generated power.

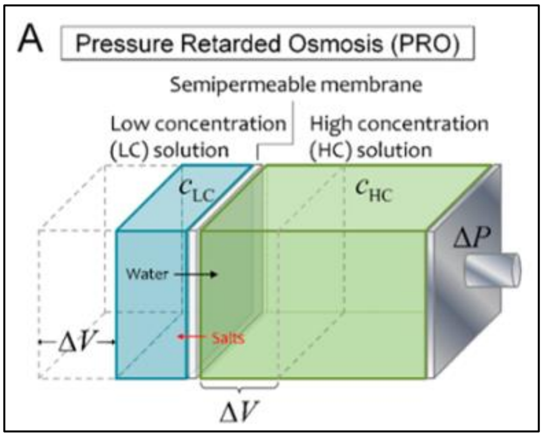


Figure 18. Pressure Retarded Osmosis (PRO) [69]

In Reversed Electrodialysis (RED) [68], there are cation exchange membranes (CEM) and anion exchange membranes (AEM), which are positioned between the cathode and the anode. The chambers between them are alternately filled with high concentration (HC) solution and low concentration (LC) solution [66]. The HC solution is seawater and the LC solution is freshwater. Due to the salinity gradient, a difference in the electric potential is created which allows the transition of ions from HC solution to LC solution. Cations are transferred to the right and anions to the left, as shown in Figure 19. This generated voltage builds up in every membrane and is converted to electricity.

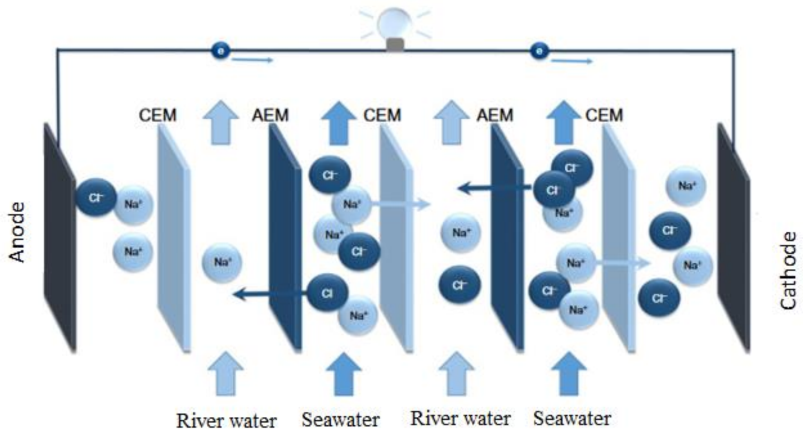


Figure 19. Reversed Electrodialysis (RED) [68]

According to Alvarez-Silva et al. [65], a significant amount of approximately 625 TWh annually of salinity gradient technologies can be exploited globally. The areas located around the equator have great potential because of stable temperatures during the year [66]. In Figure 20 can be seen surface salinity in the Mediterranean region. The Mediterranean Sea is an area with favourable conditions for the exploitation of salinity gradient energy because of more evaporation than precipitation and runoff, which makes the sea saltier, particularly in the eastern part [65]. As for the Croatian part of the Adriatic Sea, the salinity gradient could be exploited in the North Adriatic Sea. This is because of the high vertical change of salinity gradient caused by river runoffs [39]. The problem is that the technology is still evolving and is not yet widely available.

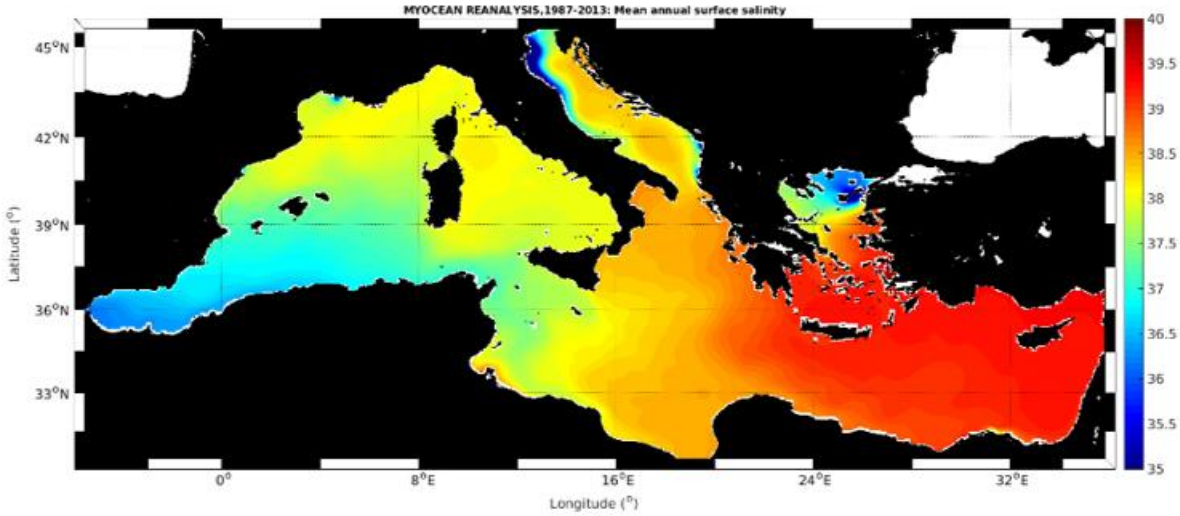


Figure 20. Mean annual surface salinity in the Mediterranean Sea for the period 1987 – 2013 [43]

2.3. Summary of the potential of Blue Energy with a view of Croatia

The analysis reported in [39] showed that from all the BE resources, offshore wind and thermal energy have the greatest potential in the Croatian part of the Adriatic Sea. The locations with the greatest potential for offshore wind are west and south-west of islands Cres and Lošinj, and also west and south-west of island Dugi otok. The seawater heat pumps have significant potential because of the temperature gradient between air temperature and seawater. Tidal energy is not the best option for the Croatian part of the Adriatic Sea, and neither is wave energy, however, by combining multiple marine renewable energy sources they could be cost-effective. The described scenarios will be developed in the following chapters.

3. METHODOLOGY

This thesis aims to carry out an analysis for the integration of selected BE technologies in Croatia. The focus will be placed on the implementation of offshore wind energy, wave energy and seawater heat pumps, for reasons explained in the previous chapter. The simulations were conducted for the locations that have the most potential for exploitation. Some assumptions have been introduced because of limited data and they will be described below.

The program EnergyPLAN [70] was used to carry out the analysis and is designed for examination of future demand and production. The overall impact that individual technologies may have on the power system is examined. This accelerates the process of analysis because the impact of several different technologies is observed. The program was used primarily to estimate production from RES, but it is also used to assess the current state of technologies in a region. Figure 21 shows the data taken into account for the simulation.

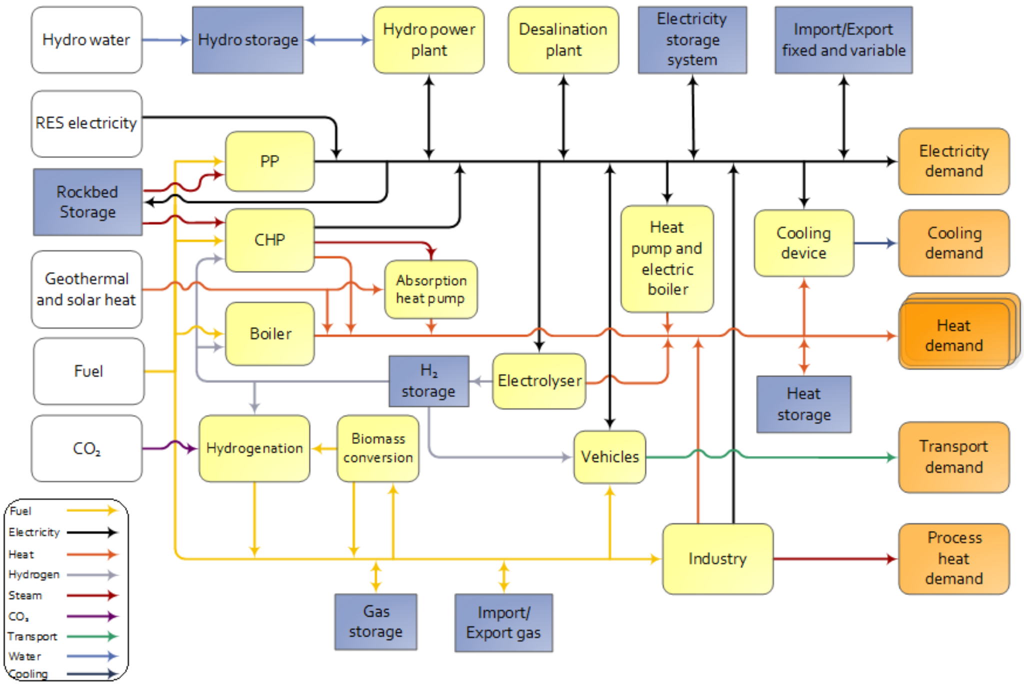


Figure 21. EnergyPLAN schematic

3.1. Modelling scenarios for 2018, 2030 and 2050

The data for 2018 was primarily collected from the annual energy report [19] for the same year. In the absence of required information, other literature was used, for example, data from IEA [10], Eurostat [71] etc. Most of the data for modelling consumption and production in 2030 and 2050 was taken from Resflex project [23]. This data was not analysed in detail, as more emphasis was placed on forecasts for RES and the potential of BE technologies. The data related to RES was taken from the Energy development strategy of the Republic of Croatia until 2030 with a view to 2050 (in the further text referred to as the Strategy) [20] and Annual Energy Report 2018 [21].

3.2. Electric demand

Electric demand is the key parameter when it comes to the modelling of energy systems. In 2018, the total electric demand in Croatia was 19.02 TWh. A large share of Croatia's electricity generation comes from hydropower, as it was mentioned in the Introduction, though there is still a substantial share from fossil-based power plants. Hydropower is the leading RES in Croatia, followed by onshore wind energy, biomass, solar and thermal energy [17]. While in 2018 electricity import was lower compared to 2017, the numbers show that Croatia is still highly dependent on them. That can be seen in Fixed Imports/Exports in Table 3. Imports of electricity amounted to 7.4 TWh/year, while exports were only 2 TWh/year.

For 2030, an annual electric demand of 17.3 TWh is predicted, while for 2050 it is expected to be around 21.8 TWh [23]. Even though countries around the world are encouraging a reduction in consumption, the demand is still expected to increase. Croatian production and supply cannot fully meet its demand, and therefore has to import most of its energy needs [72]. However, this is not the case only for Croatia. Other European countries also rely on import, some more than others. This implies a great dependency from non–European countries, and therefore one of the reasons why the whole of Europe is turning to RES. Moreover, this shows a great need for better interconnection between European countries to ensure the overall stability of continental grid.

Table 3. Electricity demand

Electricity demand	**2018** [19]	**2030** [23]	**2050** [23]
Total electric demand	19	17.3	21.8
Fixed Import/Export	-5.4	0	0

3.3. Heating and cooling demand

The residential sector represents a large share of Croatia's energy consumption. as seen in Table 4. It should be emphasized that a significant percentage of the buildings is expected to be insulated in the upcoming years to reduce the demand for heating and cooling. Therefore, the assumption is that the demand per building will be reduced from 15 000 kWh/year in 2018 to 10 000 kWh/year in 2030, and 7 500 kWh/year in 2050.

Biomass and natural gas boilers are most commonly used in individual heating. Oil boilers and electric heaters are used to a much smaller extent, while the share of coal boilers is the lowest. Air conditioning systems are a common option for cooling. The demand for cooling has been increasing as temperatures continue to rise due to global warming. The technology efficiencies were taken from EnergyPLAN [70] and Resflex, as indicated in Table 4.

Table 4 also shows the scenarios for 2030 and 2050, which assume that seawater heat pumps will be used. There are no forecasts for seawater heat pumps, so the heat demand is assumed as follows. The total amount of heat demand from coal boilers in 2018 has been added to the existing 2 TWh/year of heat demand for heat pumps in 2030. This means that it was assumed that the heat demand of 0.03 TWh/year for the coal boilers will be covered by heat pumps in 2030. It is expected that coal boilers will be out of operation by 2030. The same heat demand transfer was done for oil boilers, which will be out of operation by 2050. Their reduction from 1.1 TWh/year in 2018 to 0.9 TWh/year in 2030 was added to heat demand for heat pumps. For 2050, the remaining 0.9 TWh/year from oil boilers were also transferred to heat pumps. This replacement of coal and oil boilers with seawater heat pumps was made to cover cooling demand needs, an option which coal and oil boilers do not provide. COP of 4 for heat pumps is put in the model as they generally have high efficiency.

Table 4. Annual heating and cooling demand in households

Type of fuel	**Fuel input [TWh/year]**			**Technology Efficiency**
	2018	**2030** [23]	**2050** [23]	
Coal boiler	0.03 [19]	0	0	80% [23]
Oil boiler	1.4 [19]	1.1	0	80% [70]
Natural gas boiler	5.4 [19]	8	0	90% [70]
Biomass boiler	12.1 [19]	10	1.2 (Efficiency: 80%)	70% [70]
Heat pump	0.2 [71]	2.3	7.4	COP = 4
Electric heating	1.5 [71]	0	0	100%
Heat demand	**16.2**	**17.34**	**8.4**	
Electric cooling	0.52 [71]	0.8	1.4	EER = 4
Cooling production	**2.1**	**3.11**	**5.6**	

District heating also contributes to covering the demand for heating, which can be seen in Table 5. The data related to district heating is defined as the heat used in residential and commercial services [71]. Smaller Combined Heat and Power (CHP) plants produce 1.3 TWh/year, and 0.4 TWh/year from large CHP plants.

Table 5. District heating by groups

District heating (TWh/year)	**Group 2**			**Group 3**		
	2018 [19]	2030 [23]	2050 [23]	2018 [19]	2030 [23]	2050 [23]
Production	0.4	0.63	1	1.3	2.5	2.4

3.4. Fuel consumption

EnergyPLAN enables classification of fuel consumption by sectors. CO_2 emissions from the transport and industry sectors are significantly lower but are still analysed as they are needed to build the reference scenario. For industry sector in 2018, oil and natural gas are used the most, while coal and biomass to a much lesser extent. Diesel and motor gasoline dominate in transport as shown in Table 7.

The prognosis for 2030 in the industry sector is that there will be no coal, while the consumption of oil will be significantly reduced. However, there will be significant growth in usage of natural gas and biomass, which is in accordance with Scenario S2. That Scenario has a more conservative approach to achieving emission reduction targets and that is why natural gas will still be used to some extent. However, in the 2050 scenario, it is assumed that oil will no longer be used, and that natural gas and biomass will have a large decrease in consumption. This can all be seen in Table 6.

Table 6. Fuel consumption in industry

Type of fuel	**Fuel consumption [TWh/year]**		
	2018	**2030** [23]	**2050** [23]
Coal	0.8 [19]	0	0
Oil	3.5 [19]	1	0
Oil – various industries	7.9	2.9	0
Oil Total	11.4	3.9	0
Natural gas	4.5 [19]	8	2
Natural gas – various industries	4.3	9.2	0
Natural gas total	8.8	17.2	2
Biomass	0.6 [19]	5	0.9
Biomass – various industries	0.1 [19]	0	0
Biomass total	0.7	5	0.9

As for the transport sector, in 2030 is expected an increase in jet fuel and motor gasoline consumption, and a decrease in diesel, natural gas and LPG consumption. However, a substantial increase in the use of electric vehicles is expected. For 2050, the only increase is expected for natural gas, biofuels and especially electric vehicles. For electric vehicles, battery storage amounts 3.6 GWh and capacity of the grid to battery connection is 671 MW for 2030. In 2050 those numbers are 80 GWh and 5 440 MW [23]. It is also predicted that there will be more hydrogen vehicles, but not in large quantities.

Table 7. Fuel consumption in transport

Type of fuel	**Fuel consumption [TWh/year]**		
	2018	**2030** [23]	**2050** [23]
Jet fuel	0.1 [10]	0.6	0
Diesel	17.2 [19]	7.6	0
Petrol / Methanol (Motor gasoline)	6.1 [19]	9.5	0
Natural gas	0.05 [19]	0.01	0.05
LPG	0.9 [19]	0.6	0
Liquid biofuels (Diesel biofuels)	0.3 [19]	0	2.7
Petrol / Methanol biofuel	0.007 [71]	0	0
H2	0	0	0.5
Electricity (Dump Charge)	0.3 [71]	2.05	0.1
Electricity (Smart Charge)	0	0.4	5.9
Capacity of grid to battery connection [MW]	0	671	5440
Battery storage capacity	0	3.6	80

3.5. Energy supply

Croatia uses hydropower and thermal power plants to cover a large part of its electricity needs. A significant amount also provides the Krško Nuclear Power Plant, which is located on Slovenian territory but is 50% owned by Croatia, with 348 MW of capacity and an efficiency of 49% [73].

In Table 8 are shown capacities for energy supply. First, it will be described what the different groups signify, according to EnergyPLAN. Group 1 represents district heating systems with no CHP, Group 2 are district heating systems based on small CHP plants and Group 3 are based on large CHP plants. Table 8 shows how the data is distributed in EnergyPLAN model for the reference year 2018. Terms marked TE-TO (*cro. Termoelektrana-toplana*) and EL-TO (*cro. Elektrana-toplana*) are heating plants. In the Boilers category are plants or units with only thermal capacities. In the CHP Condensing Mode category are cogeneration plants which do not have any useful heat production and are used only for electricity generation. The CHP Back

Pressure Mode category represents the thermal capacities of cogeneration plants. In Condensing PP2 are plants which produce only electricity. And lastly, in category Industrial CHP are cogeneration plants which are used in the industry. The meaning of the abbreviations is described in the legend below the table.

Table 8. Thermal power plants and CHP facilities

Boilers – Group 3 [74]	MW_{topl}
TE-TO Sisak PK1	20.2
TE-TO Sisak PK2	20.2
TE-TO Zagreb VK3	58
TE-TO Zagreb VK4	58
TE-TO Zagreb VK5	116
TE-TO Zagreb VK6	116
TE-TO Zagreb PK3	55
TE-TO Zagreb Block M	2x24
EL-TO Zagreb Block G (VK3)	116
EL-TO Zagreb Block K (VK4)	121
DH Velika Gorica	69,6
DH Samobor	16,6
DH Zaprešić	20,4
Total	≈835
Combined Heat and Power (CHP) - Condensing Mode Operation [74]	MW_{el}
TE-TO Sisak Block C	235
TE-TO Sisak Block D	3
TE-TO Zagreb Block C	120
TE-TO Zagreb Block K	202
TE-TO Zagreb Block L	110
EL-TO Zagreb Block H	25
EL-TO Zagreb Block J	25
TE-TO Osijek Block A	45
TE-TO Osijek Block B1 and B2	2x25
TE-TO Osijek Block F	3
TE Plomin – Block B	199
Total	1 017
Small CHP [75]	84.6
Total CHP Condensing Operation Electric Capacity	1 101.6
Combined Heat and Power (CHP) – Back Pressure Mode Operation – Group 2 [75]	MW_{topl}
Small CHP – Back Pressure Mode operation	190
Combined Heat and Power (CHP) – Back Pressure Mode Operation – Group 3 [74]	MW_{topl}
TE-TO Sisak Block C	50
TE-TO Sisak Block D	10
TE-TO Zagreb Block C	230
TE-TO Zagreb Block K	150
TE-TO Zagreb Block L	132
EL-TO Zagreb Block H	62,8

EL-TO Zagreb Block J	62,8
TE-TO Osijek Block A	130
TE-TO Osijek Block B1 and B2	37
TE-TO Osijek Blocks C, D and E	35
TE-TO Osijek Block F	10
Total	909,5≈910
Condensing PP2 [74]	MW_{el}
KTE Jertovec KB A	38
KTE Jertovec KB B	38
TE Rijeka	303
Total	379
Industrial CHP [19]	TWh/year
CHP Electricity – Group 2	0.01
CHP Electricity – Group 3	0.4

*PK (*cro. Parni kotao*) – steam boiler; VK (*cro. Vrelovodni kotao*) – hot water boiler; PK (*cro. Pomoćna parna kotlovnica*) – auxiliary steam boiler room; DH (*cro. Centralizirani toplinski sustav*) – district heating; KB (*cro. Kombinirani blok*) – combining block; TE-TO (*cro. Termoelektrana-toplana*) – cogeneration power plant; EL-TO (*cro. Elektrana-toplana*) – cogeneration power plant, KTE (*cro. Kombi termoelektrana*) – power plant for electricity generation; TE (*cro. Termoelektrana*) – power plants for electricity generation

For 2030, in Boiler Group 3 is predicted an increase in thermal capacities to 1 488 MW and a decrease in CHP Condensing mode to 830 MW. For Group 2, the capacities for CHP Back Pressure Mode are 270 MW, and for Group 3 an electric capacity of 620 MW. All capacities for PP2 are predicted to be shut down, as well as industrial CHP power plants. For 2050 there is no change for Boiler Group 3 and PP2 capacities. For CHP Condensing mode is predicted a decrease to 600 MW of installed capacity. For CHP Back Pressure Mode are predicted 200 MW in Group 2 and 480 MW in Group 3. There is also an increase in industrial CHP heat demand to 2.9 TWh. The efficiencies for the mentioned facilities were taken from Resflex.

In

Table 9 can be seen the list of hydropower plants in Croatia [19]. The total dammed hydro and river hydropower from the table is put in EnergyPLAN. For the year 2018, total dammed hydropower capacity is 1 373.6 MW, while for river hydro 438.4 MW. Data from IEA shows that total hydropower production in 2018 was 7.7 TWh and it represents the sum of dammed hydro and run-of-river hydro capacities. River hydro production was calculated in EnergyPLAN and amounts 2.1 TWh. Therefore, dammed hydropower production is 5.6 TWh, which means that the set value for dammed hydro water supply is 3.5 TWh. It should be mentioned that hydropower plant Velebit has a storage capacity of 3.4 GWh, which was put in Electricity storage in EnergyPLAN. Its capacity amounts 276 MW and 3.4 GWh of storage capacity. Storage for Dammed Hydro is taken from Resflex. It amounts 4 100.7 GWh. A further increase in dammed hydro is not expected but run-of-river hydropower is presumed to grow.

Table 9. Hydropower plants in Croatia in 2018 [19]

Unit	Power capacity [MW]	Type
HE Zakučac	538	Dammed hydro
HE Orlovac	237	Dammed hydro
HE Senj	216	Dammed hydro
HE Dubrovnik	117.5 [74]	Dammed hydro
HE Vinodol	90	Dammed hydro
HE Kraljevac	46.4	Dammed hydro
HE Peruća	60	Dammed hydro
HE Đale	40.8	Dammed hydro
HE Sklope	22.5	Dammed hydro
Total dammed hydro storage	1 368.2	
RHE Velebit	276	Pumped-storage
RHE Fužina	4.6	Pumped-storage
RHE Lepenica	0.8	Pumped-storage
Total pumped-storage	5.4	
HE Varaždin	94.6	Run-of-river
HE Čakovec	77.4	Run-of-river
HE Dubrava	79.8	Run-of-river
HE Gojak	55.5	Run-of-river
HE Rijeka	36.8	Run-of-river
HE Miljacka	20	Run-of-river
HE Lešće	41.2	Run-of-river
Total run-of-river	405.3	
Small hydropower plants	33.1	
Total Dammed Hydro Power	**1 373.6**	
Total River Hydro	**438.4**	

3.6. Transmission line capacity

HOPS [76] is Croatia's transmission line operator. It is responsible for managing and observing the electrical grid. The 400 kV voltage systems of Croatia with neighbouring countries are:

- 400 kV line Ernestinovo-Ugljenik (Bosnia and Herzegovina);
- 400 kV line Konjsko-Mostar (Bosnia and Herzegovina);
- 400 kV line Ernestinovo-Sremska Mitrovica 2 (Serbia);
- 2x400 kV line Žerjavinec-Héviz (Hungary),
- 2x400 kV line Ernestinovo-Pécs (Hungary);
- 2x400 kV line Tumbri-Krško (Slovenia)
- 400 kV line Melina-Divača (Slovenia)

In addition to these 400 kV voltage systems, it also has eight 220 kV lines and eighteen 110 kV lines. In Figure 22 are shown other operators of transmission system who regulate and enable cross-border transmission.

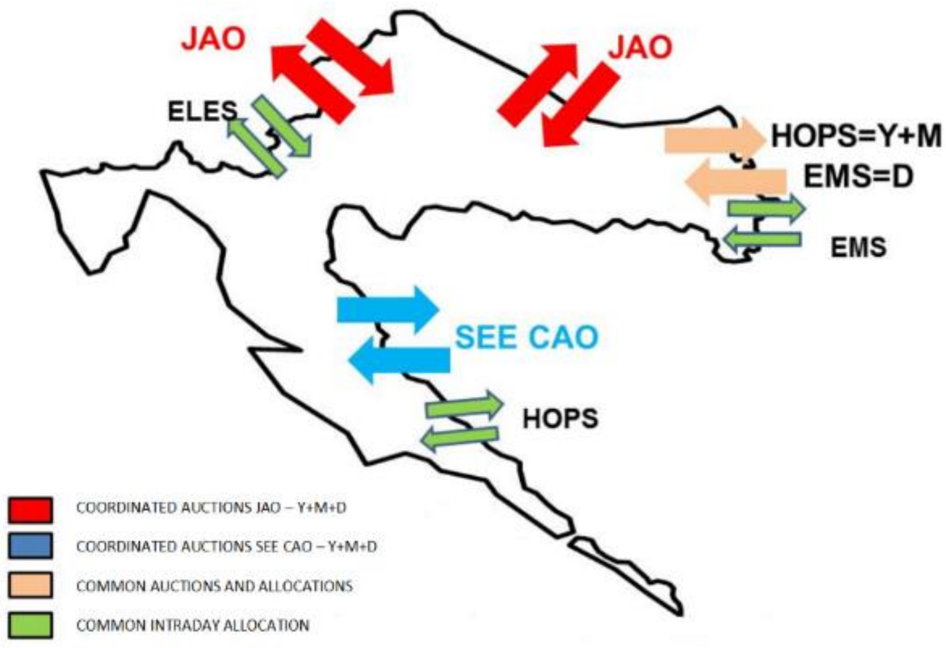


Figure 22. Distribution of Croatia's interconnection lines [77]

The total transmission line capacity in EnergyPLAN is presented as average Net Transfer Capacity (NTC). It amounts to 4 000 MW [17]. For 2030 the same amount is predicted, while for 2050 it is assumed that it will be 5 000 MW [23].

3.7. Renewable energy sources

Croatia still imports 40% of electricity demand, 60% of gas and 80% of oil [78]. However, it has the potential to generate a large percentage of its energy from renewable sources. In this way, it could ensure energy independence, which after all is the general objective of most strategies. In this thesis, predictions for RES were taken according to Scenario S2 from the Strategy. Although smaller RES capacities are assumed under this scenario, it is nonetheless clear from Figure 23 that their capacities will increase significantly.

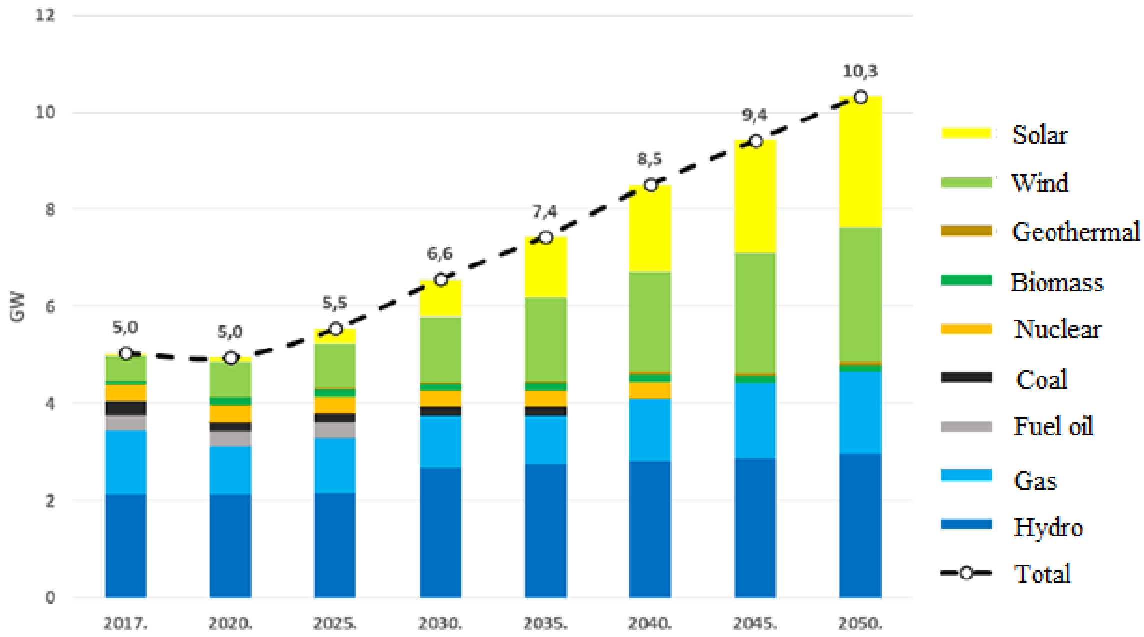


Figure 23. Installed capacity predictions between 2017 and 2050 [20]

In Table 10 are shown input data for variable renewable energy capacities.

Table 10. Variable renewable energy sources capacities

Technology capacity [MW]	**2018** [19]	**2030** [21]	**2050** [21]
Geothermal	10	17	50
Onshore wind	586.3	1 364	2 792
Solar PV	67.7	768	2 692
River Hydro	438.4	924.9	1 216.9

All hydro capacities planned for 2030 and 2050 are put as river hydro, as it is assumed that all dammed hydropower has been exploited. Those hydro capacities are 924.9 MW in 2030, and 1 216.9 MW in 2050.

The same capacities for solar thermal in 2030 are predicted as for the referent scenario, while for 2050 is predicted an increase to 0.7 TWh in Group 3. Installed capacities of compression heat pumps are 200 MW in 2030 and 100 MW in 2050 with COP of 2.5 [23].

3.8. Fuel distribution

For the purposes of the calculation, it is necessary to indicate how much fossil fuel and biomass is used for electricity and heat. The distribution in 2018 is shown in Table 11.

Table 11. Fuel distribution [10]

	Coal	Oil	Natural gas	Biomass
CHP3	0.04	0.2	6.2	2.7
Boiler 3	0	0.06	0.5	0
PP1	3.4	0	0	0
PP2	0	0.01	0	0.08

For 2030 fuel distribution is similar, except in PP2 field there are no fuels. This is because it is assumed that there is no more production from PP2 by 2030. In 2050, the situation is entirely different because it is assumed that there will be no more thermal power plants. Therefore, the only fuel for power plants among those in Table 11 is biomass. For DHP, CHP2, Boiler2, Boiler3 and PP1 is assumed 0.4 TWh/year of biomass fuel. For CHP3 that amount is 0.4 TWh/year, for PP2 it amounts 1 TWh/year and for CHP2 in electrofuel category 0.4 TWh/year [23]. Electrofuel includes synthetic gas and liquid fuel production [79].

3.9. Distributions

When all the input data has been gathered, the annual hourly distributions need to be loaded to simulate the behaviour and analyse the impact of RES. It is important to see when the peak loads occur to determine which fuel is the most suitable. Those distributions are text files with hourly values for the one-year period (366 days × 24 hours = 8 784 hours). Most of the distributions are taken from Resflex, except for cooling load and distributions for BE technologies.

In Figure 24 is shown the annual distribution of electric consumption. The electricity consumption is similar in the summer and winter months, because of high consumption in the summer, which is related to the tourist season, while in winter many households still use electric heaters for heating purposes.

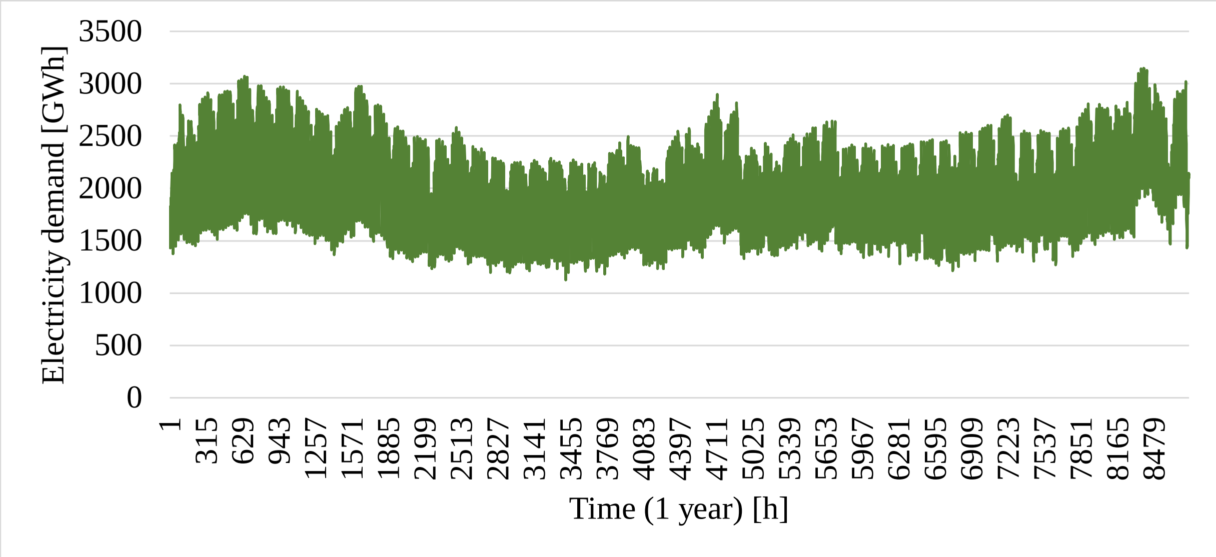


Figure 24. Distribution of electricity demand for one year [23]

The heating demand is shown in Figure 25 and the graph indicates that it is the highest during January.

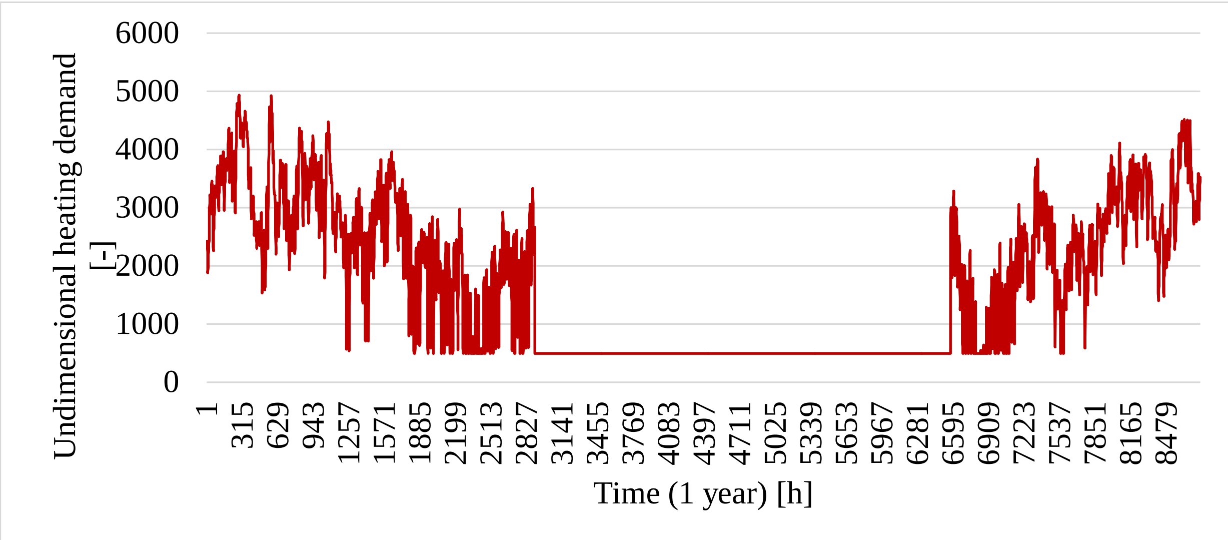


Figure 25. Individual heat demand [23]

Cooling demand has been approximated according to meteorological data. As can be seen in Figure 26, the cooling load is high from June to August, with peak load in July.

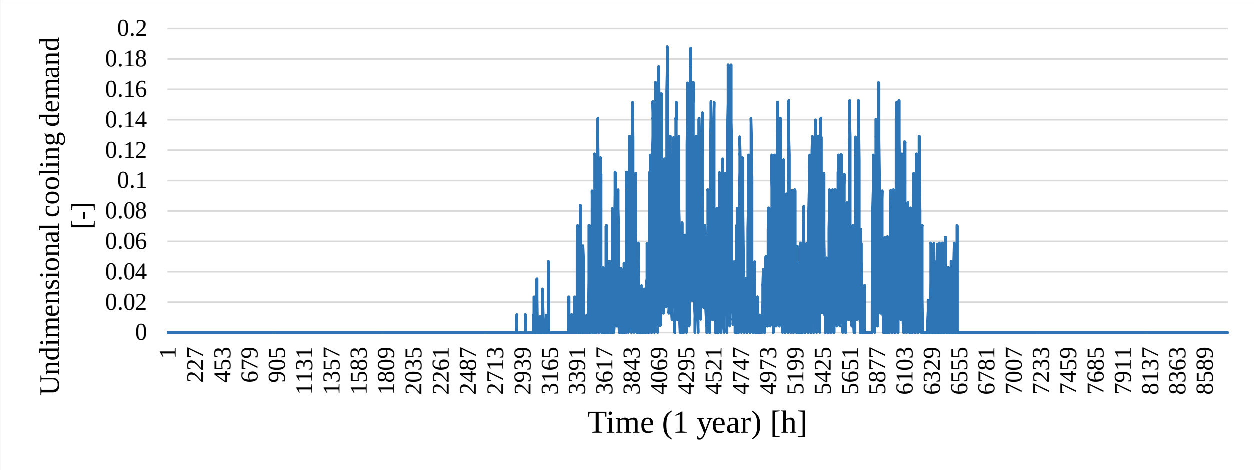


Figure 26. Cooling demand

Solar production is shown in Figure 27. As expected, the largest production is during summer, with the highest production between May and September.

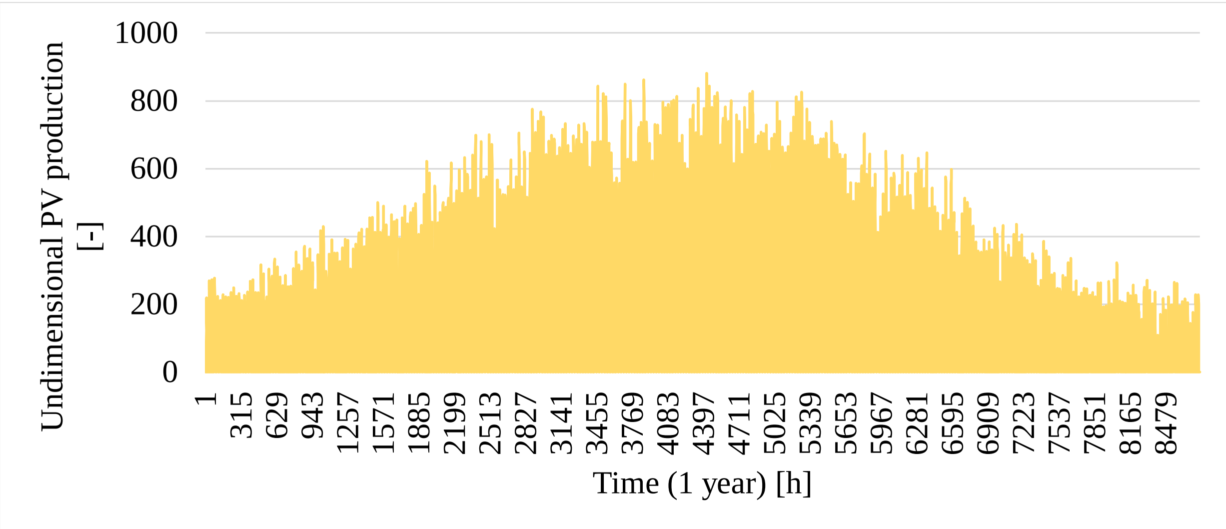


Figure 27. Solar PV production for Croatia [23]

4. ASSESSMENT OF BLUE ENERGY POTENTIAL IN CROATIA

4.1. Offshore wind

To determine the potential offshore wind capacities in the Adriatic Sea, it is necessary to identify the areas where they can be built. Those will be determined by taking into account certain criteria which will be explained in this chapter. The average wind speed in Croatia can be seen in Figure 28. The impact along the Croatian part of the Adriatic Sea is examined in this thesis, and it is visible from this picture which areas have the highest wind speeds. The coastal region below Velebit has the highest speed, but due to its proximity to the coast, these areas are not suitable for offshore wind energy. The interesting regions are the open sea south of the city of Pula, and more noticeably the open sea region parallel to the area between the Kornati archipelago and the city of Primošten [80].

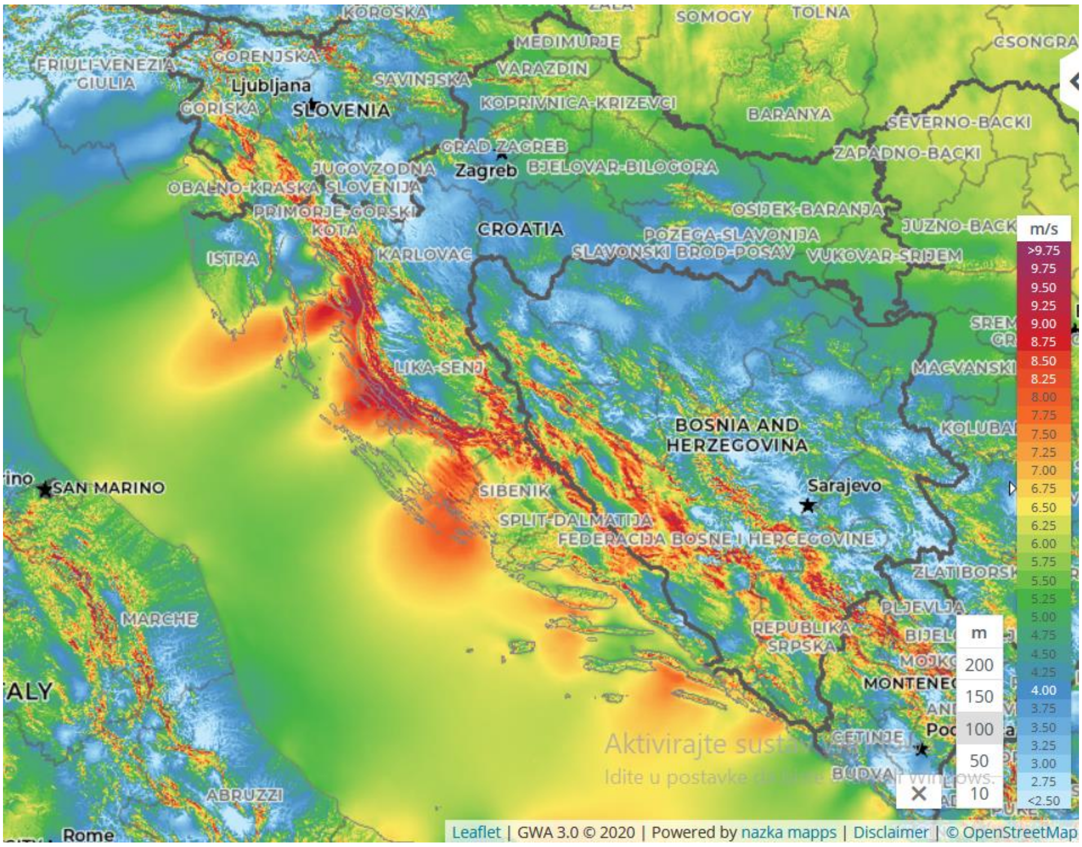


Figure 28. Mean annual wind speed [81]

The wind turbines whose impact will be observed in this thesis were manufactured by REpower Systems SE. The manufacturer was meanwhile taken over by Senvion SE. These wind turbines have a rated power of 5.08 MW [82]. The diameter of the rotor is 126.5 meters with a swept area of 12.5 m^2. The minimum starting speed of the wind turbine is 3.5 m/s, whereas the rated wind speed is 14 m/s. Wind turbines must be switched off during strong winds and the speed limit of the observed turbine is 30 m/s [83].

The annual distribution from offshore wind is presented in Figure 29. An 8 MW turbine scenario was also analysed in this thesis, and the same distribution was used. Due to data availability, the same spatial dimensions of a 5 MW turbine were used for the 8 MW turbine, even though it is expected that their construction and performance characteristics will differ.

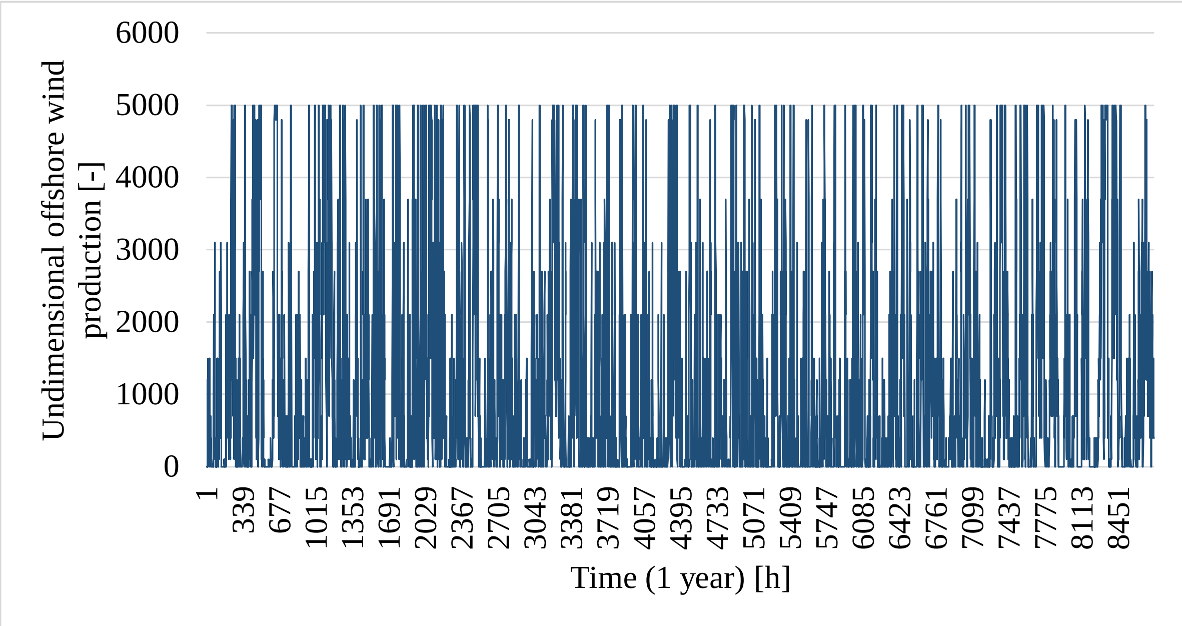


Figure 29. Offshore wind production

In Figure 30 division of territorial and offshore waters by countries is shown. The region of interest in this thesis is highlighted in the lighter shade of blue in the Adriatic Sea. That area is called the Exclusive Economic Zone (EEZ) [84]. It is an area outside the territorial waters where special rights apply. That includes the possibility of research and utilization in that area. In this case, it is important because it defines the locations where it will be possible to exploit marine RES.

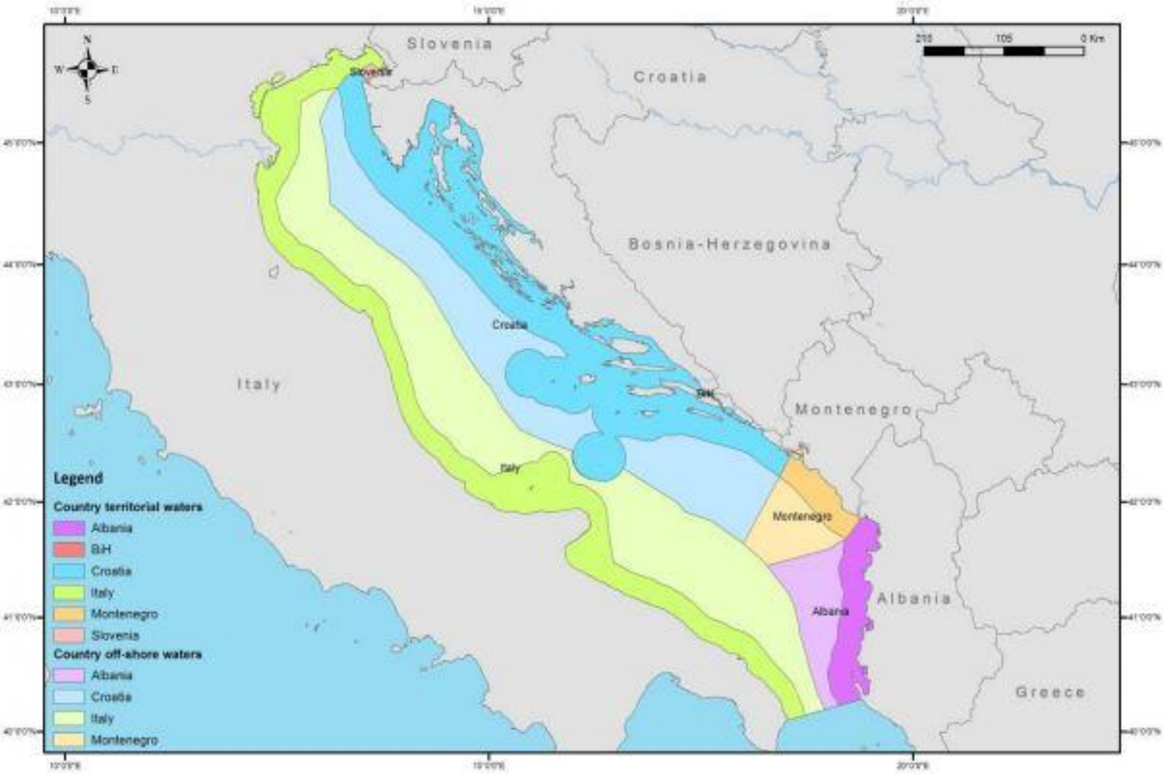


Figure 30. Maritime jurisdiction within the Adriatic Sea [85]

The locations for offshore wind which will be put in the EEZ zone are selected according to certain criteria [86], such as: distance from shipping lines, distance from the coastal zone, distance from Natura 2000 and military areas, distance from main fishing grounds etc. For military and Natura 2000 areas that distance is a minimum of 2 km, however, those requirements were not problematic since such locations are not near EEZ. Distance from shore was set at a minimum of 10 km, but similarly to military and Natura 2000 areas, there are no islands which would prevent the installation of offshore wind turbines in the EEZ zone. In regard to the shipping lines, it was determined that the locations had to be placed at least 5 km away so that the ships would be able to sail without disturbance. There is a smaller number of shipping lines in the northern part, and more of them towards the central and southern part of Croatia's part of the Adriatic Sea. The shipping lines can be seen on the map from Maestrale Webgis [87].

Another important parameter is sea depth. In Figure 31, 3D bathymetry of the Adriatic Sea is shown. As can be seen, Croatia's part is very shallow, with an increasing depth towards the southern part. According to those depths, it was decided to divide potential areas into four categories. Zone A represents depths up to 40 meters, zone B are depths 40 – 60 meters, zone C 60 – 80 meters and zone D 80 – 120 meters. To divide areas according to depth as accurately as possible, Maestrale Webgis was used. When bathymetry is selected in Maestrale Webgis, it is possible to display the exact depth of the desired location.

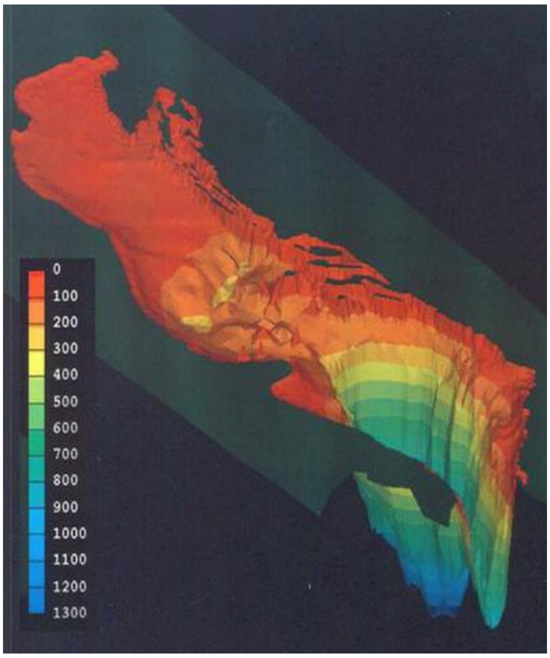


Figure 31. 3D bathymetry of Adriatic Sea [85]

When all parameters are analysed, the resulting zones are as shown in Figure 32. The zones are fragmented into sections depending on the shipping lines. The densest network of shipping lines is in the southern part, which is why the areas are more fragmented in those zones. The largest number of offshore wind turbines can be installed in zone C and the smallest amount in zone D.

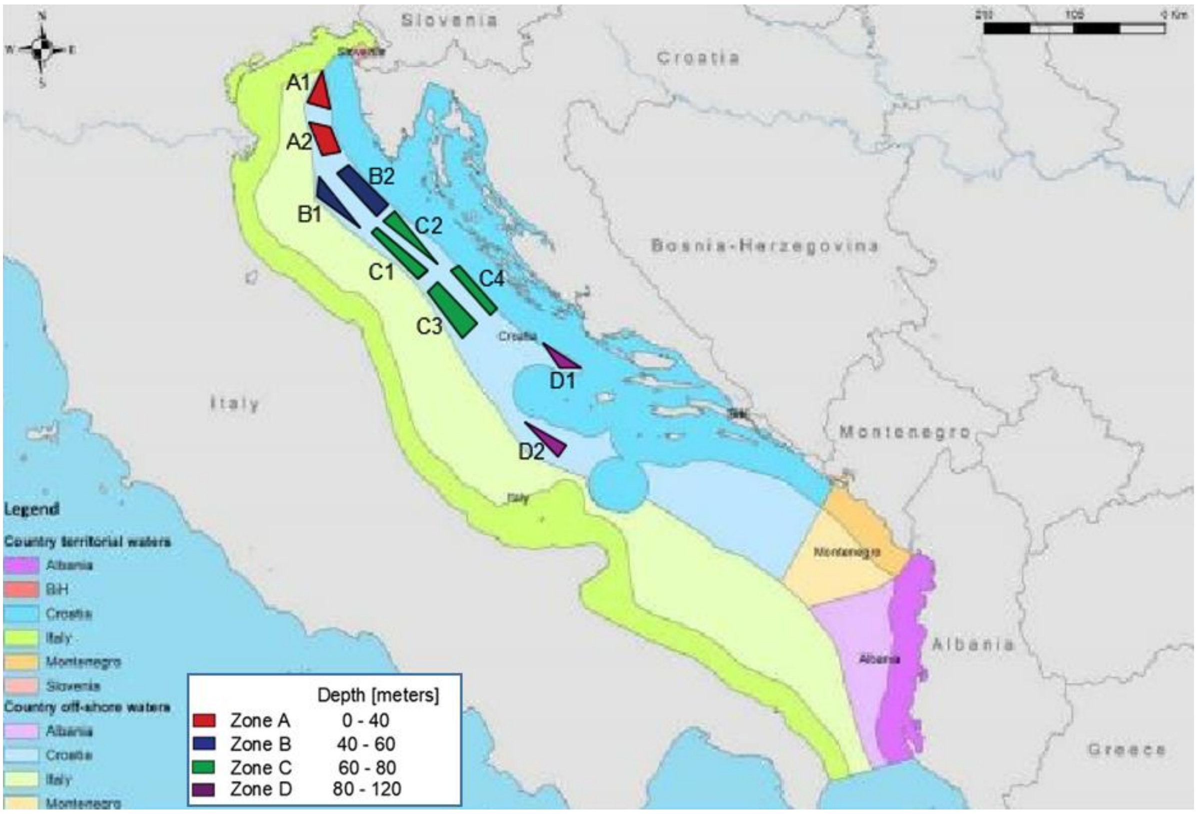


Figure 32. Areas suitable for offshore wind exploitation

After defining the zones, it is necessary to determine the number of turbines that can be placed in those areas. The capacity density values vary depending on the locations. For example, in the North Sea, the average capacity is as much as 6 MW per 1 km^2, while in the Baltic Sea 5.5 MW per 1 km^2 [88]. For European offshore wind farms, the average capacity density is 5 to 5.4 MW per 1 km^2. In this thesis, it will be assumed that an area of 3 km^2 will be provided for 5 and 8 MW wind turbines. This conventional value of 3 km^2 per turbine is bigger than those mentioned above but is taken for safety reasons. Another reason is the presence of gas drillings in the north Adriatic Sea. The area of 3 km^2 ensures that the wind turbines are sufficiently far away from those drillings.

Table 12 shows how much area each zone occupies. Offshore wind capacities will be distributed according to those areas. The assumptions are that 5 MW turbines will be installed in zones A and B, while 8 MW turbines will be installed in zones C and D.

Table 12. Areas and potential capacities for offshore wind energy

Zone	Area [km^2]	Sea depth [meters]	Total area [km^2]	Number of turbines	Turbine power	Total capacity [MW]
A1	476.28	0 – 40	A = 1 289.8	429	5	2 145
A2	813.47					
B1	586.18	40 – 60	B = 1 734.6	578	5	2 890
B2	1 148.44					
			Total capacity for zones A and B			5 035
C1	656.36	60 – 80	C = 3 068.1	1 022	8	8 176
C2	689.06					
C3	1 148.44					
C4	574.22					
D1	344.53	80 – 120	D = 803.9	267	8	2 136
D2	459.38					
			Total capacity for zones C and D			10 312

The predicted capacity projections are for 2030 in zones A and B, with a total capacity of 5 035 MW. The predicted capacities are for 2050 for all zones with a total of 15 347 MW.

4.2. Wave energy potential

Wave energy does not have much potential in Croatia because waves do not reach great heights, as it was mentioned in the Introduction. However, combined with the offshore wind it would be more cost-effective. Therefore, the considered capacities will not be large wave power plants, but smaller capacities of 1 MW and converters installed with offshore wind turbines. Table 13 shows locations for wave energy potential which were analysed in this thesis.

Table 13. Locations for wave energy potential

	Latitude	Longitude
Location 1	45.1138	13.3512
Location 2	44.139	14.252
Location 3	43.314	16.10388

Those locations are shown in Figure 33. Location 1 is marked red, Location 2 is green and Location 3 blue.

Figure 33. Wave energy distribution locations

Figure 34, Figure 35 and Figure 36 show the distributions of wave energy production for marked locations.

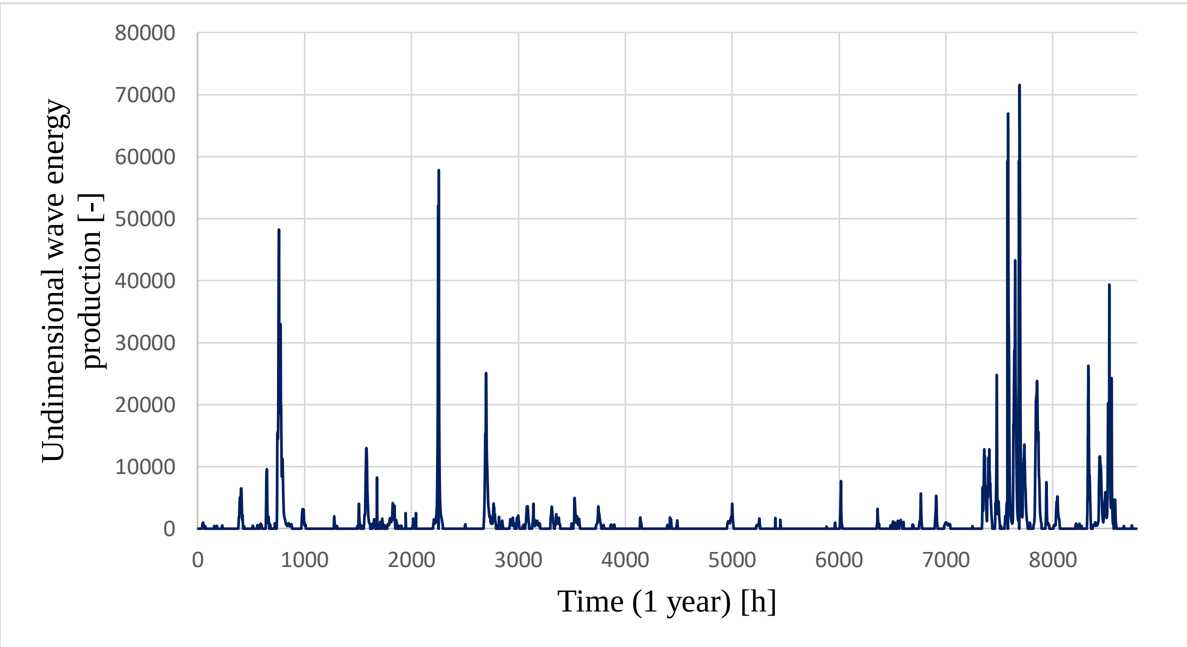


Figure 34. Potential wave energy production on Location 1

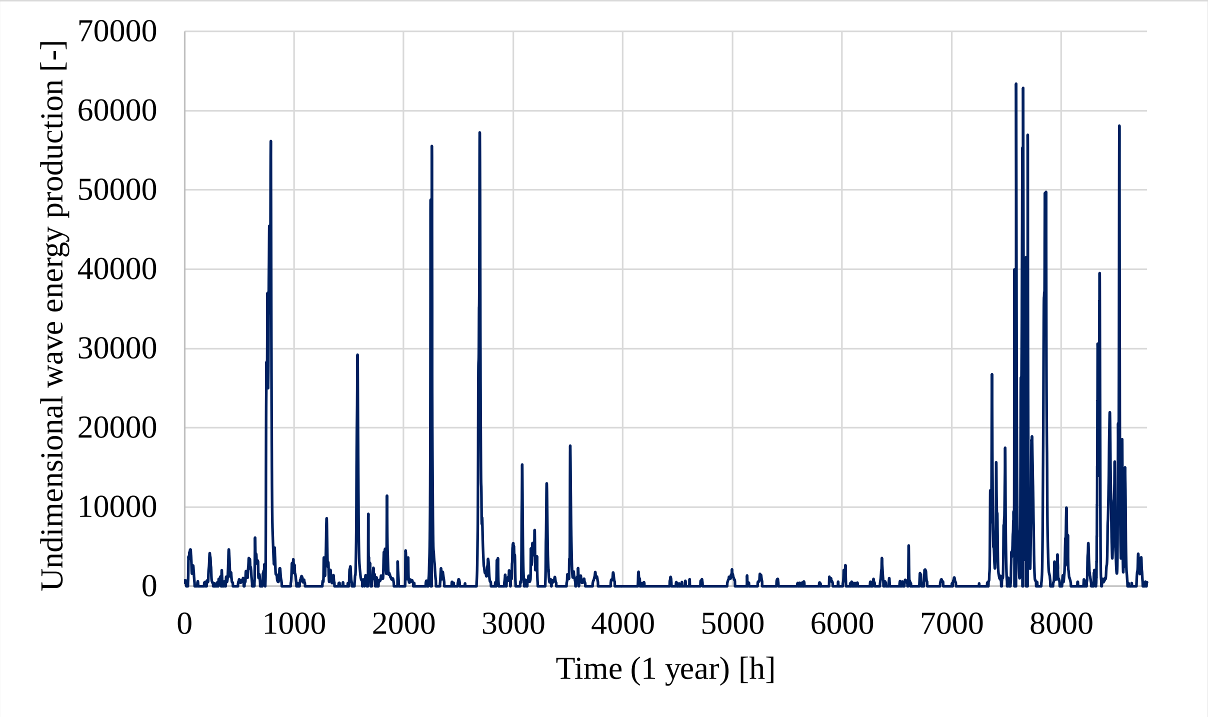


Figure 35. Potential wave energy production on Location 2

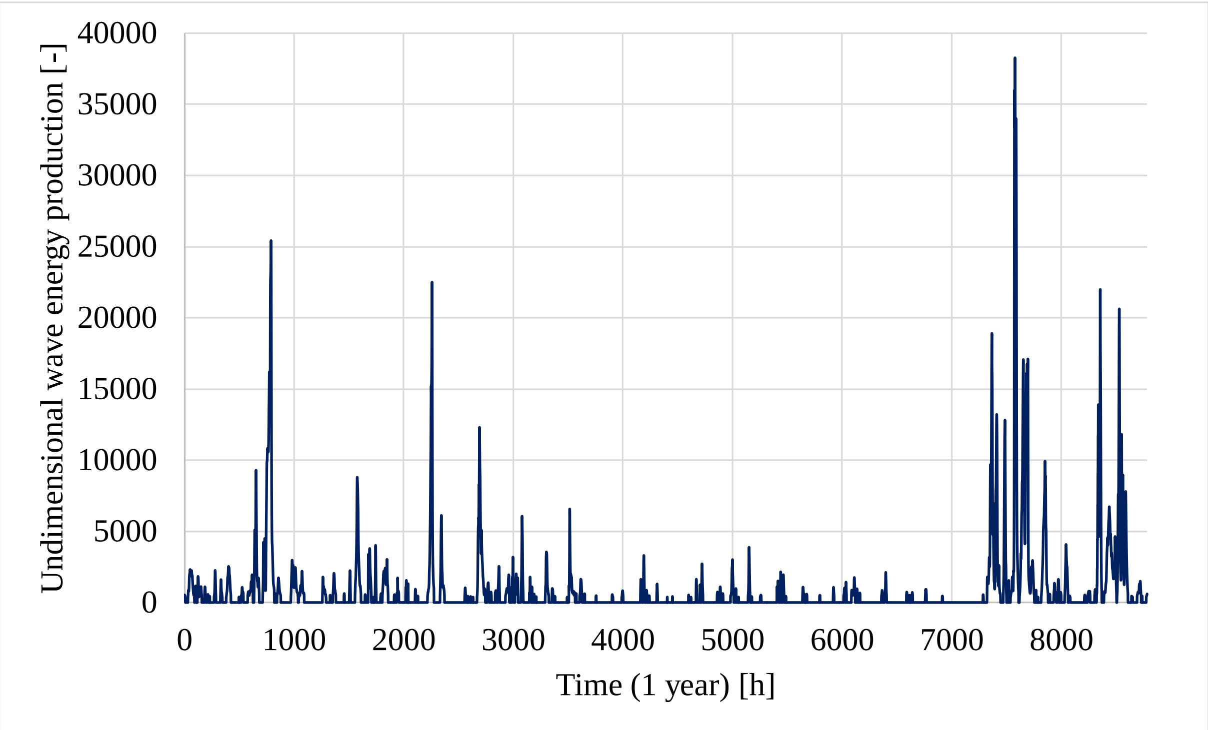


Figure 36. Potential wave energy production on Location 3

As can be seen from Figure 34, Figure 35 and Figure 36, the distributions behave similarly throughout the year. Even though the peak wave energy production is achieved at Location 1, overall production is the highest at Location 2. In accordance with the zones for offshore wind, Location 1 falls into zone A1, while Location 2 coincides with zone C2. Distribution for Location 3 does not coincide with any offshore wind zones but will be used for wave power plants of 1 MW.

It is assumed that in 2030 no wave energy converters will be installed, meaning that all considered capacities will be installed in 2050. Those capacities include five onshore 1 MW floating wave power plants and the so-called Wave Line Magnet wave converter of 100 kW capacity which will be placed next to each offshore wind turbine. This wave converter will be described below. In Table 14 the planned capacities for the Wave Line Magnet are shown. In accordance with offshore wind, 42.9 MW of Wave Line Magnet converters are assumed to be installed in zone A, 57.8 MW in zone B, 102.2 MW in zone C and 26.7 MW in zone D. These capacities were distributed in EnergyPLAN as follows: for distribution on Location 1 capacities from zone A and B amount to 100.7 MW, for distribution on Location 2 capacities from zone C and D amount to 128.9 MW, and distribution on Location 3 five nearshore floating wave power plants with a capacity of 1 MW will be utilized.

Table 14. Areas and potential capacities for offshore wave energy

Zone	Number of wave converters	Capacity [MW]
A	429	42.9
B	578	57.8
C	1 022	102.2
D	267	26.7

In the broad selection of converters, one converter was considered for combined use with offshore wind energy. That is the Wave Line Magnet [89] shown in Figure 37. It uses recycled materials, which results in less environmental impact and lower costs. Moreover, it is mostly made of plastics which make it lightweight and simplify maintenance and transport. This device is simple in design so it can be manufactured in large quantities. Also, it is modular so its capacity can be changed as needed.

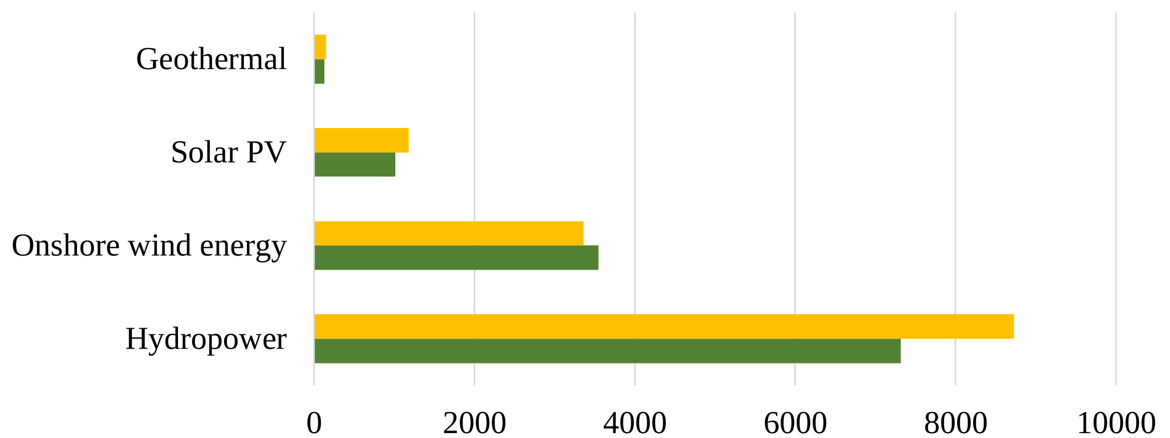
Figure 37. The Wave Line Magnet [89]

5. RESULTS AND DISCUSSION

This chapter will analyse the impacts and production of BE technologies on the Croatian electricity system. Observed BE technologies are offshore wind, seawater heat pumps and wave energy. Wave energy includes capacities for both the Wave Line Magnet converter and 5×1 MW wave power plants.

Firstly, electricity productions for individual RES technologies in 2030 and 2050 are compared in Figure 38 and Figure 39. This section does not yet include BE technologies but is presented to see a comparison of Scenario S2 under the Strategy and the calculated EnergyPLAN model. As can be seen, there are differences in EnergyPLAN model compared to Scenario S2 for 2030 and 2050, however, the most significant difference in estimated production is for hydropower. This is partly because hydropower is difficult to predict, as it depends on the amount of rainfall in observed years. The amount of rainfall affects the water levels in the reservoirs and can therefore influence production from hydropower plants.

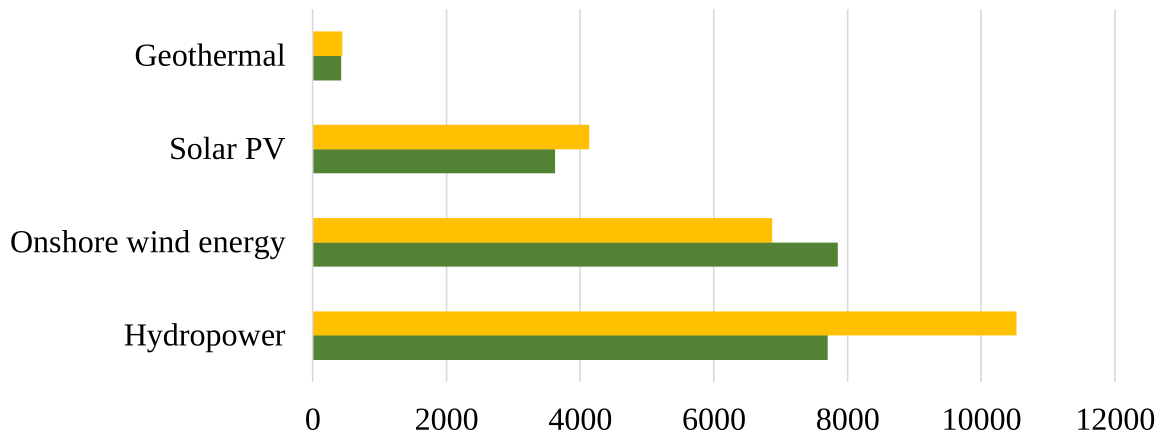
In 2030, electricity production from geothermal energy, solar PV and hydropower is higher in EnergyPLAN model than in Scenario S2. For geothermal and solar it is 16.5% higher, and for hydropower 19.3% higher. On the other hand, it is lower by 5.3% for onshore wind.



	Hydropower	Onshore wind energy	Solar PV	Geothermal
EnergyPLAN	8730	3360	1180	150
Scenario S2	7319	3549	1013	129

Figure 38. Electricity production from RES in 2030

In 2050, when comparing predictions of EnergyPLAN model and Scenario S2, electricity production for EnergyPLAN is higher by 2.9% for geothermal energy, 14.2% for solar PV and 36.7% for hydropower. On the other hand, onshore wind is lower in EnergyPLAN than Scenario S2 by 12.6%.



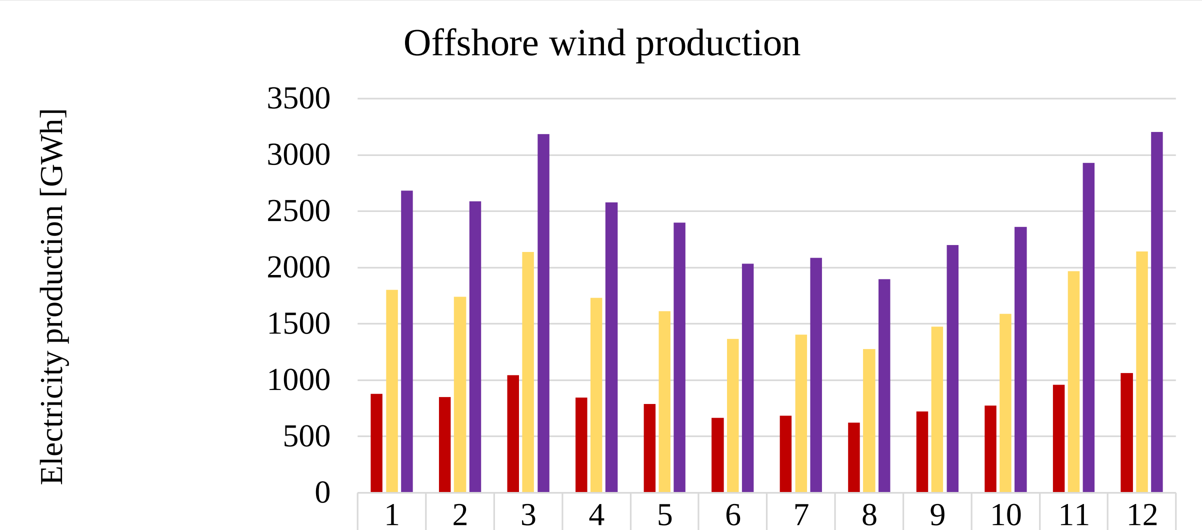
	Hydropower	Onshore wind energy	Solar PV	Geothermal
EnergyPLAN	10530	6870	4140	440
Scenario S2	7703	7859	3624	428

Electricity production [GWh]

EnergyPLAN Scenario S2

Figure 39. Electricity production from RES in 2050

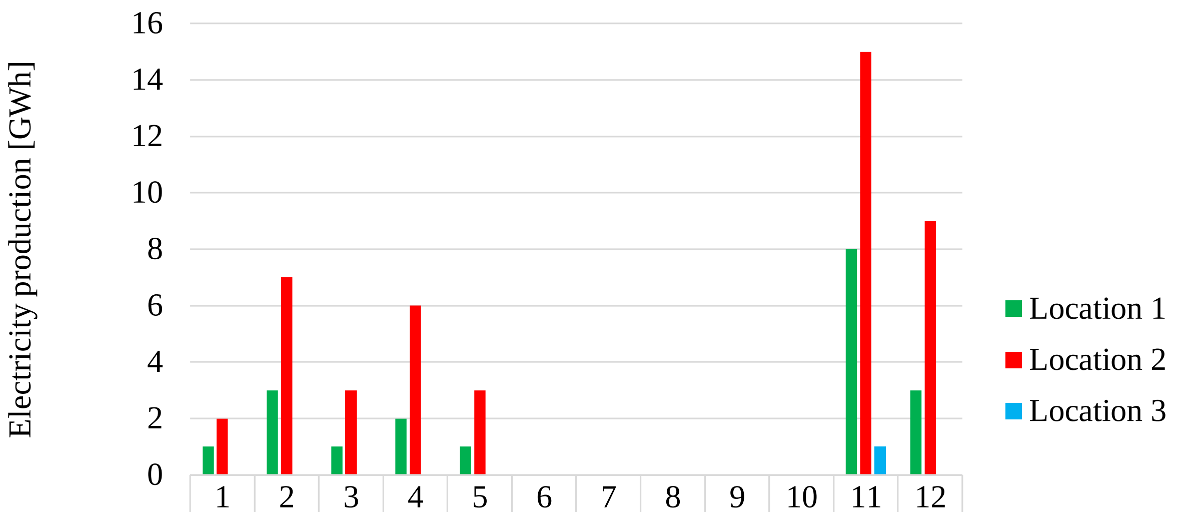
The open sea has higher wind speeds in winter, so electricity production from offshore wind is higher than in the summer months. This can be seen in Figure 40. The first column in the graph represents electricity production from 5 035 MW located in zone A and B in 2030, the second column is electricity production from 10 312 MW located in zone C and D added in 2050, and the third column is the sum of previous two, which represents the electricity production from all the capacities. The largest production is expected in March for both years, with 1 045 GWh for 2030 and 3 184 GWh for 2050. The lowest production occurs between June and September, as the wind speeds are lower in the summer.



	1	2	3	4	5	6	7	8	9	10	11	12
Zone A and B (2030)	880	850	1045	846	788	667	685	622	721	775	961	1063
Zone C and D (2050)	1802	1740	2139	1733	1612	1367	1403	1274	1477	1588	1969	2143
Total in 2050	2682	2590	3184	2579	2399	2035	2088	1896	2198	2363	2930	3206

Figure 40. Annual production from offshore wind turbines in 2030 and 2050

Wave energy distribution is similar in behaviour to that of offshore wind, i.e. wave height is higher in winter than in summer. Therefore, energy production is significantly higher in the winter months, while in the summer months the production is negligible, as can be seen from Figure 41. It should be noted that electricity production is different for various distribution locations. The maximums are reached in November. In Location 1 the maximum production is 8 GWh, in Location 2 it is 15 GWh and in Location 3 it is only 1 GWh. Electricity production for Location 3 is low due to small estimated wave capacities of 5 MW in that area. The wind speeds in the central part of the Adriatic Sea are higher due to mountain ranges from which the winds descend, thus creating higher waves. When comparing Figure 40 and Figure 41, it can be seen that the potential for wave energy production is significantly lower than for offshore wind.



	1	2	3	4	5	6	7	8	9	10	11	12
Location 1	1	3	1	2	1	0	0	0	0	0	8	3
Location 2	2	7	3	6	3	0	0	0	0	0	15	9
Location 3	0	0	0	0	0	0	0	0	0	0	1	0

Figure 41. Annual production from wave energy in 2050

As mentioned before, in this thesis it is assumed that seawater heat pumps will replace coal and oil boilers. Until recently, most buildings did not have any cooling systems, but due to global warming, there is an increasing need for cooling energy and less for heating. Seawater heat pumps are convenient because they can provide the necessary cooling energy, which the coal and oil boilers cannot. Seawater heat pumps that have been installed so far have mostly been installed in hotels and are primarily used for domestic hot water and pool heating, as opposed to space heating. Therefore, the demand for cooling is much higher than for heating. The heating and cooling production from seawater heat pumps is higher in summer as can be seen in Figure 42 for the year 2030.

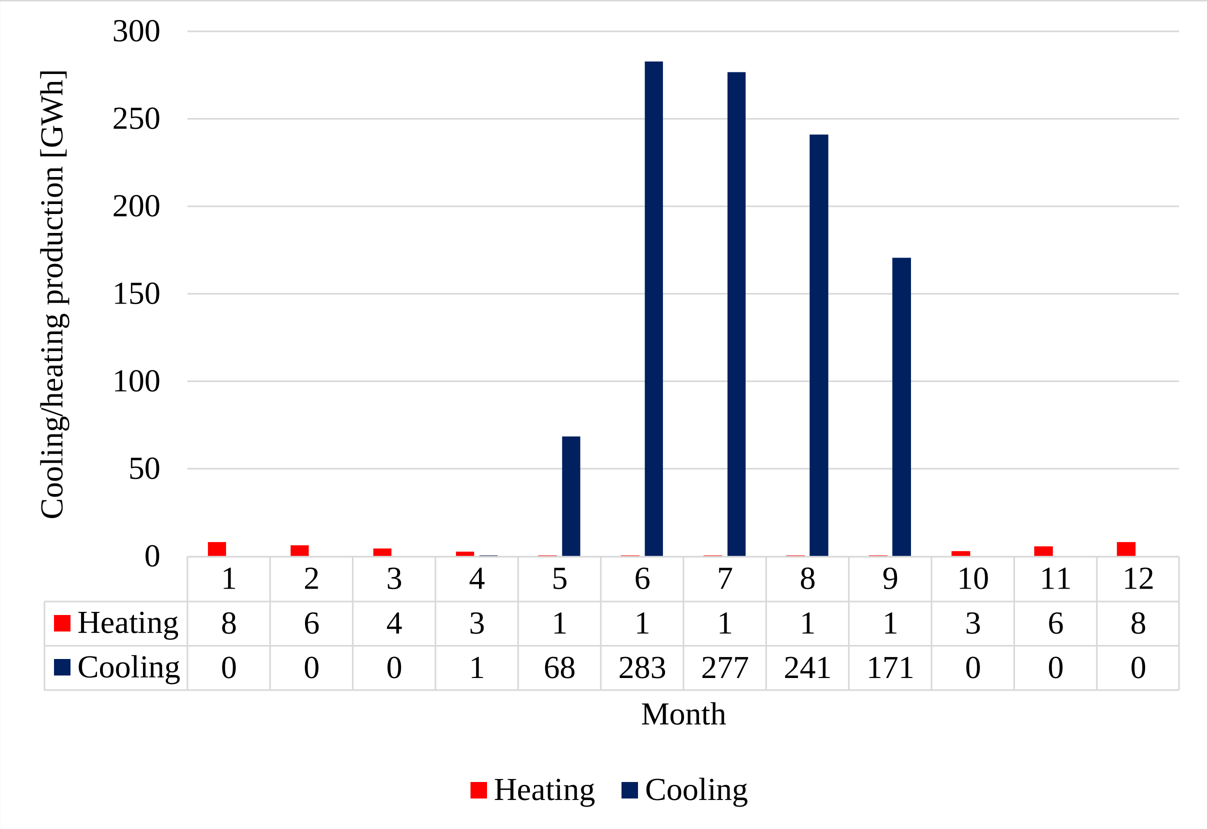


Figure 42. Annual heating and cooling production from seawater heat pumps in 2030

Figure 43 shows the production of seawater heat pumps in 2050, which behaves similarly to heat pumps in 2030. However, there is an increase in production, which is significantly higher in 2050 as opposed to 2030.

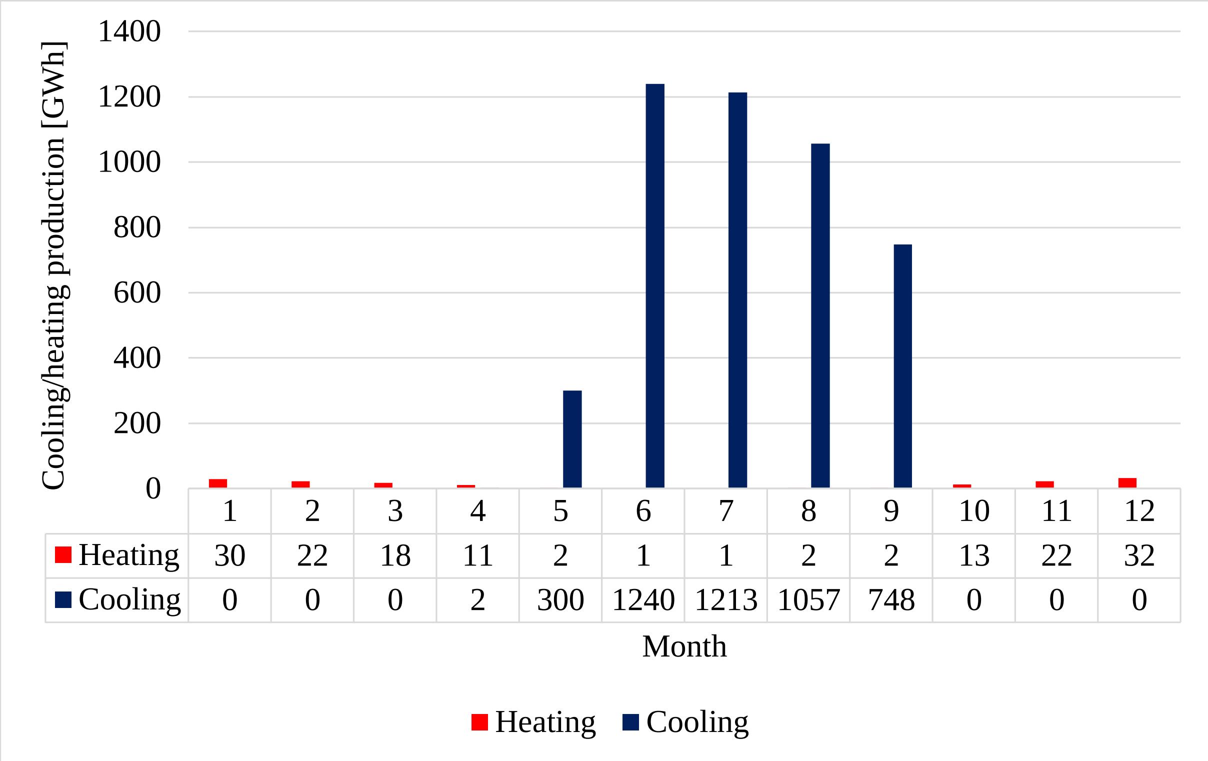


Figure 43. Annual heating and cooling production from seawater heat pumps in 2050

The following figures and tables will show the results regarding CO_2 emissions, fossil fuel consumption and share of RES for 2030 and 2050. Columns labelled *Without BE technology* mark a scenario with all the forecasts for 2030 or 2050, but without offshore wind, wave energy and seawater heat pumps. Then, the mentioned BE capacities were added and observed in EnergyPLAN models.

Firstly, the data regarding CO_2 emissions were observed. Table 15 shows the comparison of emissions from EnergyPLAN model and available data from IEA and Eurostat for the year 2018. It shows that EnergyPLAN model emissions are the same as IEA data, and are also similar to data provided by Eurostat.

Table 15. Comparison of CO_2 emissions Mt of CO_2 in 2018

IEA	Eurostat	EnergyPLAN
15.3	15.6	15.3

CO_2 emissions for 2030 are shown in Figure 44. According to Scenario S2, a maximum of 14.1 Mt CO_2 should be reached in 2030. Furthermore, the EnergyPLAN model emissions are 0.5 Mt CO_2 lower than the given value.

When looking at BE technologies for 2030, CO_2 emissions recorded a significant drop of around 1.2 Mt CO_2 when offshore wind energy was added, as can be seen in Figure 44. It is predicted that no wave energy converters will be installed in 2030. When adding seawater heat pumps, CO_2 emissions are slightly increased compared to when only offshore wind capacities are installed. This is because in EnergyPLAN it cannot be specified from which source the heat pump draws electricity. Another setback by adding heat pumps is that cooling capacities rise and therefore electricity demand also increases. However, this increase of CO_2 emissions due to added seawater heat pumps is very small and does not have a major impact on emissions. Although the heat pump is a renewable source because of its ability to produce more energy than it needs for its operation, it is still in many cases supplied with electricity from fossil fuels. A decrease of CO_2 emissions could be realized if it could be indicated in EnergyPLAN that its electricity comes from a renewable source, for example solar PV. Furthermore, if all electricity was generated from renewable sources, there wouldn't be an increase in CO_2 emissions.

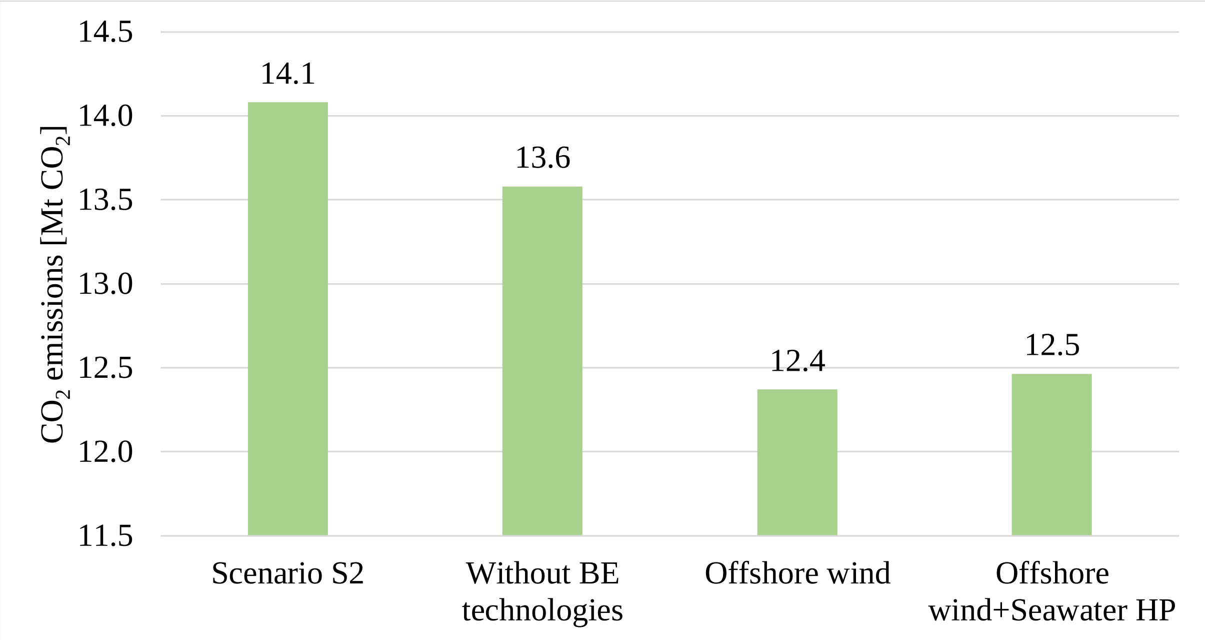


Figure 44. CO_2 emissions for 2030

The trends for 2030 and 2050 are similar, but because the share of RES is higher, CO_2 emissions are lower. Firstly, it can be seen that emissions for 2050 from Scenario S2 and EnergyPLAN model *Without BE technologies* are different. The data for EnergyPLAN was taken from Resflex, because it could not be otherwise predicted. The data from Resflex assumes significantly lower fossil fuel consumption which results in lower emissions. When BE technologies are added, the largest decrease is recorded with the integration of offshore wind. It lowers CO_2 emissions by 55% compared to the case without BE technologies. There is no change in CO_2 emissions when wave energy installations are added. As in the case above, emissions slightly increase when seawater heat pumps are added.

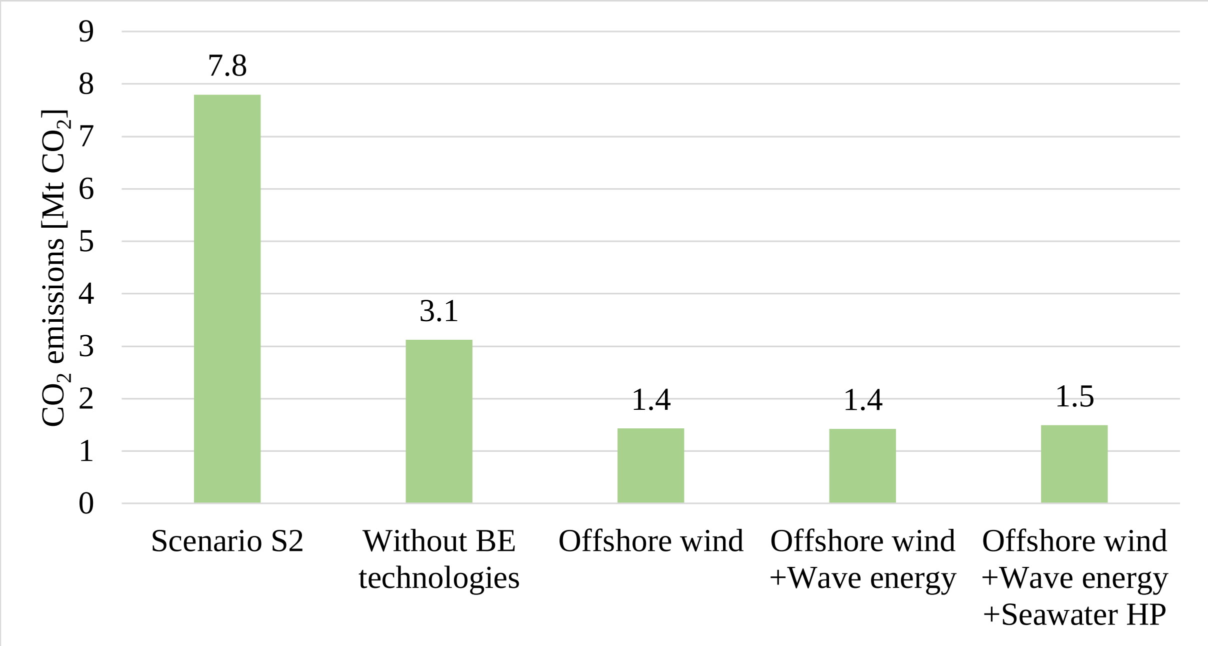


Figure 45. CO_2 emissions for 2050

Cost savings from reductions of CO_2 emission are shown in Table 16, after BE capacities are added in 2030 and 2050. The prices of CO_2 emissions today are around 25.2 €/t [90], but those prices are likely to rise. This is another way to encourage the transition to RES because fossil fuel technologies are becoming less cost-effective as CO_2 emissions price rises. For 2030, the anticipated price is around 70 €/t CO_2 and for 2050 around 275 €/t CO_2 [91]. The data in the table shows that BE technologies can have a very beneficial effect on the cost savings. Savings range from around 77 million euros in 2030 to almost 470 million in 2050. This economic factor could certainly be very influential in the implementation of BE technologies.

Table 16. Cost savings of CO_2 emission reductions

2030		
Price of CO_2 emissions = 70 €/t CO_2		
Scenarios	Emission difference compared to a scenario without BE technologies	Cost savings
Offshore wind	1.2 Mt CO_2	84 million €
Offshore wind + seawater heat pumps	1.1 Mt CO_2	77 million €
2050		
Price of CO_2 emissions = 275 €/t CO_2		
Scenarios	Emission difference to a scenario without BE technologies	Cost savings
Offshore wind	1.7 Mt CO_2	467.5 million €
Offshore wind + wave energy	1.7 Mt CO_2	467.5 million €
Offshore wind + wave energy + seawater heat pumps	1.6 Mt CO_2	440 million €

Figure 46 and Figure 47 show the influence of BE technologies on fossil fuel consumption, so the sum of coal, oil and natural gas was observed.

Primary fossil fuel consumptions in Scenario S2 and EnergyPLAN model are relatively similar for 2030, as can be seen in Figure 46. EnergyPLAN model has higher fossil fuel consumption then Scenario S2 because it is assumed that natural gas consumption will increase. Also, due to increased cooling demand, fossil fuel consumption is rising. When offshore wind capacities are added, fossil fuel consumption is 8% lower compared to the scenario without BE technologies. When seawater heat pumps are added, the consumption rises slightly, by 0.8%. The production of offshore wind and wave energy is lower in summer than in winter months, and it can therefore be concluded that electricity for seawater heat pumps is supplied either from fossil-based power plants in 2030 or from imports in 2050.

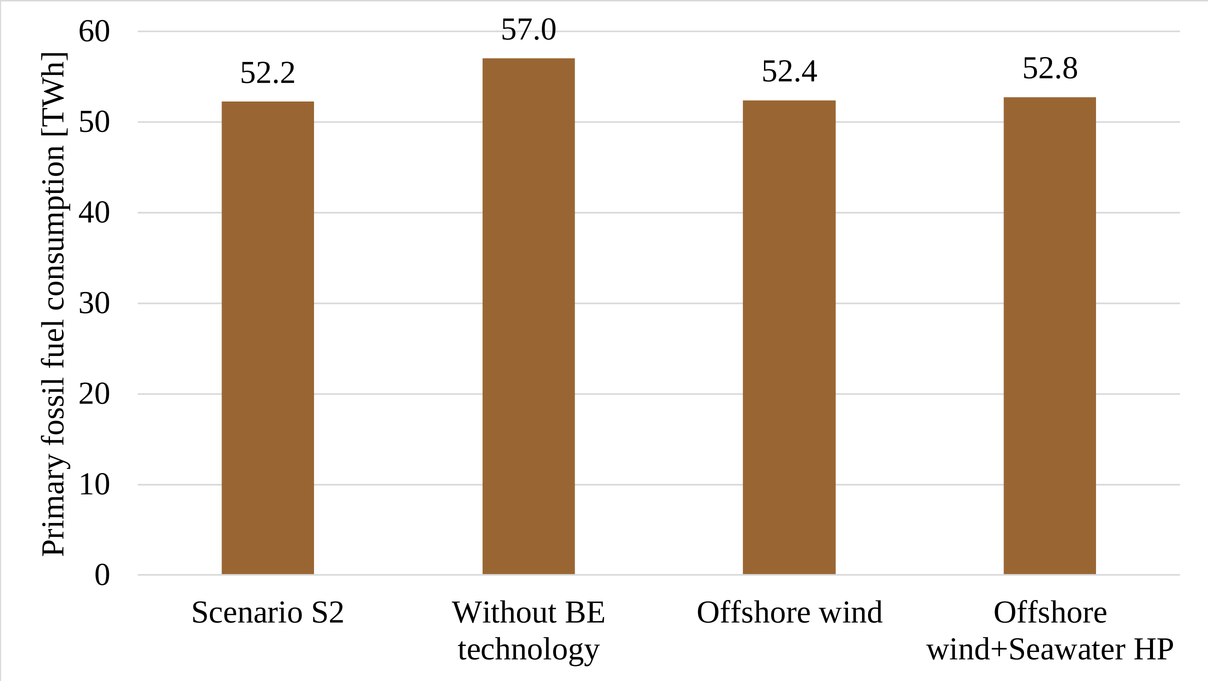


Figure 46. Primary fossil fuel energy consumption in 2030

In 2050 the consumption of fossil fuels visibly decreases. There is a significant difference between Scenario S2 and EnergyPLAN model without BE technologies, as shown in Figure 47. This is because according to data taken from Resflex, the consumption of oil and natural gas in various sectors in EnergyPLAN is very small or next to none. In the Resflex model, a high level of electrification is assumed which is why the demand for oil and natural gas is reduced. Compared to the scenario without BE technologies, offshore wind reduces fossil fuel consumption by 52%. Wave energy does not influence consumption, and when seawater heat pumps are added, they increase fossil fuel consumption by 4%.

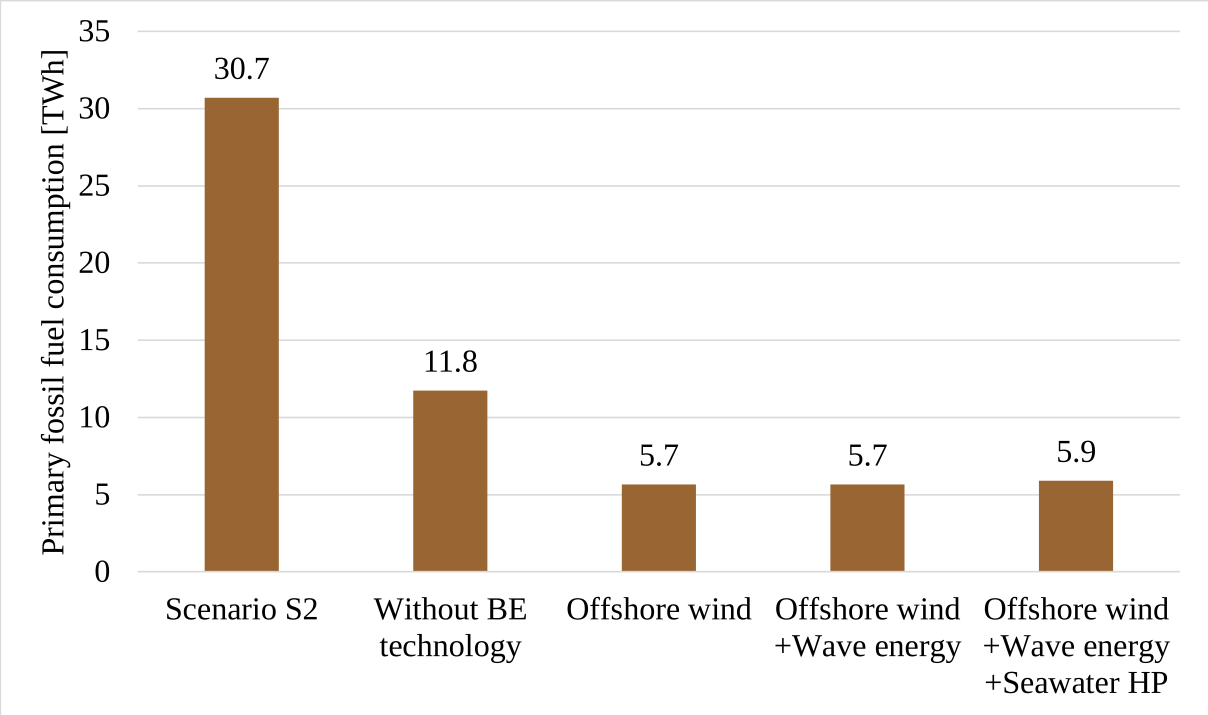


Figure 47. Primary fossil fuel energy consumption in 2050

Figure 48 and Figure 49 show the share of RES in electricity production in 2030 and 2050. For Scenario S2 the values of gross final energy consumption were taken.

From Figure 48 it can be seen that data for Scenario S2 and EnergyPLAN model without BE technologies are relatively similar. However, the share of RES in the former is slightly higher than in the latter. When BE capacities are added, the share of RES surpasses the Scenario S2 prognosis. The greatest increase in the share of RES is achieved with offshore wind, which raises it by 21% in 2030. Seawater heat pumps do not show an impact on the share of RES.

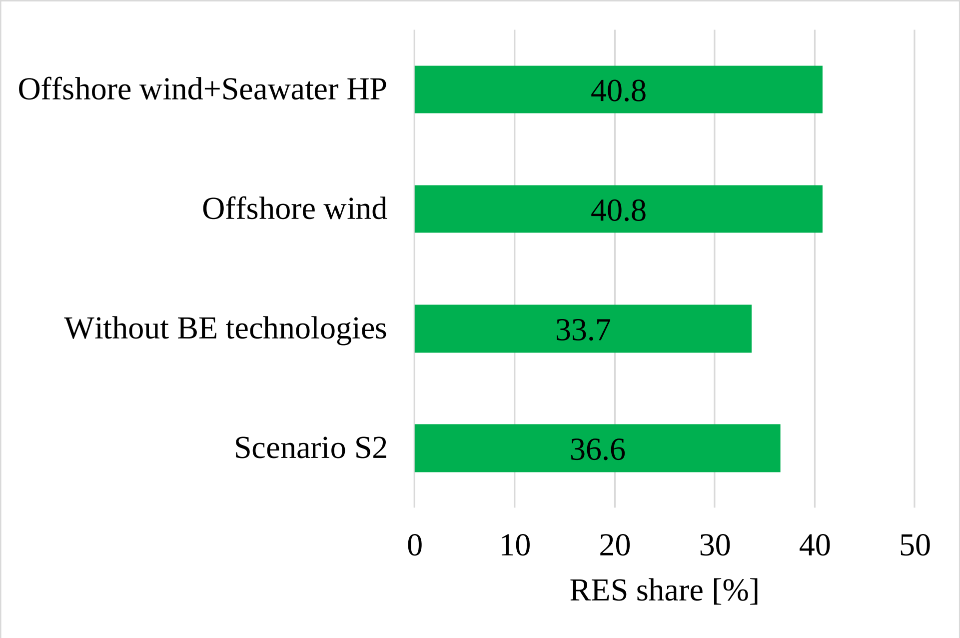


Figure 48. Share of RES in gross final energy consumption in 2030

In 2050, the share of RES from EnergyPLAN model surpasses the prognosis of Scenario S2. When the offshore wind is added, it raises the share by as much as 28%, compared to the scenario without BE technologies in 2050. Therefore, offshore wind capacities suggested in this thesis could have a significant impact on the Croatian power system. For wave energy in 2050, a lack of potential can be seen as it does not affect the share of RES. Seawater heat pumps slightly reduce the share of RES, for the same reasons as stated for CO_2 emissions.

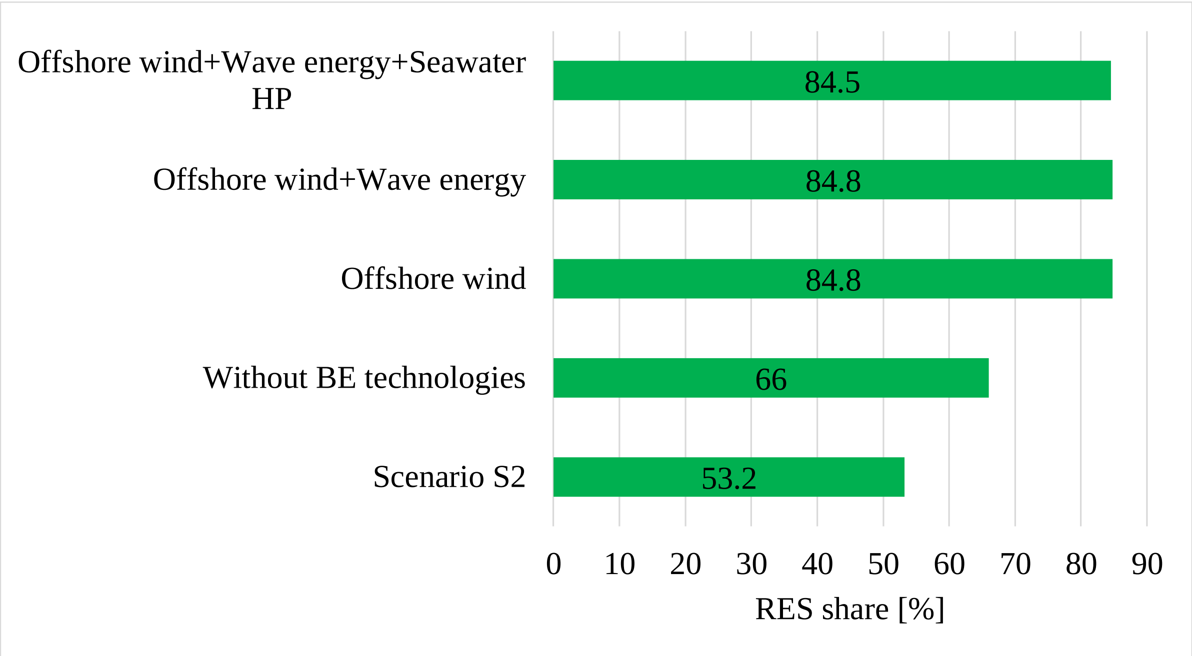


Figure 49. Share of RES in gross final energy consumption in 2050

The following figures compare the overall impact that BE technologies could have on the Croatian energy system by years. The results from EnergyPLAN model for 2018 are presented in the first column, followed by a comparison of the Scenario S2 and EnergyPLAN model that includes all analysed BE technologies in the years 2030 and 2050.

As can be seen in Figure 50, EnergyPLAN models for BE scenario show reduced emissions compared to Scenario S2. In 2030 the difference between Scenario S2 and Energyplan model with all BE technologies is 11%, while in 2050 it is as much as 80%.

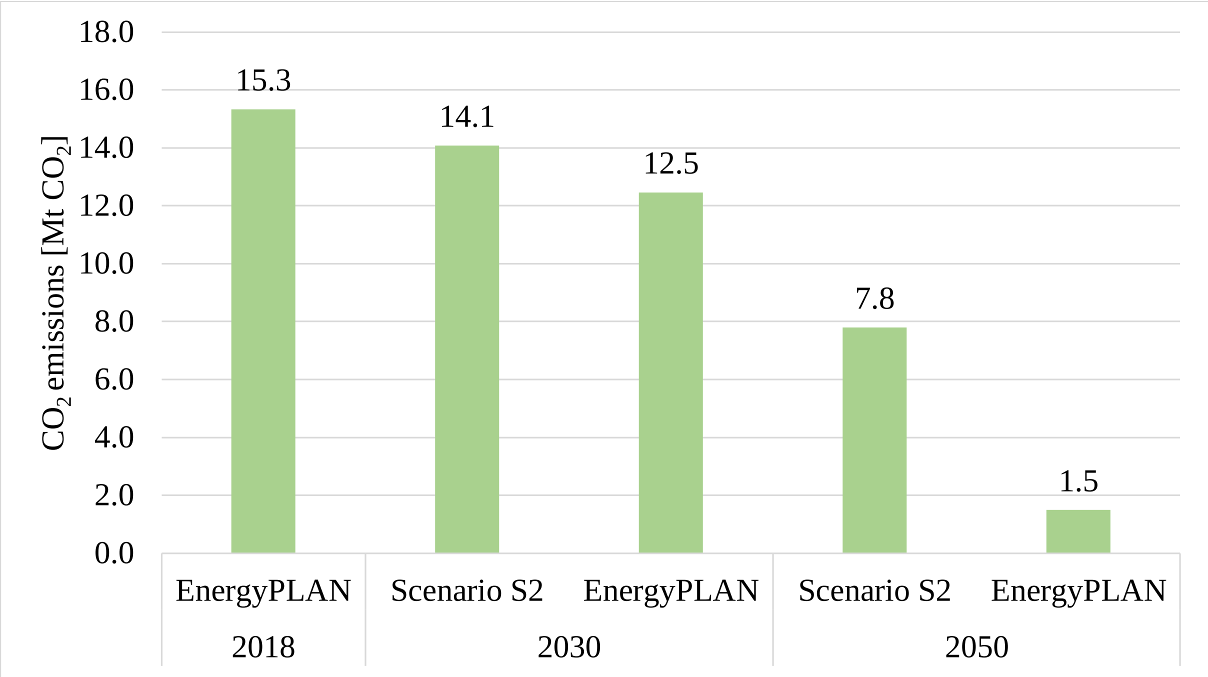


Figure 50. Comparison of CO_2 emissions in 2018, 2030 and 2050

When comparing the Scenario S2 and EnergyPLAN models in Figure 51, the predictions are similar but EnergyPLAN model with all BE technologies has 1% higher value than Scenario S2 in 2030 and 80% lower value in 2050. The reason for this large fall is explained in the text before Figure 47. It should be mentioned that obtained results from the simulation for 2050 do not represent the realistic case regarding the primary fuel consumption but just a rough approximation.

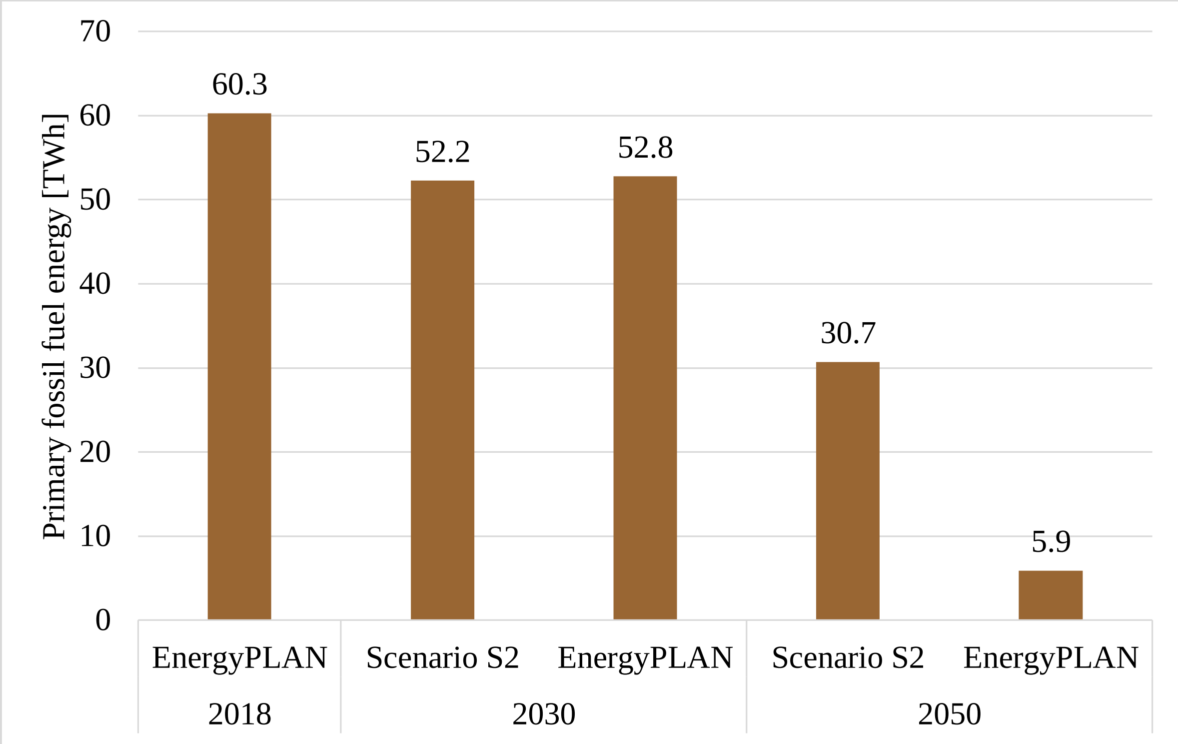


Figure 51. Comparison of primary fossil fuel energy consumption in 2018, 2030 and 2050

The next two figures show data related to the share of RES in gross final energy consumption and RES electricity production. The behaviour is similar in both cases. Given that a large share of RES has already been achieved in 2018, it is likely that the objectives of Scenario S2 will be met. BE technologies can considerably affect the Croatian electricity system, with significant increases in 2030, and especially in 2050.

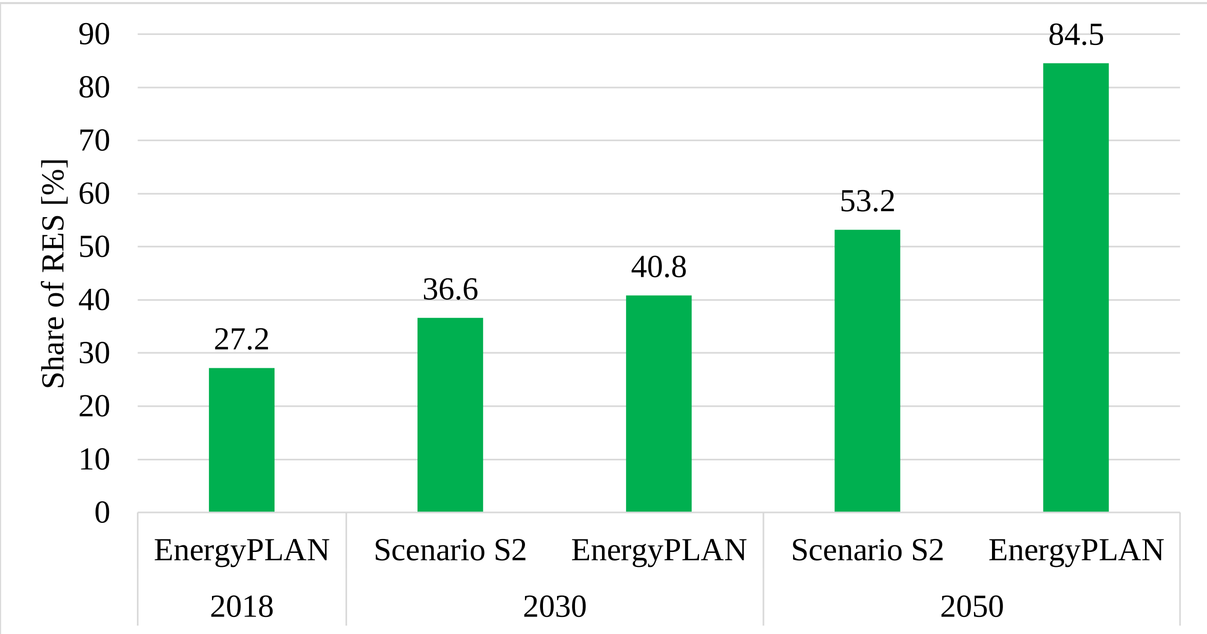


Figure 52. Comparison of the share of RES in gross final energy consumption in 2018, 2030 and 2050

As can be seen in Figure 53, production from RES is rising. If all the BE capacities were integrated in 2030, the production could exceed the expected 20.2 TWh according to Scenario S2 for 2050. The growth of RES production in 2050 would continue, exceeding the expected value from Scenario S2 by 2.6 times.

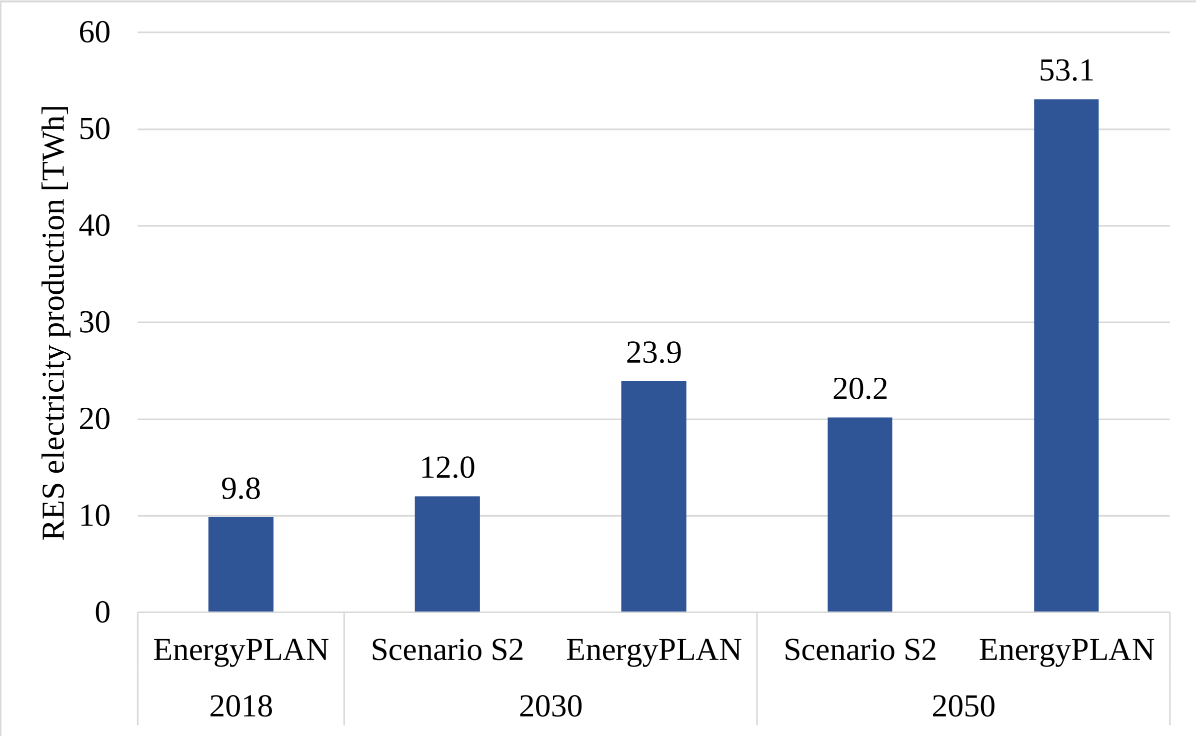


Figure 53. Comparison of RES electricity production in 2018, 2030 and 2050

Another important parameter which should be taken into account is critical excess electricity production (CEEP). CEEP is interpreted as produced electricity which exceeds both electricity demand and transmission line capacity [92]. In general, if CEEP is higher than 0, the capacities which cause higher value are not integrated into power systems. However, it is common to assume that CEEP of newly installed RES should not exceed 5% because in that case, the installation of those capacities is not cost-effective. There are multiple options for ensuring that CEEP value does not exceed mentioned limitations. Curtailment is one of them, and it implies restricting production from renewable sources. However, this means that the full potential of the built technologies is not used, which is not cost-effective. Other options include building battery storage facilities to store energy so that those capacities can be used when demand from other sources is not met. Greater integration of electric vehicles and synthetic fuels would also ensure that CEEP does not increase [93]. Additionally, if more transmission capacities were integrated, more electricity could be exported which means that there would be no curtailment. The final option would be not to install all theoretically possible capacities, but rather to explore the most favourable microlocations. In Table 17 are shown CEEP from EnergyPLAN models for 2018, 2030 and 2050. In 2018 and 2030, CEEP percentages are below 5%, while in 2050 CEEP percentage in demand is 25%. This means that in 2050, one of the aforementioned options should be implemented.

Table 17. CEEP percentage in electricity demand

2018	2030	2050
0	1	25

The goal of this thesis was to explore the possibilities of BE integration. All available areas have been considered, but in future work, it is not necessary to install all capacities from this thesis. Optimization of RES potential could be the next step to ensure that integrated RES do not disrupt system stability.

To sum up, from the presented results it can be concluded that offshore wind farms could have the most significant impact on electricity systems. Seawater heat pumps could also make a difference but to a much lesser extent. In contrast, wave energy showed a very low impact on the electricity system, so it does not have a high potential in Croatia.

6. TECHNO-ECONOMIC ANALYSIS

The techno-economic analysis was carried out according to Enerpedia [94], [95] and [96]. Estimated investment costs were collected, as well as operation and maintenance costs for BE technologies. Since the mentioned technologies are still expensive, a significant amount of loan is assumed. The calculations were performed in Microsoft Excel and the results are shown in the attachment [96]. The data regarding investment costs, operation costs, maintenance costs, operating hours, lifetime and construction time was taken from the Danish Energy Agency's data sheets in Microsoft Excel [97]. The procedure for all technologies is the same and is calculated with capacities and prices predicted for 2050. It should be mentioned that the benefits of CO_2 emission reductions could also be taken into account. Those benefits include the calculated cost savings described in Table 16. However, this is not taken into account in the thesis.

First, the required investment is determined as a product of capital costs and capacities. Then, operation and maintenance costs are calculated as a product of capacities and maintenance costs. Costs of amortization represent the investment divided with the useful lifetime of the technology [95]. The product of produced energy and the selling electricity price represents gross revenue. The average electricity price in Croatia is 0.1301 €/kWh [71]. The tax base is profit minus expenses, amortization and loan interest. If the tax base is positive, the income tax is calculated. According to [98], for revenues of less than 7.5 million HRK income tax is 12%, while for revenues greater than 7.5 million HRK is 18%. Net profit is gross profit minus operation and maintenance costs, tax and loan. The loan is calculated as a sum of principal amount which was calculated in Excel with the function PPMT, and interest which is calculated with the function IPMT. In the following are the input data for techno-economic analysis for selected BE technologies.

Installation costs for offshore wind energy amount to an average of 1 780 €/kW. Operation and maintenance costs are around 32.5 €/kW/annually. The assumed lifetime of a wind turbine is 30 years [99]. The analysis was conducted for maximum capacities, i.e. 15 347 MW for 2050. The production of electricity which will be calculated as gross revenue is 30.15 TWh. Wind turbines have the highest investment priority over other renewable energy technologies. This is due to good winds in the Croatian part of the Adriatic, the high development of technology and wide global use [100]. Lifetime is around 30 years and the amortization is calculated for a period of 10 years. The loan interest rate is 4%, the payback period is 18 years and the share of own investment is 30%. The value of 6% was taken as the discount rate [101].

When looking at wave energy, five 1 MW wave power plants were observed first. Installation costs for wave energy can vary significantly depending on the type of converter. For this analysis, the investment costs are 1 600 €/kW. Operation and maintenance costs are 0.007 €/kWh/annually and that amount is multiplied by 4 500 hours in operation, giving the final maintenance costs of 31.5 €/kW/annually. The production is 0.7 GWh. The analysis was conducted for 5 MW capacities predicted for 2050 on Location 3 according to Figure 33. The lifetime is 30 years, and the amortization is calculated for a period of 10 years. The gross revenue is small, because of the low production. Loan interest rate is 4%, the payback period is 10 years and the share of own investment is 30%. The value of 15% was taken as the discount rate [102].

Since there is no investment and operation cost data for Wave Line Magnet, the assumption was made. Due to their simple design with cheap parts, it is presumed that their costs are significantly lower than for other wave converters. According to [103], the average price of electricity for Wave Line Magnet was around 1 600 €/kW, while for an average marine technology is 5 400 €/kW [97]. That means that price of Wave Line Magnet is approximately 3.3 times lower. That is why, in this techno-economic analysis, the values for previous wave energy costs were divided by 3.3 to obtain prices for Wave Line Magnet. That means that investment costs are 485 €/kW, and operation costs are 9.5 €/kW/annually [97]. For 2050 is planned a total of 229.6 MW for Wave Line Magnet converters. The amount of electricity production is 40 GWh/year. Loan interest rate is 4%, the payback period is 10 years and the share of own investment is 30%.

Investment costs for seawater heat pumps are 380 €/kW while operating and maintaining costs are 4 €/kW/ annually. The revenues of seawater heat pumps were presented as saving in fossil fuel consumption generated in EnergyPLAN. The average operating time of a seawater heat pump was calculated according to a representative example from Norway [104]. The system capacity of that heat pump is 14 MW and it supplies 67 GWh of energy. This means that it operates approximately 4 785 hours per year. The amount of electricity production is in total 300 GWh/year. When this amount is divided by 4 785 hours, a capacity of 62.7 MW is obtained and put into Excel for analysis. Lifetime is 25 years and the amortization period is calculated for the period of 10 years. Loan interest rate is 4%, the payback period is 10 years and the share of own investment is 30%. The value of 7% was taken as the discount rate [105].

When all the data is entered into Excel and processed, the Net Present Value (NPV) is observed. If it is positive, the project is profitable. For offshore wind NPV value is positive and it can therefore be concluded that it is cost-effective. A positive value in cumulative cash flow is reached in little less than 5 years, meaning that this technology can accumulate a lot of profit in the remaining 25 years of operation. For 5 MW wave power plants, NPV is negative and therefore it can be concluded that this installation is still not cost-effective in Croatia. The same applies to the Wave Line Magnet. Even with decreased capital and operating costs of wave energy, the production too low for this technology to be cost-effective. For seawater heat pumps NPV is positive which means that they can be profitable. This is because they are smaller systems, which means they cost less and therefore it can be concluded that they are cost-effective.

7. CONCLUSION

The purpose of this thesis was to show the potential of BE technologies in the Croatian part of the Adriatic Sea using the program EnergyPLAN. The potentials for offshore wind, wave energy and seawater heat pumps were analysed. This thesis contains an overview of currently operating power plants, fuel consumption in various sectors and other parameters relevant for the analysis. The forecasts for 2030 and 2050 were taken from Resflex project since they are hard to predict, but are relevant for estimating the final consumption, production and CO_2 emissions. The capacities for RES were taken from the Energy development strategy of the Republic of Croatia until 2030 with a view to 2050. The potentials of BE technologies in the Adriatic Sea was determined as follows.

For offshore wind, the regions with highest wind speeds were located near the city of Pula, and more noticeably the open sea area parallel to the region between the archipelago of the Kornati and the town of Primošten. For the latter, it was shown that the largest number of capacities could be installed. The Adriatic Sea was divided into zones in the EEZ area. The zones were determined according to sea depth, distance from shipping lines, distance from the coastal zone and other parameters. It was concluded that the largest number of offshore wind turbines can be installed in zone C in the central part and the smallest amount in zone D in the southern part. The results from EnergyPLAN have shown that offshore wind energy could have a significant impact on the electricity system of Croatia. Three locations were observed for wave energy capacities. The greatest potential was once again seen in the central part of the Adriatic. The assumed capacities are significantly lower than for offshore wind. The results have shown that wave energy does not have a significant impact on the electricity system of Croatia. It was assumed that seawater heat pumps will replace coal and oil boilers. Heat pumps can produce energy for both heating and cooling which is considered a great benefit. From the results in EnergyPLAN it was shown that seawater heat pumps slightly increase CO_2 emissions and fossil fuel consumption and lower the share of RES in electricity production. This is because in EnergyPLAN it cannot be specified from which source the heat pump draws electricity. It was concluded that seawater heat pump potentials are much lower compared to the offshore wind but are still promising.

The final important factor is the price which has a great influence on the implementation of BE technologies. Because of that, a techno-economic analysis was conducted, concluding that offshore wind is cost-effective after about 5 years and could generate high revenue in the remaining operating lifetime. Analysis for 5 MW wave energy capacities and the Wave Line

Magnet converter has proven that they are still not profitable due to low revenues, high capital and high maintenance costs. Even with a reduction in these costs, the production is too low for this technology to be cost-effective. The seawater heat pumps have proven to be cost-effective as they are smaller devices and therefore have lower costs.

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ATTACHMENTS

1. Techno-economic analysis

FINANCIAL CASHFLOW	0	1	6	12	18	24	30
Investment (own funds)	-8 195 298 000.00 €						
Loan							
Principal amount		745 644 536.36 €	907 190 589.32 €	1 147 885 506.07 €	1 452 441 361.88 €		
Interest		764 894 480.00 €	603 348 427.04 €	362 653 510.29 €	58 097 654.48 €		
Loan instalment		1 510 539 016.36 €	1 510 539 016.36 €	1 510 539 016.36 €	1 510 539 016.36 €		
Gross revenue		3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €
O&M		-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €
Amortization		-2 731 766 000.00 €	-2 731 766 000.00 €	0.00 €	0.00 €	0.00 €	0.00 €
Tax base		-72 124 936.00 €	89 421 116.96 €	3 061 882 033.71 €	3 366 437 889.52 €	3 424 535 544.00 €	3 424 535 544.00 €
Income tax		0.00 €	-16 095 801.05 €	-551 138 766.07 €	-605 958 820.11 €	-616 416 397.92 €	-616 416 397.92 €
Net profit	-8 195 298 000.00 €	1 913 996 527.64 €	1 897 900 726.59 €	1 362 857 761.57 €	1 308 037 707.53 €	2 808 119 146.08 €	2 808 119 146.08 €

ECONOMIC CASHFLOW	0	1	6	12	18	24	30
Investment (own funds and loan)	-27 317 660 000.00 €						
Gross revenue		3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €	3 922 515 000.00 €
Expenses		-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €	-497 979 456.00 €
Tax		0.00 €	-16 095 801.05 €	-551 138 766.07 €	-605 958 820.11 €	-616 416 397.92 €	-616 416 397.92 €
Net profit	-27 317 660 000.00 €	3 424 535 544.00 €	3 408 439 742.95 €	2 873 396 777.93 €	2 818 576 723.89 €	2 808 119 146.08 €	2 808 119 146.08 €
NPV	7 681 962 316.13 €						

Techno-economic analysis: 5 MW wave energy capacity – Location 3

FINANCIAL CASHFLOW	0	1	5	10	15	20	25	30
Investment (own funds)	-2 400 000.00 €							
Loan								
Principal amount		466 429.29 €	545 656.30 €	663 874.32 €				
Interest		224 000.00 €	144 772.99 €	26 554.97 €				
Loan instalment		690 429.29 €	690 429.29 €	690 429.29 €				
Gross revenue		96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €
O&M		-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €
Amortization		-800 000.00 €	-800 000.00 €	-800 000.00 €	0.00 €	0.00 €	0.00 €	5.00 €
Tax base		-1 084 705.60 €	-1 005 478.59 €	-887 260.57 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 700.60 €
Income tax		0	0	0	0	0	0	0
Net profit	-2 400 000.00 €	-751 134.89 €	-751 134.89 €	-751 134.89 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 705.60 €

ECONOMIC CASHFLOW	0	1	5	10	15	20	25	30
Investment (own funds+loan)	-8 000 000.00 €							
Gross revenue		96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €	96 794.40 €
Expenses		-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €	-157 500.00 €
Tax		0	0	0	0	0	0	0
Net profit	-8 000 000.00 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 705.60 €	-60 705.60 €
NPV	-8 304 667.36 €							

Techno-economic analysis: the Wave Line Magnet – Location 1 and 2

FINANCIAL CASHFLOW	0	1	6	12	18	24	30
Investment (own funds)	-33 396 363.64 €						
Loan							
Principal amount		6 490 434.22 €	7 896 605.63 €				
Interest		3 116 993.94 €	1 710 822.53 €				
Loan instalment		9 607 428.16 €	9 607 428.16 €				
Gross revenue		5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €
O&M		-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €
Amortization		-11 132 121.21 €	-11 132 121.21 €	0.00 €	0.00 €	0.00 €	5.00 €
Tax base		-11 236 751.52 €	-9 830 580.10 €	3 012 363.64 €	3 012 363.64 €	3 012 363.64 €	3 012 368.64 €
Income tax		0	0	-361 483.64 €	-361 483.64 €	-361 483.64 €	-361 484.24 €
Net profit	-33 396 363.64 €	-6 595 064.52 €	-6 595 064.52 €	2 650 880.00 €	2 650 880.00 €	2 650 880.00 €	2 650 879.40 €

ECONOMIC CASHFLOW	0	1	6	12	18	24	30
Investment (own funds+loan)	-111 321 212.12 €						
Gross revenue		5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €	5 204 000.00 €
Expenses		-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €	-2 191 636.36 €
Tax		0	0	-361 483.64 €	-361 483.64 €	-361 483.64 €	-361 484.24 €
Net profit	-111 321 212.12 €	3 012 363.64 €	3 012 363.64 €	2 650 880.00 €	2 650 880.00 €	2 650 880.00 €	2 650 879.40 €
NPV	-96 202 856.01 €						

<u>FINANCIAL CASHFLOW</u>	0	1	5	10	15	20	25
Investment (own funds)	-7 147 335.42 €						
Loan							
Principal amount		1 389 052.74 €	1 624 995.24 €	1 977 055.17 €			
Interest		667 084.64 €	431 142.14 €	79 082.21 €			
Loan instalment		2 056 137.38 €	2 056 137.38 €	2 056 137.38 €			
Gross revenue		39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €
O&M		-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €
Amortization		-2 382 445.14 €	-2 382 445.14 €	-2 382 445.14 €	0.00 €	5.00 €	10.00 €
Tax base		35 729 686.52 €	35 965 629.02 €	36 317 688.95 €	38 779 216.30 €	38 779 221.30 €	38 779 226.30 €
Income tax		-6 431 343.57 €	-6 473 813.22 €	-6 537 184.01 €	-6 980 258.93 €	-6 980 259.83 €	-6 980 260.73 €
Net profit	-7 147 335.42 €	30 291 735.35 €	30 249 265.70 €	30 185 894.91 €	31 798 957.37 €	31 798 956.47 €	31 798 955.57 €

<u>ECONOMIC CASHFLOW</u>	0	1	5	10	15	20	25
Investment (own funds+loan)	-23 824 451.41 €						
Gross revenue		39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €	39 030 000.00 €
Expenses		-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €	-250 783.70 €
Tax		-6 431 343.57 €	-6 473 813.22 €	-6 537 184.01 €	-6 980 258.93 €	-6 980 259.83 €	-6 980 260.73 €
Net profit	-23 824 451.41 €	32 347 872.73 €	32 305 403.08 €	32 242 032.29 €	31 798 957.37 €	31 798 956.47 €	31 798 955.57 €
NPV	269 346 271.51 €						