Assessing wave energy's value for decarbonizing the steel industry

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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It has been struggling at times with the complexity of a forecasted energy system but amusing to discuss and overcome it with everyone involved.

ABSTRACT ENGLISH

In the current energy transition to reach a net zero-carbon scenario, the steel industry is one of the hardest sectors to abate, due to its high energy demand and the use of carbon for its synthesis. It has been proven that through changing the process of production, the carbon can be substituted with hydrogen, allowing a nearly fully eradication of the carbon emissions. However, the hydrogen must come from a renewable source at a constant supply due to the industrial production particularities. Currently, electrolysis is the most advanced technology to produce green hydrogen but is tied to the intermittent electricity supply from renewable sources. Energy storage systems for industrial volumes are with today’s technology an unfeasible option. On the other hand, alternative renewable sources such as wave energy, has demonstrated to bring a predictable, less variable, and complementary production profile to the conventional wind and solar energy. The study has been based on H2GS´s future steel factory in the Iberian Peninsula including a 1GW electrolyser, that must be operational for 8000hours, equivalent to a 90% utilization. The paper suggests that when including wave energy to the supply mix, the total installed capacity can be reduced by a 46%. This leads to a significant cost reduction where the LCOE is decrease by a 26%. Furthermore, the total AEP is reduced which implies less over-capacity sold to the grid, where the technological and geographical similarities entail a low selling price, translating to a project risk reduction.

KEY WORDS EN

Decarbonization, Steel industry, green hydrogen, Wave energy, Electrolyser

ABSTRACT PORTUGUESE

Na actual transição energética para atingir um cenário de neutralidade de carbono, a indústria do aço é um dos sectores mais difíceis de reduzir, devido à sua procura elevada de energia e à utilização de carbono para a sua síntese. Está provado que, através da alteração do processo de produção, o carbono pode ser substituído por hidrogénio, permitindo uma erradicação quase total das emissões de carbono. No entanto, o hidrogénio deve ser derivado de uma fonte renovável com um abastecimento constante, devido às particularidades da produção industrial. Actualmente, a electrólise é a tecnologia mais avançada para produzir hidrogénio verde, mas está ligada ao fornecimento intermitente de electricidade a partir de fontes renováveis. Os sistemas de armazenamento de energia para volumes industriais com a tecnologia existente são, atualmente, uma solução impraticável. Por outro lado, as fontes renováveis alternativas, tais como a energia das ondas, demonstraram trazer um perfil de produção previsível, menos variável, e complementar à energia eólica e solar convencional. O estudo foi baseado na futura fábrica de aço da H2GS na Península Ibérica, incluindo um electrolisador de 1GW, que deve estar operacional durante 8000 horas, o que equivale a uma utilização de 90%. O estudo sugere que, ao incluir a energia das ondas na mistura de fornecimento, a capacidade total instalada pode ser reduzida em 46%. Isto leva a uma redução de custos significativa onde o LCOE é reduzido em 26%. Além disso, a AEP total é reduzida, o que implica menos sobrecapacidade vendida à rede, onde as semelhanças tecnológicas e geográficas implicam um preço de venda baixo, traduzindo-se numa redução do risco do projecto.

KEY WORDS PO

Descarbonização, Indústria siderúrgica, Hidrogénio verde, Energia das ondas, Eletrolisador

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List of Abbreviations

AWE	Alkaline Water Electrolysis
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CF	Capacity Factor
CFE	Carbon Free Electricity
COP	Conference of the Parties
CPO	CorPower Ocean
CRF	Capital Recovery Factor
DRI	Direct Reduced Iron
DTU	Danmarks Tekniske Universitet
EAF	Electric Arc Furnace
ETS	Emission Trading System
EU-SCORES	European Scalable Offshore Renewable Energy Sources
GHI	Global Horizontal Irradiance
GoO	Guarantees of Origin
GW	Gigawatt
H2GS	H2 Green Steel
HOMER	Hybrid Optimization Model for Multiple Energy Resources
KPI	Key Performance Indicator
KTH	Kungliga Tekniska Högskolan
LCOE	Levelized Cost Of Electricity
MIBEL	Mercado Ibérico Eléctrico
MW	Megawatt
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
OMIE	Operador del Mercado Ibérico de Energía
OMIP	Operador del Mercado Ibérico Portugués
OPEX	Operational Expenditures
PCI	Pulverized Coal Injection
PEM	Polymer Electrolyte Membrane
PPA	Power Purchase Agreement
PV	Photovoltaic
RED	Renewable Energy Directive
RES	Renewable Energy Source
RET	Renewable Energy Technology
RP	Renewable Penetration
SDG	Sustainable Development Goals
TEN-E	Trans-European Networks for Energy
UNFCCC	United Nations Framework Convention on Climate Change
WEC	Wave Energy Converter

1 Introduction

1.1 Background

The world is facing the major challenge of changing the course of climate change. Throughout the last century we have built an unsustainable society and industrial model which is now showing its repercussions, affecting our planet and all living on it.

Taking responsibility for our actions, a global climate response is in place. The United Nations Framework Convention on Climate Change, as stated; established an international environmental treaty to combat "dangerous human interference with the climate system", in part by stabilizing greenhouse gas concentrations in the atmosphere.

The energy used for heavy industry accounts for a 24.2% of these greenhouse gas emissions. Where the steel and iron industry take up to a global 7.2% [1]. These are considered hard to abate industries due their difficulty to decarbonize due to their current dependency on coal and high energy demand. Only in Europe the steel energy demand is 300TWh every year, more than six Portugal's combined. Additionally, the global steel demand is on the rise.

Through highly climate focused regulations that have been implemented throughout the years, there is not only an obligation to decarbonize the steel industry, but also a new growth strategy in the European Union, automatically leading to a transformation of the process of steel making. Some regulations worth mentioning can be the carbon penalties, both from direct emissions and imports. Furthermore, the clients of steel are also requiring carbon-free steel for their products, as many automotive companies have stated to go carbon-free in the entire life cycle of their products.

The most promising way to decarbonize the steel industry is changing the process. In industrial terms this is a long-term and heavy-investing procedure which must start now to reach the environmental goals. Currently the most efficient process to decarbonize the industry is with indirect electrification through hydrogen iron ore reduction, the raw material needed for steel production. In this case, massive renewable electricity would be needed and a major evolution in big scale electrolysers.

The European Union has also focused on this aspect as it is a new high demand of electricity, where in the regulatory framework aim to reach two main requirements in the hydrogen production. The hydrogen must be produced from a renewable source, hourly matching in the long term, and from new installed renewable sources to not interfere with the current electricity market, which would cause a market and grid instability.

On the other hand, the steel industry requires a constant production where the electrolyser runs continually. This means an industrial load base fulfilling the downstream requirements. Otherwise, the business case for the production would not be feasible according to experts in the steel industry.

Currently the renewables sources cannot provide a stable base load and the utilities must solve the gap of the intermittent wind and solar energy. The solution could run through storage systems with excess of renewable sources. This thesis aims to study an alternative renewable source with a high base load, wave energy.

To master the systemic view of this challenge, many variables come into place. Volumes of energy must be studied, hours of production of the electrolyser and its efficiencies, the role of the grid with its behaviour, cost of electricity, grid tariffs and ancillary services, emissions with its penalties and regulations, the guarantees of origin of the supplied electricity, etc.

1.2 Purpose

The use of green hydrogen as a solution to decarbonize this hard-to-abate industry has been receiving increasing amounts of attention, although a stable renewable energy supply is required. As both solar and wind have high variation output, there is a need to complement these sources with an energy source with a complementary production profile. There are strong indications that wave energy has the largest potential with at least 500GW of practical resource and a production profile that is more predictable, less variable and with a complimentary profile to enable this large transformation.

The main objective of the present master thesis is to analyse in-depth whether wave energy can be a key enabling technology for the decarbonization of the steel industry, calculating the value of CorPower Ocean's (CPO) wave energy technology as a solution in this market. Taking into consideration CPO's technology, as well as electrolyser costs and efficiencies, a business case for green steel production using wave-powered hydrogen will be developed, evaluating the project economics for different renewable energy systems, as well as relevant legislation, regulatory, and carbon credits frameworks.

The principal research question of this thesis is: What is the value of wave energy to decarbonize the steel industry? The system value is a "holistic framework that evaluates economic, environmental, social and technical outcomes of potential energy solutions". This framework aims to "shift political and commercial focus beyond cost, to include value".

1.3 Scope and Delimitations

This study covers a site-specific case in the north of Portugal for 2030. A future joint programme between "H2 green steel" (H2GS), Swedish green steel manufacturer, and Iberdrola, Spanish energy company, plan to develop a 1GW electrolyser powered by renewable energies to produce hydrogen for direct reduced iron (DRI) production. The need of a constant supply of electricity from renewable sources to cover the electrolyser demand is their main key performance indicator (KPI). This study aims to see wave energy's impact to the traditional renewable energy system, constituted by wind and solar. A production and financial study will be carried out to analyse its feasibility.

The site selected is located in Viana do Castelo, a hypothetical site for the electrolyser's facility. The offshore farm is located 20km from the shore where the Wind Float Atlantic offshore wind project is located, due to data availability. Photovoltaic and onshore wind has also been included in the study, which have been located next to the main site.

Wind, wave and solar resources have been obtained for years 2018 and 2019 due to available resources. Calculations are based on modelled data from the obtained time-series. A broader timeline could be used to obtain more accurate results, as well as physically measured data. The project duration is 25 years.

Grid prices are volatile and hard to forecast. With the Russian gas situation in Europe which sets the price for electricity for our current electricity market, assumptions have been made for year 2030 taking into account the future energy mix of the grid.

Other aspects such as land space, grid connection (voltage, congestion, etc.), supply chain for manufacturing has not been taken into consideration for this study. Including storage was taken off from the study due to various reasons but would be a positive post-study.

All data, including CorPower Oceans power matrixes, are originally made from specific conditions which would have to be re-analysed for future concrete projects.

1.4 Method

The research of the involved resources and assets has been obtained through research papers, renewable energy resource sites as Copernicus and Ninja Renewables, CPOs private documentation and other public and research data bases, such as the Iberian electricity market, OMIE, the National Renewable Energy Laboratory, NREL, etc. Contact with H2GS was held to understand their demands, expectations and KPIs.

For the modelling the software HOMER PRO was used [2] , provided by the KTH university. Developed by NREL the Hybrid Optimization Model for Energy Resources, HOMER, it nests three powerful tools in one software product, so that engineering and economics work side by side. As a complementary tool, excel has been used for pre-processing data and post-processing results.

Thesis process:

1. Research problem and objectives – Site specific business case.
2. System perspective. Scheme, delimitations, KPIs.
3. Quantitative and qualitative approach.
4. Modelling with tools.
5. Results and analysis. General and site-specific conclusions. Sensitivity analysis.
6. Discussion and future work.

2 The steel industry

Steel is one of the core pillars of the modern industrial ecosystem. Its diverse properties make it a unique material, present in our house appliances all the way to the construction and transport sectors, including many of the renewable technologies such as the wind industry.

2.1 Europe's current state

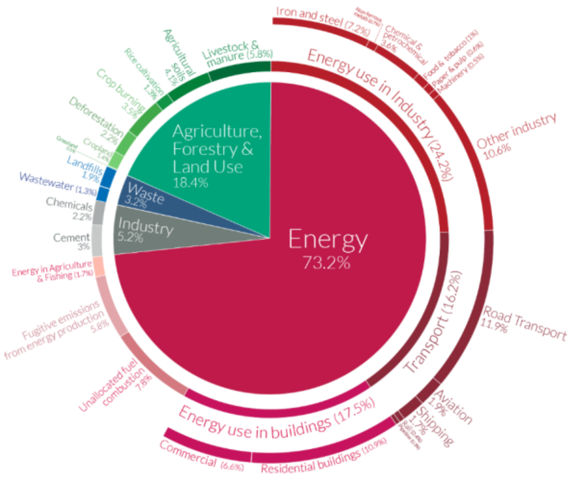
Europe has been a leader in its production throughout its history and it is grained in the industry chain with 2.6 million direct and indirect jobs throughout the EU [3]. However, in the last decades, China, India and other countries outside Europe's borders, have overtaken the market with quantity and price as main strengths, where Europe would only be able to stay competitive with innovation, quality and environmental performance. Additionally, the world-wide pandemic has affected the drastically the demand and supply chains leaving it in a fragile position.

Simultaneously, climate change started becoming a priority in most countries' political road maps. The first big milestone was the Paris Agreement in 2015 adopted by the majority of parties from the United Nations Framework Convention on Climate Change, UNFCCC. The Paris Agreement, referred to as COP 21, was the first major climate plan taken place, with the goal to limit the global warming by 1.5ºC to 2ºC. Europe created the Energy Union strategy to fulfil the goals settled in the COP 21.

Several years later, in 2019, the European parliament declared a climate emergency increasing its measures towards fulfilling the Paris Agreement. Through the European Green Deal, Europe aims to reduce the greenhouse gas emissions from 40% to at least 55% and reach climate neutrality, by 2050. Under this Green deal as umbrella, the climate law was founded and approved by the European commission, the parliament and the state members to legislate and execute a roadmap towards a carbon free Europe by 2050 [4]. Programmes as Fit for 55, Repower EU and RED III have been designed as a growth strategy for Europe to decarbonize the industry in a legislative, competitive and innovative manner. These plans will be seen further on how they affect the steel industry transformation and the renewables sources feeding this transition.

To meet these objectives, abating carbon intensive industries is crucial. In Europe these industries account for 15% of the total carbon emissions, where a 5.7% is directly and indirectly originated from the steel industry. The European average emissions are 2 tonnes of CO2 per tonne of steel produced. In 2019, the European Union produced around 150 million tonnes of steel, accounting for 221Mt of greenhouse gas emissions, considering direct emissions (scope 1), electricity demand (scope 2) and raw materials (scope 3) [5].

The global steel demand was 1800 million tonnes in 2021 with a forecast to grow significantly in the next decades [6]. In Figure 1, the global greenhouse gas emissions can be seen by sector. Where 7.2% originates from the iron and steel industry.



OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020). Licensed under CC-BY by the author Hannah Ritchie (2020).

Figure 1. Global greenhouse gas emissions by sector [1].

2.2 Steel production

To understand the full value chain around steel and how this sector can be decarbonized, it is important to acknowledge the upstream and downstream of the industry.

The raw material needed for steel production is iron ore, which is extracted from the mines and must be transformed to direct reduced iron (DRI) for steel production. The iron ore must be pre-treated to form sinter or pelletised iron ore. This sintered iron ore contains the compound of hematite, where the iron must be separated from the oxygen through various reactions. For this process a reduction agent is needed at very high temperatures.

The conventional reduction agent is coke, a treated coal with a higher calorific value and carbon density. The coke and the sinter react in the blast furnace (BF) at high temperatures, producing liquid iron as final output. As infamous by-product, carbon dioxide is released. Further on, the liquid iron is converted into crude steel in a basic oxygen furnace (BOF), reducing its carbon content through adding oxygen and scrap.

The crude steel is then post-processed in various ways through casters, rolling, etc. to obtain the final product desired by the customer. The full conventional route is represented in Figure 2.

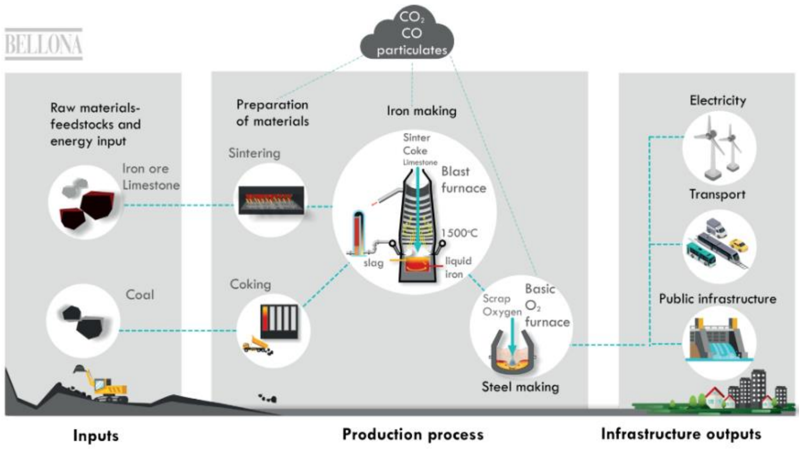


Figure 2. Conventional route for steel production [7].

The BF-BOF route, also known as the primary or integrated production route, accounts for 60% of steel production in Europe. The majority of the emissions come from the blast furnace and the coke plant. [5]. The other 40% is made through the recycling route, where scrap steel is recycled in an electric arc furnace (EAF). In the EAF, high-power electric arcs melt the scrap into liquid steel, they can also be used with specific pre-treated DRI. It is important to notice that high-quality new steel for certain sectors, requires iron ore.

There are low-carbon steel production processes that have not yet met the Technology readiness levels, TRL, but are being assessed and evaluated. Some of them are:

- BF/BOF efficiency methods. Optimizing the iron content of the raw materials to reduce the coal needed to reduce it, increasing the fuel injection with pulverized coal injection (PCI) or natural gas, biomass, hydrogen, etc. are some of the options to decrease the carbon dioxide emissions. An improvement, but not enough to reach the desired carbon free production.
- Carbon capture and storage. Still in a premature state, the usage of carbon captured from the conventional processes could be used for products in the chemical industry.
- DRI and EAF optimization. A high-quality scrap for the EAF route is necessary to produce quality steel, the limited availability and increase of demand of scrap would create an unstable production. The optimized DRI method requires a constant supply of natural gas, which emits less carbon dioxide than the BF route, currently also in an unstable supply. Imports of DRI or in shape of Hot Briquetted Iron (HBI) from countries with cheap natural gas is a commonly practiced by European steel producers.
  It is important to take the recycling scrap method in high regard for sustainability reasons, a circular economy within the steel industry through EAF is and will be an important percentage of the steel manufacturing.
- DRI and EAF using hydrogen. By using green hydrogen, instead of fossil fuels in the chemical reduction process, it would enable nearly emission-free steel production. Additionally, it plays a big role in the

heating demand needed. This is the best long-term solution from the here stated, to achieve a climate neutral steel production.

2.3 Green steel production

The main green route for DRI production from iron ore would be produced through primarily hydrogen as the reduction agent, instead of coke. The oxygen from the hematite ($3Fe_2O_3$) reacts with the hydrogen, through multiple reactions, producing reduced iron (Fe) and mainly water as by-product as seen in below

$$\begin{gathered} 3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O \\ Fe_3O_4 + H_2 \rightarrow 3\ FeO + H_2O \\ FeO + H_2 \rightarrow Fe + H_2O \end{gathered} \quad (1)$$

Finally, the EAF, powered by renewable energy sources, substituting the BOF, would heat the DRI up to temperatures around 2000°C, to produce raw steel. This full process reduces the carbon dioxide emission by a 95%. [7]

A green hydrogen based DRI/EAF route includes the major challenge of producing high volumes of hydrogen.

2.3.1 Electrolysers

Electrolysers produce hydrogen by passing a direct electric current through water decomposing it into hydrogen, H2, and oxygen. To produce one kilogram of hydrogen, 9L of water and 50kWh are approximately needed, depending on the efficiency of the electrolyser.

Giga-electrolysers have not yet been developed, with some pilot projects under planning as for example in the Netherlands. There is still a technological race between Alkaline Water Electrolysis (AWE) and Polymer Electrolyte Membrane (PEM) being the main solutions. Both have similar CAPEX, 730€/kW and 830€/kW respectively [8]. Production flexibility, heat management, pressure will be the core performance factors to consider for different applications. Efficiencies are set to improve at the same ratio, being able to go under the 45 kWh/kgH2 [9]. It is important for financial reasons to have the electrolyser running for the biggest number of hours possible according to steel industry experts.

It has been researched that to decarbonize the entire steel industry it would require a capacity of 600GW of electrolysers, whereas for today the total capacity is around 300MW [10]. As hydrogen is gaining protagonism to become a critical element of the energy transition, support schemes are leading the investments towards electrolysers and are forecasted to reach 8.5GW by 2026 [11].

2.3.2 Hydrogen

Hydrogen has been used for different applications as in refineries and ammonia production for fertilizers. The current route of production is mainly through steam methane reforming, but is also done with oil and coal. This hydrogen is called grey hydrogen and the production is highly polluting but have been the most economical production route till the date. If these processes include carbon capture and storage the hydrogen would be considered blue. Hydrogen produced through nuclear power is called pink hydrogen and is considered a potential competitive solution for a base load hydrogen production, but also has its environmental trade-offs. There is a large scale of colours for hydrogen production but to be able to produce green hydrogen, sufficient electricity from renewable sources will be required.

Cost drivers

It is clear that the key cost drivers for green steel, are the costs of hydrogen and therefore electricity. Hydrogen costs are directly linked to electricity costs and the efficiencies of the electrolyser. Currently green hydrogen is almost double the expensive than hydrogen produced with fossil fuels but is predicted to turn around by 2030 with lower cost of renewables and falling costs of electrolysers.

A breakdown of the different production routes of steel is shown in Figure 3. The numbers of the different processes will be based on the cost of electricity for the electrolyser and the EAF. Other factors such as the ETS cost will also affect some routes as the conventional integrated mill. In the upcoming years they will change position in relation to these factors.

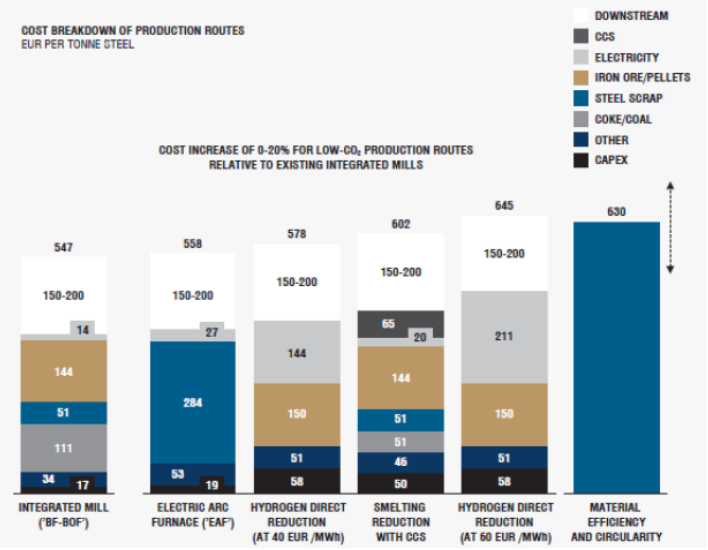


Figure 3. Cost breakdown of different production routes [3].

McKinsey did a sensitivity study relating the cost of producing green steel via electrolysers, directly proportional to the cost of hydrogen and electricity with the previously mentioned ETS. The results are the following:

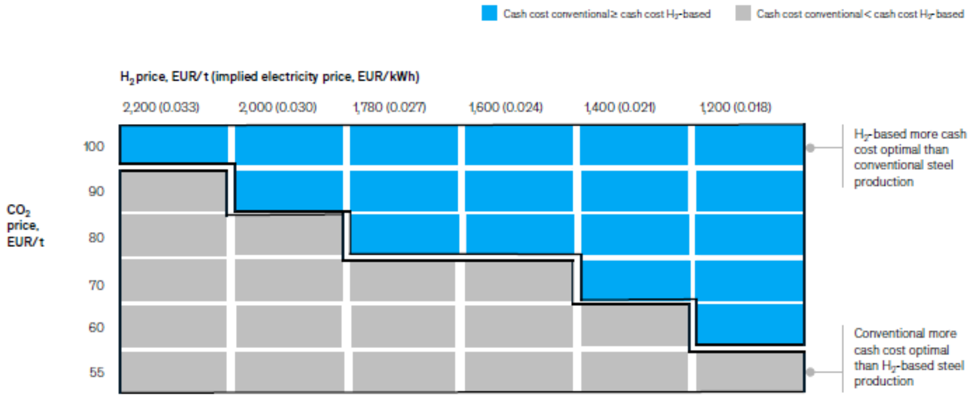


Figure 4. Sensitivity analysis on hydrogen cost and carbon penalties [12].

Lastly, the full cost of green steel cannot fall only on the steel producer. Steel customers and therefore final customers of the products will probably also see a slight rise in prices. Are consumers of vehicles willing to pay 300€ more for a green car or 20€ more for a green washing machine? Despite the answer, many automobility companies as Volkswagen and BMW have signed pledges to include low-carbon steel in their vehicles and even pre-ordered green steel from future producers [13].

2.3.3 H2GS

H2 Green Steel is a Swedish company whose goal is to produce green steel through green hydrogen-based DRI/EAF route powered by fossil-free electricity. They are building an “*impact company with sustainability at its core – for our people, customers, investors and planet”.* Their process as described previously on how green hydrogen is produced is shown beneath.

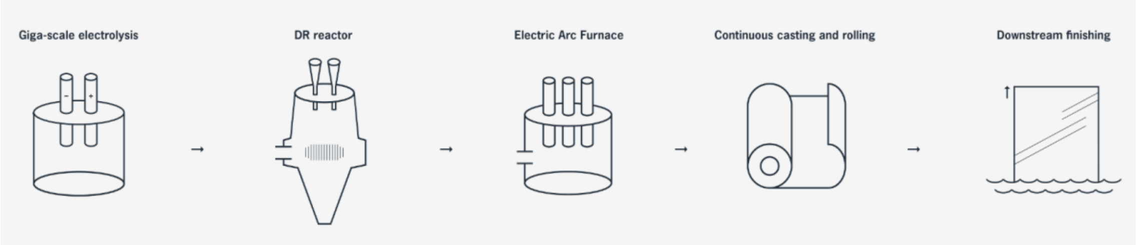


Figure 5. H2GS Value proposition [14].

Currently they are setting up their first factory in the north of Sweden, but other competitors are looking into similar ways to produce DRI facilities with hydrogen. The full set-up is quite unique from H2GS business model where the costs and security of electricity supply will stay as the main remaining challenge.

2.3.4 H2 policies

Hydrogen will play a big role to decarbonize heavy industries which through electricity are hardly abatable. Therefore, hydrogen is a hot topic in the European and worldwide political roadmaps.

The European commission published the public consultation on the Delegate Acts (tool to accelerate legislation done by the EU) about green hydrogen policies. There were strict rules that hydrogen has to follow “additionality”, where the electricity demand for green hydrogen has to come from newly installed capacity. This was done so the increase in demand for green electricity wouldn’t interfere with the current electricity market. Moreover, the electricity must have guarantees of origin (GoO) with an hourly matching between production and consumption.

This put a burden on both producers and consumers of hydrogen and halted the intentions of investing in the sector. However, the strict rules were modified and let, till 2027, the possibility to obtain the electricity through PPAs from renewable projects that has been operational for maximum 3 years. Regarding the GoO, the production must match monthly with the electrolyser’s operation. After 2027, this might become a problem as the levelized cost of hydrogen will increase the more halt there is on the electrolyser’s operation.

There are some exceptions to these rules as when the market price drops below €20/MWh. But it is important for investors to have a standardised regulation regarding the matter to see a prosperous development [15]. This legislation must go through the European Parliament and the European council for approval and amendments.

There are distinguished approaches to decarbonize the steel industry, different business models where different stakeholders take the investment risks, from adopting gradually or directly a green hydrogen system.

Even if the policies suffer changes to facilitate the deployment of hydrogen, the end goal has a common path; to decarbonize the steel industry, what we know till this date is that is must go through green hydrogen. The variables that will speed up the process are many; power supply, hydrogen supply security, raw material supply, production technology, willingness of steel customers to transition to green steel, etc. Therefore, a supportive regulation will play a key role.

2.4 Europe’s action plan

The current support for green steel is limited and not yet rewarding enough to create a change in the status-quo of the steel industry.

To assess the holistic view of the costs of green-hydrogen steel production in Europe, one key element will support its path, regulation. In this particular case, the European toolbox towards a sustainable and resilient steel industry [16].

Funding and budget programmes

After the pandemic, the European Union has secured a “stimulus package” of EUR 1.8 trillion from the long-term budget and the Next Generation EU recovery package. It aims to foster the green and digital transition as a fresh start post-covid. Additionally, research and innovation projects regarding a carbon free steel production will be supported to develop, test and scale new technologies regarding the matter. Many goals are set to be reached by 2030 and specifically be funded by the Horizon Europe plan [17].

The innovation fund, established under the EU Emission Trading System (ETS), is one of the largest funding programmes towards low-carbon technologies. Through this penalty system of carbon dioxide emissions, it aims to provide EUR 18 billion.

The InvestEU fund, will finance a wide range of investments, including energy-intensive industries. Allowing both public and private investments of around EYR 370 billion. Together with the Sustainable Financing Taxonomy, where private investors will be more aware and rewarded to invest sustainably, the market will move towards green investment. Some of these indicators are the sustainable development goals (SDG) and the Environmental, Social and Governance (ESG), where these non-financial factors are analysed to identify material risks and growth opportunities.

Supportive regulatory environment

- EU Emissions Trading System (ETS). Is a "cap and trade" scheme where a limit is placed for carbon dioxide emissions. Companies can trade emission rights and it covers around 45% of EUs greenhouse gas emissions. Currently the cost per tonne of CO2 emitted lays around 80€, and affects power plants, industry factories and aviation.
- Affordable, accessible and abundant decarbonized energy is the big challenge for an increasingly electrified society. The demand that the steel industry would need, together with electric vehicles, heat pumps, etc. need a strong action plan in terms of grid upgrading and supply variability. It is important to match and integrate the renewable energy production and the demand in geographical sense where the TEN-E Regulation will play a big role with grid projects.
- Carbon Border Adjustment Mechanism (CBAM) is essentially an environmental measure to enable the EU's increased climate ambition by reducing carbon leakage risks. CBAM will ensure that the price of import reflect their carbon emissions. This will make the European steel industry more competitive towards production abroad.
- A standardisation process is also to be set to create these markets for clean technologies, enabling a life cycle approach and giving accurate data to investors.

Allowances

Some industries, including the steel industry, receive a share of their emission allowances for the ETS. This allocation is based in benchmarks that reward the most efficient installations. This proportion will decrease gradually till they fully disappear. The free allocation is measured by the greenhouse gas emissions [18].

The problem is that these allowances aren’t working well enough for the steel industry as companies might change a small process of the conventional route of production without tackling the main problem which is the heavy emitting core route. This keeps the current big steel industries not doing substantial changes.

Despite the EU steel sector facing challenging times, these regulations aim to maintain the EU economy strong and able to invest in transforming itself to become climate-neutral and circular, following the ambitions of the EU Industrial Strategy.

3 Offshore energy

It is now clear that if green hydrogen is the key component to decarbonize the steel industry, there will be a major increase in the demand of renewable electricity. The demand is not only raised by the steel industry, but in other sectors such as transport with electric vehicles, residential heating, other industries requiring hydrogen, etc. This is what is known as the overall electrification of our energy system, which seems to be the future for a sustainable society.

In 2020, 22.1% of Europe's total energy consumption was covered by renewable sources, a 37.5% of the electricity consumption [19]. The European Parliament voted in favour of a 45% target for renewables in the European energy mix. Today, hydro, wind and photovoltaics are the main renewable sources covering 84% of the renewable production.

The question arises if the current renewable sources will be enough to cover this electrification process. Hydro is a hardly expandable resource, limited by its geographical characteristics and its natural obtention of water, therefore its capacity increase is set to stay or even decrease from today's levels due to other important purposes of water for the society. Wind energy and PV are key technologies to keep deploying but have natural limitations such as land space, but a more important fact are their production profiles.

Electricity must be consumed at the same time it is produced, in other words, the production must meet the demand almost instantly, which creates a very complex system to balance as the electricity demand doesn't necessarily match when the sun is shining, or the wind is blowing. We are already seeing the effect of over production of electricity at some hours of the day, where the electricity prices tend to drop to cero. This is called the cannibalization effect of the renewables, where with the current electricity market function, the marginal costs are cero of the renewable sources, and lead to, in a way, free electricity for the customer. The same concept can be applied to hours of non-renewable energy, where the prices are set by fossil-fuel power plants and peak.

Here is where the first part of the title of the thesis comes in. Storage systems will be a crucial element to balance the grid and store over-production from the conventional renewable technologies. But there is another source of renewable energy that till the date is considered the world's largest untapped source of energy, the offshore energy.

With a potential of 20000TWh - 80000TWh of energy per year, which accounts for 100% to 400% of the total current global electricity demand, this source of energy becomes highly attractive [20].

3.1 EU trends and policies

It has already been 30 years since the first prototype of an offshore technology was tested in Denmark in the form a wind turbine. Since then, diverse technologies have been developed including wave, tidal, floating photovoltaics, etc. added to the previously mentioned wind. The offshore technologies have one of the greatest potentials to scale up, being the world’s largest untapped source of energy. Specially Europe with its favourable sea surroundings which will play a crucial role to achieve its climate neutrality goals.

As mentioned, the characteristics of offshore energy technologies makes it an ideal partner to wind and solar energy due to its time of production and predictability, enabling a better balancing between supply and demand. Europe is already leading the technology with performing projects, but there are many challenges ahead for a complete successful outcome.

The European goal is to install 60GW of floating offshore and 1GW of other ocean technologies by 2030 and 300GW and 40GW respectively by 2050 [21].

Therefore, Europe has presented a strategy enabling a framework for all offshore technologies. Facilitating and planning grid connections with support of the Trans-European Networks for Energy (TEN-E), accelerating permitting of projects, strengthened supply chains and investment programmes and funds are some of its points. Many of these technologies that are not a fully mature nor in an industrialized phase, will receive financial support, by de-risking the projects with support of funds such as the NextGeneration EU recovery fund. This is important to address the technological transfer of research projects from the laboratory into practice.

The European Parliament voted to raise the share of renewables in its final energy consumption to 45% by 2030. This would account of a total of 1236GW installed capacity by 2030, compared to the approximately 500GW of today [22]. Backed by the RePowerEU package, Renewable Energy Directive III (RED III), added that; out of the new installed capacity by 2030, 5% should come from innovative renewable energy technology [23]. This is an important booster for many unmatured offshore technologies.

In specific, there is a program from the horizon 2020 green deal project, called EU-SCORES, standing for European scalable offshore renewable energy sources, which aims to deliver the world’s first bankable hybrid offshore marine energy parks with a €45M budget, where CPO is a partner and set to install 1.2MW wave energy aside the WindFloat Atlantic project of floating wind in the north of Portugal [24].

The support of these technologies is important as the natural resources and the sea basins in Europe are different in each location, where a specific technology will suit best. In Figure 6, Europe’s sea basin can be seen by depth.

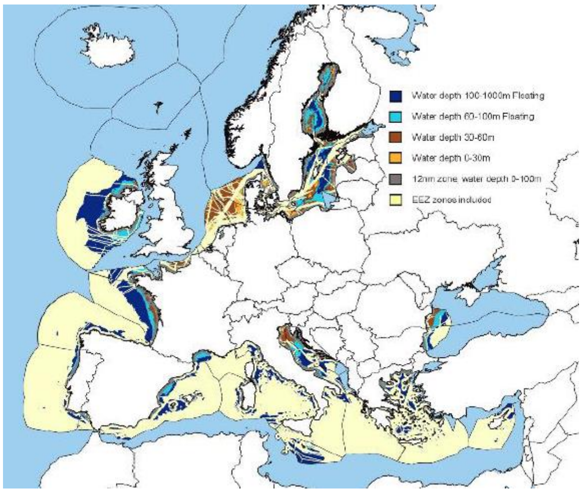


Figure 6. European sea basins [25].

Bottom-fixed wind turbines in Europe are currently the biggest renewable offshore technology if it can be considered a fully offshore technology, as its limitations are linked to the depth where 50-60m are the current maximum depth. As previously seen in Figure 6. This leaves a limited sea space for this technology. In this section, technologies less mature and in deeper sea levels will be presented.

3.2 Floating wind

Floating offshore wind opens a new market for wind power locations, in many regions of the world, the sea depth increases exponentially fast from shore, making this the only feasible solution for wind power. The seabed quality also plays a factor where sometimes the bottom fixed offshore wind is economically unviable. Around 80% of the offshore wind resources are in waters of more than 60m depth [26]. Usually, the average wind speeds are higher, more consistent, and less turbulent further from shore too.

On the other hand, high capital investments may restrain the market growth which is currently at 113MW of installed capacity [27]. The main cost drivers for floating wind compared to bottom-fixed are the floating structures which require a major investment in manufacturing and the supply chain side. Additionally, the grid connections offshore are also very costly. The platform, cables and offshore substation can account for almost 70% of the CAPEX compared to the 33% in fixed offshore foundations [28]. Currently the costs of the pre-commercial projects lay around 200€/MWh, so it is important to get to levels of maturity and big investments to reach competitive commercial costs.

On the other hand, the industrial links with hydropower, shipbuilding, wind turbine manufacturing and offshore oil and gas, floating wind has an advantage not only in the technology maturity but in the supply chain.

In Portugal the target for the offshore wind auction was raised to 10GW to be installed before 2030, aiming to move faster in the country´s energy transition [29]. Currently they have one floating wind farm operating since

2019, 20km offshore Viana do Castelo. It consists of three 8.4MW Vesta's wind turbines floating on a depth of 100m. They are the first full-scale project to use semi-submersible technology for the platform [30]. Floating wind in Portugal will play a key role in offshore wind strategy as water depths grow quickly after 10km offshore in the majority of regions.

An interesting solution for floating platforms is the CROWN buoy developed by BREZO Energy. A floating platform made by concrete reducing costs and manufacturing times as it enables local production [31].

3.3 Ocean Energy

The ocean energy is the world´s biggest untapped source of energy. It is the energy that can be harnessed from our oceans through waves, tides, currents, thermal and salinity differences, etc. Its resource has a great potential and is considered an ideal partner to wind and solar. They are predictable, produce in a more constant matter, enabling a better balancing between supply and demand. It is also socially accepted with less impact to society and environmentally studies show that marine life is not affected in a damaging way. Additionally, it brings new opportunities for traditional maritime industries and revitalize coastal regions.

The main barrier comes again as any novel technology, with the commercialization of ocean energy and the huge investments required. The challenge will be to obtain the sufficient and well-targeted funding, to bring costs down and bring the technologies to the market in the right timing. But the price is big, deploying 100GW of ocean energy worldwide would create a new industrial sector, creating 400000 skilled "green" jobs all along the supply chain [32].

Europe are world leaders in ocean energy and have the opportunity to capture this global market, estimated to be worth €50B annually in 2050. The technologies are proven to be ready for industry take-off.

3.3.1 Wave Energy

Waves are created by weather systems, strong winds blowing over the sea surface. They are built up over several days across the oceans, where the energy concentration generated depend on the wind speeds, their duration and fetch, currents, and the bathymetry of the seabed. They travel almost uninterrupted to the coastlines where its kinetic energy content can be harvested through wave energy converters (WECs). The longer the waves have travelled, the more energy they include that is measured through their period and wave height.

Waves formed from these offshore ocean swells include much more energy than waves produced by local winds close to shore. The best wave resource is found along the western coasts, delivering a stable, mass concentrated resource, typically in populated areas, benefiting in this way to feed directly settled grids. A map of the ocean's wave resource can be seen in Figure 7.

Depending on the site, wave energy can have a very complementary profile to wind energy due to the wind travelling than the waves. But its main strength is the consistency and stability. Wave can also be subject to seasonality effects, as seen in Europe. Other sites as Chile have a very constant wave resource throughout the year. The global potential wave resource is measured to be around 2TW with a quarter of it extractable [33].

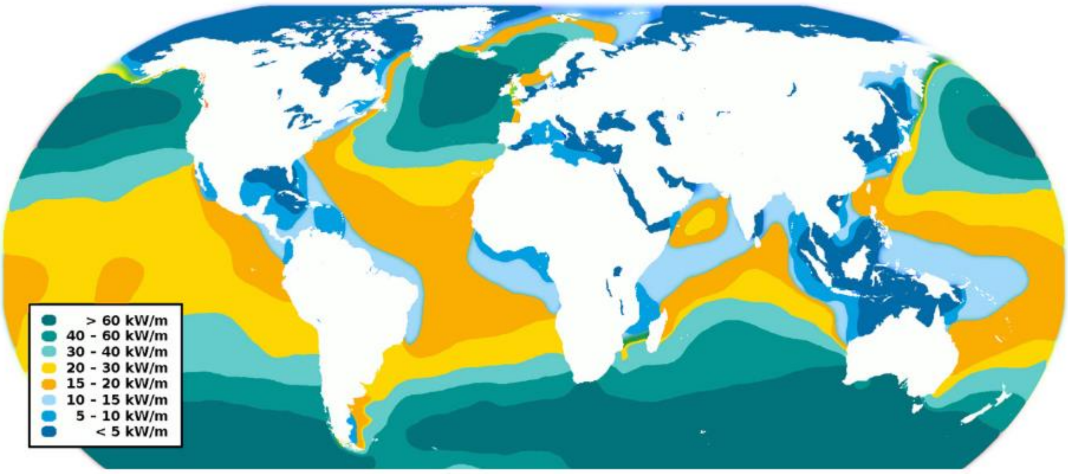


Figure 7. Wave resource in our oceans [34].

There have been many designs of WECs pursued over the years with some main technologies striving:

- Attenuator: Operates parallel to wave direction. It captures energy from the relative motion of two arms while the wave passes them.
- Point absorber: Floating structure which obtains the energy from all directions through the movements at the water surface converting the motion of the buoyant into electricity through different power-take-off systems.
- Oscillating water column: Hollow structure that uses the wave power to rise the water column and compress the air column to a turbine.
- Rotating mass: Through the motion of the heaving and swaying, it drives a gyroscope causing precession and producing electricity with an inner generator.

Other technologies worth mentioning are the overtopping device, submerged pressure differential, bulge wave [35].

Wave energy brings a major industrial opportunity for long-term economic development. The concept of needing many relatively small units enables coastal regions to create an economic growth in the development, manufacturing, installation, and operation of these farms.

The benefit also lays in creating multi-purpose farms along with floating wind, where the electricity systems could be shared, aquiculture powering, isolated areas as islands, etc. gives an advantage for the deployment of wind farms.

Lastly, for hydrogen projects, wave energy can help supply a more stable electricity output improving the business for hydrogen production, running on higher load factors. The capacity installed would be reduced and rely less on fossil-fuel electricity.

3.3.2 CorPower Ocean

CorPower Ocean (CPO) is a turnkey supplier of wave energy systems. It is inspired by the pumping principle of the human heart, which uses stored hydraulic pressure to provide the force for the return stroke. In a similar way, the wave energy converter uses a pre-tension system to pull the buoy downwards, this replaces the mass that would otherwise be needed to balance the buoyancy at midpoint, reducing the cost and carbon footprint. Wave swells push the buoy upwards, while the stored pressure provides return force to drive the buoy downwards. This classifies it as a point absorber WEC. The composite buoy, interacting with this wave motion, drives a Power Take Off inside the buoy that converts the mechanical energy into electricity through a novel mechanical drive train known as a cascade gearbox. CPO C4 WEC illustrated in Figure 8, from the hull to the anchoring system, has a rated capacity of 300kW.

The main innovation from CPO is its novel phase control technology through its wave spring technology which allows the buoy to be tuned and detuned, altering the system’s response to the conditions. In storm conditions, the detuned state creates transparency to incoming waves, similar to the survival function for wind turbines which pitch their blades to protect from over loading. In normal sea states, the buoy is tuned and set in optimal timing with the incoming waves, amplifying the motion and power capture. A 1-metre wave for instance is amplified to a buoy motion of 3 meters – making it highly efficient in capturing wave energy.

These have been two of wave energies main challenges throughout the years, storm survivability and an efficient electricity output, both tackled with the wave spring innovation.

Figure 8. CPO's WEC.

The buoy hull is a spherical composite structure designed for high volume low-cost production. The novel mobile factory concept is used to fabricate the hulls locally on customer’s site, improving the requirements for an optimal business case.

CorPacks are a cluster of WECs that can be installed side-by-side creating big arrays as seen in Figure 9. The electricity from each CorPack is exported through a collection hub, that can work together with floating offshore wind farms creating a multi-use farm. The CorPack consists then of WECs with their mooring systems, anchoring effective in different seabeds, electrical collection hub and a remote control and communication system. The real-time control system runs on state-of-the-art model-based optimal control algorithms that maximizes the power output while ensuring safe operation in all condition, which is improved with WEC arrays.

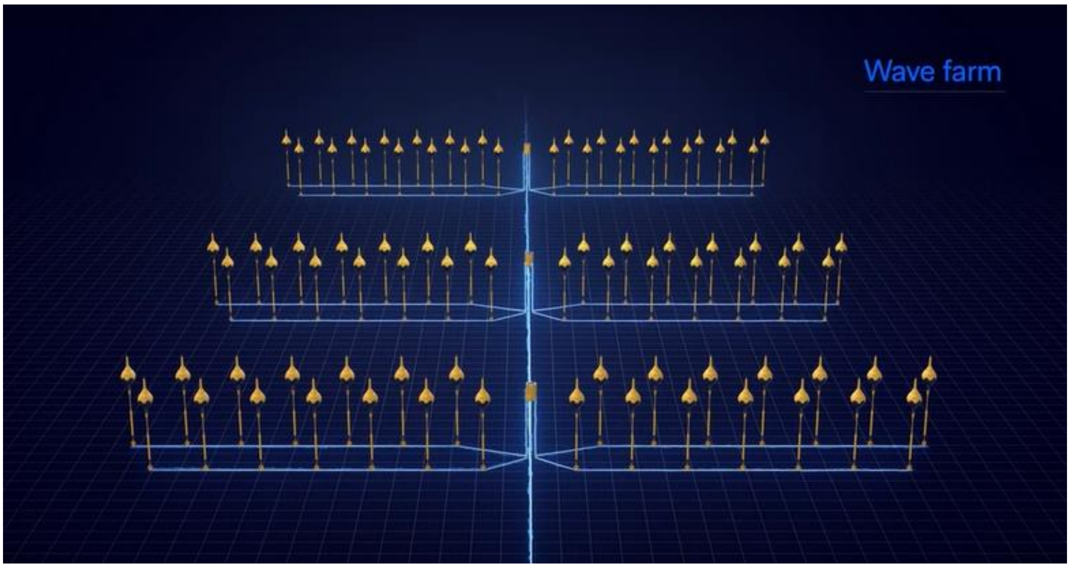


Figure 9. CorPack design [36].

With a spatial density of 15 MW/km2, these wave farms can deliver 3-5x more power from the same ocean space compared to a typical offshore wind farm. Each device is quite small compared to a modern offshore wind turbine. The high-density clustering is what makes this so powerful. Just like batteries are made up by many small cells packaged in modules, CPO´s wave clusters make use of many small identical wave devices. This modular approach allows efficient industrial roll-out, and economies of scale to kick-in early. It also enables local supply chain to be used to construct, install and service the wave farms, providing high local content through the entire project life cycle.

HiWave–5

The HiWave-5 project aims to demonstrate CPO WECs technical performance and a competitive LCOE in the near future. The overall goal of the project is to obtain a 3rd party certificate demonstrating its performance for bankability. The first step is a demonstration and prototype certification of the full-scale C4 in fall 2022, with an extension and type certification of a pilot array with three C5 WECs by 2024. The project is located in

Aguçadoura, Portugal, and will be connected to the Portuguese national grid. On CPO´s road map, a pre-commercial stage will follow with upgrades in the WEC designs through various projects worldwide by 2026, leading to a posterior commercial stage with a more “final” WEC by the end of the decade.

CPO matches the previously mentioned advantages of marine technology with a global opportunity of 500 to 800GW. These are higher numbers than the total nuclear installed and close to the total hydropower installed capacity globally. Its strength is the consistent power profile which makes it uniquely valuable by providing power in hours of low wind and solar production.

4 Methodology

This report is based on a site-specific business case where the system value of CPOs technology has been attempted to be measured. The conclusions can be extrapolated to similar cases around the world with similar wave resource, manifesting the advantages of wave power in any energy mix.

H2GS and Iberdrola announced a partnership to build a 1GW electrolyser plant to produce green hydrogen, which will be fed directly to a direct reduction tower, producing around 2 million tons of DRI. This would enable the production of green steel with 95% less CO_2 emissions.

The obtention of the amount of renewable electricity to feed the electrolyser and the electric arc furnace (EAF) will be an unprecedented challenge. It can be compared to the total maximum consumption of the Iberian Peninsula which reaches around 40GWh.

The purpose of the study is to proof the value of wave energy in the energy system for an independent power producer or a utility to meet the plant´s electricity demand. It is done through an energy system modelling with specific software's developed for this purpose and the specific demands of H2GS´s plant. H2GS wants to procure 24/7 carbon free electricity (CFE) to cover its 1GW electrolyser demand. The EAF consumption is not considered in this study. A production and financial study are carried out to analyze its feasibility.

Without knowing the exact location for the upcoming plant, the site has been selected due to available wind, wave, and solar resources. The offshore farm has been set where the WindFloat Atlantic project was deployed and assuming for the onshore farm and the green steel plant, the closest onshore location, next to the town of Viana do Castelo.

Figure 10. Site location.

The methodology and set-up of the project is defined in detail in this chapter. It includes key performance indicators (KPIs), assumptions for modelling, system boundaries and the characteristics of the energy system.

Two models have been done according to the renewable energy technologies. Model 1 includes an offshore multi-use farm of wave and wind, together with an onshore PV plant. Model 2 includes a stand-alone wave farm, an onshore wind farm and a PV plant.

4.1 Key Performance Indicators

To be able to study the feasibility of this project, there are some crucial KPI´s to follow closely.

4.1.1 Renewable Penetration

Maybe the most important indicator to measure the “green stamp” of a product, the renewable penetration is calculated as the amount of the electrolyser’s consumption covered by renewable electricity. It is important to note that when there is over-production of renewable electricity, this surplus is deducted from the total renewable production as its not supplying to the load but selling to the grid or dispatched in some other way

$$\mathrm{RP} = \frac{\mathrm{E_{RET}} - \mathrm{E_{su}}}{\mathrm{E_{load}}} \ , \qquad (2)$$

where:

$\mathrm{RP} = \text{Renewable Penetration [\%]}$,

$\mathrm{E_{RET}} = \text{Energy from renewable technologies [kWh]}$,

$\mathrm{E_{su}} = \text{Surplus energy [kWh]}$,

$\mathrm{E_{load}} = \text{Energy consumed by the load [kWh]}$.

The renewable penetration is usually calculated yearly to measure the total load covered by renewable electricity, but it is originally measured hourly.

4.1.2 Emissions and ETS

The second environmental KPI is directly linked to the renewable penetration but is important to measure due to its role in the European emission trading system (ETS) for industries. The modelling is done partially by buying electricity from the grid which has a certain CO_2 emission attached. These are known as emissions of scope 2. For every ton of CO_2 emitted the heavy industries will have to pay a penalty.

The renewable energy technologies included don’t have any emissions accounted for their assets (emissions of scope 3).

4.1.3 NPC and NPV

The total net present cost is the main financial performance indicator together with the LCOE. NPC is commonly used in projects where there are no sales or incomes. As this project doesn't have the priority of making profit from selling electricity to the grid but covering H2GS´s demand, the NPC is found more suitable. Nevertheless, the NPV will be calculated as the difference between the NPC of the specific system and the base case where electricity is bought entirely from the grid.

The NPC is calculated as the systems present value of all the costs over its lifetime, minus all the revenues at the same period. The costs incurred include capital costs (CAPEX), operational costs (OPEX), emission penalties (ETS) and grid purchases. The revenues include the grid sales

$$\mathrm{NPC} = \mathrm{CAPEX} + \mathrm{OPEX} + \mathrm{ETS} + \mathrm{Grid\ Purchases} - \mathrm{Grid\ Sales}\ , \quad (3)$$

The NPC is calculated by total discounted cash flows in every year of the project's lifetime. This is done by applying a discount factor (f_d) for each yearly cost

$$f_d = \frac{1}{(1+i)^N}\ , \quad (4)$$

where:

$\mathrm{i} = \text{real discount rate [\%]}$,

$\mathrm{N} = \text{number of year [y]}$.

Lastly, to calculate the real discount rate, the following equation is used based on the nominal discount rate and the expected inflation

$$\mathrm{i} = \frac{\mathrm{i}' - \mathrm{f}}{1+\mathrm{f}}\ , \quad (5)$$

where:

$\mathrm{i}' = \text{nominal discount rate [\%]}$,

$\mathrm{f} = \text{expected inflation rate [\%]}$.

4.1.4 LCOE

The levelized cost of electricity is a well know metric to determine the viability of renewable energy projects and comparing different renewable technologies. The simplest LCOE is calculated by summing the total costs over the lifetime of the project and dividing it by the total electricity generated. In this way the cost of one unit of energy is obtained.

The LCOE also have its flaws, as it doesn't account for the real value of the electricity. In this case and in many future projects, it is particularly important to include the variable of time and its circumstances. When is the electricity delivered? The electricity doesn't have the same value and thereby price, at different hours of the day. (E.g., The electricity market). This is basics supply and demand.

Therefore, three different LCOE are presented named in the most representative way:

4.1.4.1 Technology LCOE

$\mathrm{LCOE_{tech}}$ is useful to compare different technologies and see where they stand at. In this study this value will be shown but it is not a key metric for the overall system

$$\mathrm{LCOE_{tech}} = \frac{\mathrm{CAPEX\ (per\ MW){+}OPEX\ (per\ MW)}}{8760{*}\mathrm{CF}} \quad , \quad (6)$$

4.1.4.2 System LCOE

$\mathrm{LCOE_{system}}$, the systems LCOE is widely used to obtain a broader picture of how the costs of the system relate with an external actor such as the grid. Conceptually only, it is represented as following

$$\mathrm{LCOE_{system}} = \frac{\mathrm{CAPEX\ {+}OPEX{+}ETS{+}Grid\ Purchases{-}Grid\ Sales}}{\mathrm{Production}} \quad , \quad (7)$$

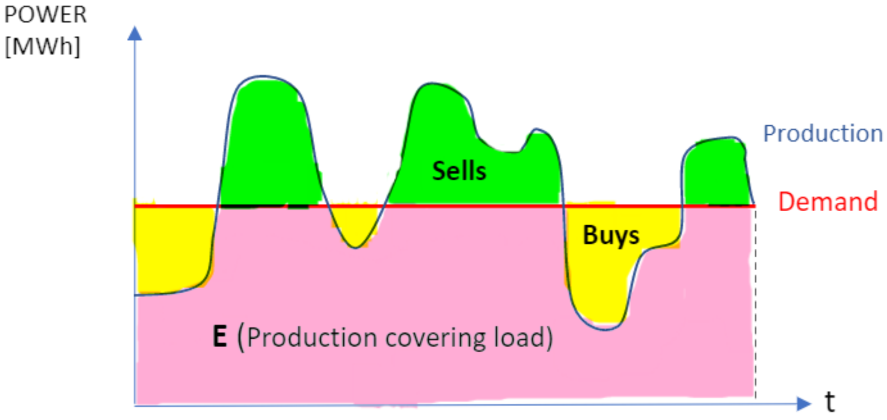


Figure 11. System production with sales and buys.

The $LCOE_{system}$ is calculated as the total annualized costs, $C_{ann,tot}$, divided by the total production of the system (blue line in sketch)

$$\mathrm{LCOE_{system}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{Production}}, \quad (8)$$

The $C_{ann,tot}$ is the annualized total NPC which is calculated by multiplying the NPC seen in section 4.1.3 by the capital recovery factor (CRF)

$$\mathrm{C_{ann,tot}} = \mathrm{CRF} * \mathrm{NPC}, \quad (9)$$

$$\mathrm{CRF} = \frac{\mathrm{i(1+i)^N}}{\mathrm{(1+i)^N - 1}}, \quad (10)$$

Where i is the real discount rate calculated as section 4.1.3, and N is the lifetime of the project.

4.1.4.3 Effective LCOE

$LCOE_{effective}$, is the cost of the system when there is no grid purchase from the grid and represents best this kind of system, here is where the external actor, the grid, is least influential. The LCOE is calculated by the discounted annualized costs minus the grid sales, divided by the effectively covered load by the renewable technologies (pink area in sketch). Conceptually the LCOE is calculated as following

$$\mathrm{LCOE_{effective}} = \frac{\mathrm{CAPEX + OPEX - Grid\ Sales}}{\mathrm{E}}, \quad (11)$$

4.2 Main assumptions

A private cable is considered to connect the substations of the sites and the electrolyser plant. This assumes no grid transmission costs. Even though, in Portugal any renewable production is considered under the qualification of proximity and reduces greatly the transmission costs.

The renewable resource and the layout are considered the same for the entirety of the site. Therefore, the scaling up of the technologies is made linearly without consideration to land occupation.

The nominal discount rate is set to 6% and the inflation is set at 2% when applied. All currencies are in Euros (€).

The project's lifetime is 25 years, and all technologies are assumed to last for the entire project.

4.3 System set-up

The system consists of H2GS´s facility with private cables to the renewable energy sites. It is still connected to the national grid, which is used in periods of under/over-supply of own RES capacity. This gives the plant a semi-islanded property. To simplify the scheme, the power supplier has been deducted.

In model 1, a multi-use offshore farm with combined floating wind and wave is connected through a direct cable to H2GS´s site. Therefore, the electrical costs of the combined farm are reduced as they share offshore substation and export cable. On land, a PV park is installed with an additional private cable to the main site.

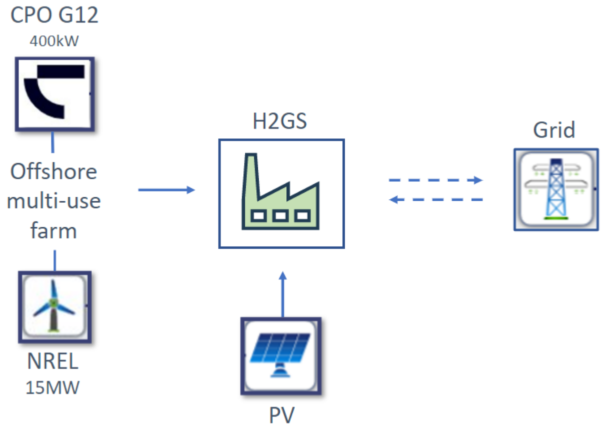


Figure 12. Model 1 setup with offshore wind.

In model 2, wave stands alone offshore, and wind is moved to an onshore site. All the technologies are directly connected to the main site.

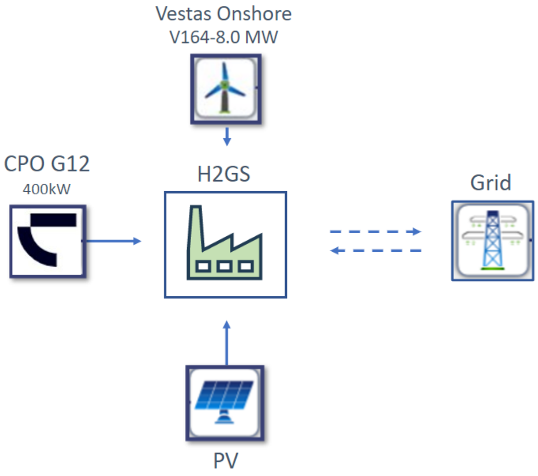


Figure 13. Model 2 setup with onshore wind.

4.4 Modelling

The main software used for the energy system modelling is HOMER Pro (Hybrid Optimization Model for Multiple Energy Resources). It was developed by the National Renewable Energy Laboratory (NREL) and subsequently enhanced and distributed by HOMER Energy.

HOMER simulates viable energy systems to meet demand, calculating the flow of energy in each hour. The optimization algorithm obtains the different configurations of technologies providing a range of chosen results.

The project starts in the year 2027 and is planned for a 25-year lifetime. The modelling is based on hourly time-series of data from yearly curves, representing the entire period of the project.

Model 1, weather data from 2018, most representative year from the available time-series. The renewable generation assets included are a multi-use offshore farm and a PV power station.

Model 2, weather data from 2019, most representative year from the available time-series. The renewable generation assets included are a single-stand offshore wave farm, an onshore wind farm and a PV power station.

Time-series of wave, wind and sun resource have been obtained to calculate the power output with their corresponding power performances. Their capital and operational expenditures are further used for the modelling.

4.4.1 Load – H2GS Facility

H2GS steel plant location hasn't been precised but is assumed to be in a close range to the renewable energy assets, Figure 24. A location close to the PV power plant would match the requirements for a beneficial location.

The load assumptions are done with a combination of literature review about electrolysers and communication with H2GS. It has been divided in two sections.

4.4.1.1 Electricity demand

The announced 1GW electrolyser´s electricity demand is the core demand that will be studied in this report. It is assumed as a flat industrial load during the full year, as the industry flow requires a constant production. Additionally, the electrolyser´s business case benefits financially from operating close to full load hours due to its high CAPEX. As stated previously, no downstream consumption for the steel production has been considered.

In the case of over-production, the electricity is sold to the grid, no H_2 storage considered in the modelling. In case of underproduction, some models might buy electricity from the grid if certain utilization factor of the electrolyser want to be reached. Through communication with H2GS and literature review, the electrolyser plant would be economically feasible if it operates 8000h a year, equivalent to a 90% utilization rate. This sets the requirements for the electrolyser. Maintenance is not considered in the study and could be planned for hours with predictable low supply of renewable energy.

4.4.1.2 Product Output

A parallel study case where a 90% utilization of the electrolyser, equivalent to 8000h of production, is analyzed to calculate the hydrogen and green DRI produced. A completely efficient electrolysis system would require 39kW/h to produce 1kg of H_2. Future PEM and AWE electrolysers are said to reach efficiencies of 85%. Therefore, it is assumed 43kW/h are needed for 1kg of H_2. Additionally, 9L of water are needed to produce 1kg of H_2. For this study a PEM electrolyser is chosen, as it has the advantage of quickly reacting to the fluctuations of renewable power generation.

The CAPEX for PEM electrolysers is predicted to be 830€/kWh by 2030, where the cells usually have to be replaced every 8th year, the highest fraction of the CAPEX. The financial analysis due to the complexity of a 1GW size and unprecedent till the date, makes it's a hard analysis to perform and has to be subject to future trends and scalability of electrolysers.

The stoichiometric consumption for reducing iron ore is 54 kg of H_2per ton of iron. The exact amount will depend on the efficiency of the project. Another translation widely used is it requires 50kg of H_2 per ton of steel, as other components are added later in the process [37].

4.4.2 Grid

The grid modelled is Portugal's national transmission grid (RNT), operated by REN. The region studied is shown in Figure 14, where transmission lines of 150kV are already installed.

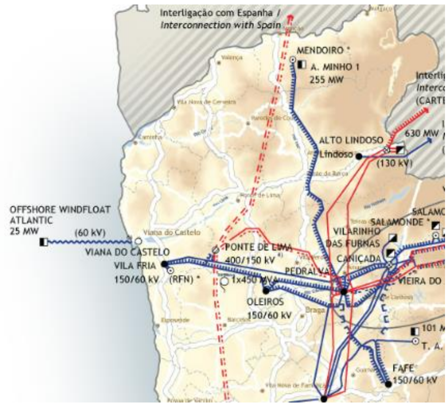


Figure 14. Portuguese national grid [38].

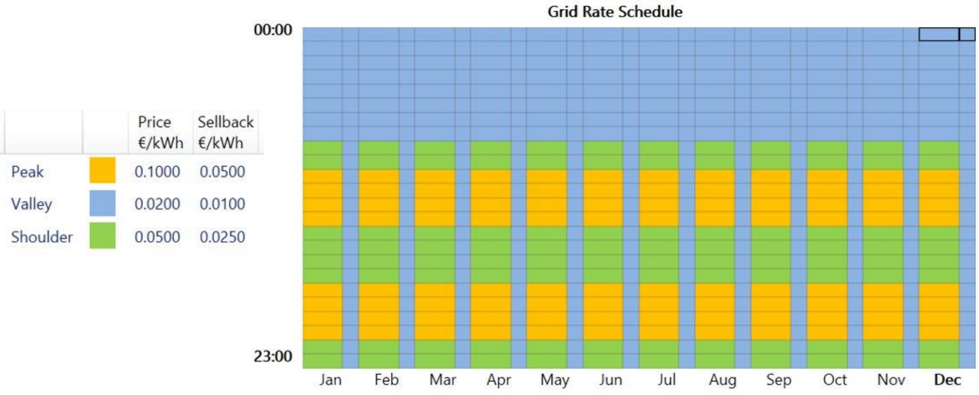
The average emissions of Portugal's grid in 2020 was 198.4g of CO_2/kWh [39]. Due to its good year of hydropower, which supported with almost half, out of the 60% of electricity consumption covered by renewable sources [40]. Considering dry and wet years affecting hydro and other trade-offs with this technology, and due to the electrification surge, the emissions of the grid have been considered the same for the study.

The emission penalties attached to carbon emissions have been considered to reach 120€/ton of CO_2, a reasonable number overlooking the trends from the past [41].

All electricity traded in the Iberian Peninsula is done in the MIBEL (Iberian electricity market) which market is operated by OMIE (Iberian electricity market operator). The electricity market is the hardest to forecast as dynamics in the market are changing with the increase of renewable energy share and external factors such as territorial conflicts and gas prices.

4.4.2.1 Grid Model 1

For model 1 a simplified grid model is used assuming similar prices to the present due to an increase in demand but also in renewable supply. Slightly polarized prices are also assumed due to the same reasons and the increase of the marginal costs of fossil fuel generation plants. The different grid-rate schedules are based on current market behavior.



		Price €/kWh	Sellback €/kWh
Peak	🟨	0.1000	0.0500
Valley	🟦	0.0200	0.0100
Shoulder	🟩	0.0500	0.0250

Figure 15. Grid rate schedule model 1.

4.4.2.2 Grid Model 2

For model 2 a more thorough and accurate grid model is developed, to compel with the goals of the project.

Iberian electricity market

The typical daily profile of the electricity price in the Iberian Peninsula is shown on the left graph in Figure 16. The average price in 2020 was 34€/MWh [42]. In 2022 this same daily average price is approximately 200€/MWh [43]. With an increase of electrification in the sectors of mobility and the residential and industry sector, the demand curve will increase. This is shown on the right graph of Figure 16, which simplified represents the electricity market price setting. Where demand and supply marry, the average daily price is obtained. Due to the increase of renewable energy technologies (RET) by 2027, the supply curve will smoothen, and the average daily price will return to close to 2020 levels.

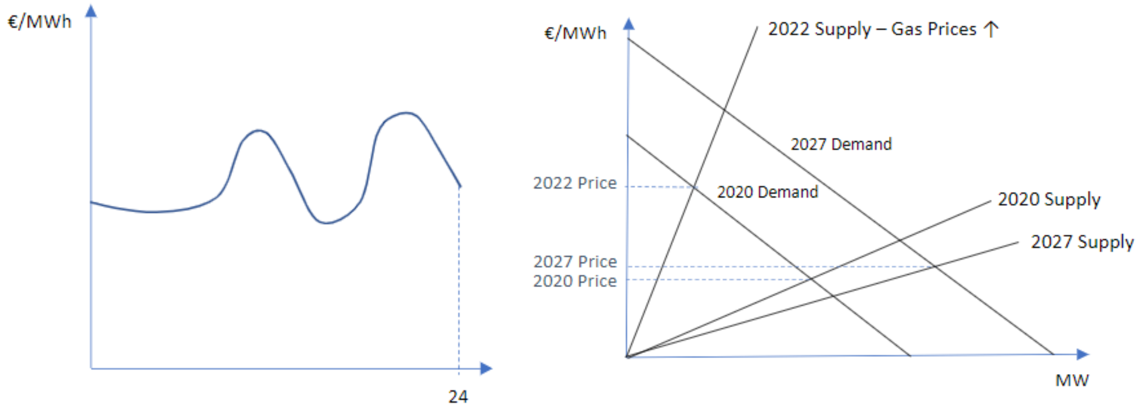


Figure 16. Daily price profile in the Iberian electricity market and future trends of average daily prices.

According to the OMIP, the organization from the Iberian electricity market that studies future electricity prices, the average daily price will be 54€/MWh in 2027 [44].

With the daily profile from Figure 16 and the average pool price obtained, the preliminary grid model presented is shown in Figure 17. The new rate schedule assumes new valley hours due to the trend of the Iberian daily production profile with the increase of PV penetration in the market and the overall electrification and night demand, more accurate to current market profiles.

Figure 17. Grid rate schedule model 2 – Preliminary.

Grid prices in a wind and solar dominated market in surplus and deficit periods

While average prices are expected to reach the previously mentioned levels, the intermittence of renewable sources will lead to a higher price volatility.

H2GS´s semi-islanded system will only use the grid in specific periods when the internal RES generation is higher or lower than the electrolyser’s demand.

H2GS having a similar production profile to the overall Iberian system (with wind and PV), the need for purchasing electricity from the grid will come when there are low production hours of these traditional renewables, thereby affected by high volatile prices and a probable peak in prices. The same principle when selling electricity, when overproduction of own assets, the overall market is likely to do the same, thereby bottom prices. This latter effect is called the renewables cannibalization effect.

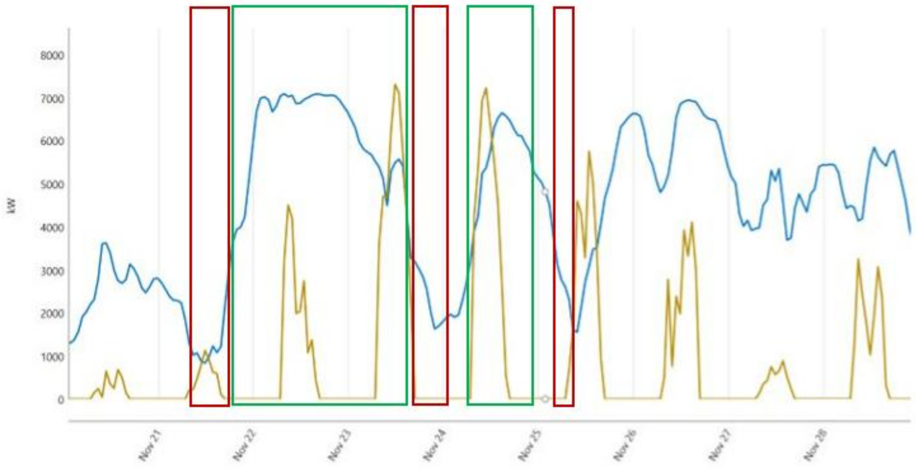
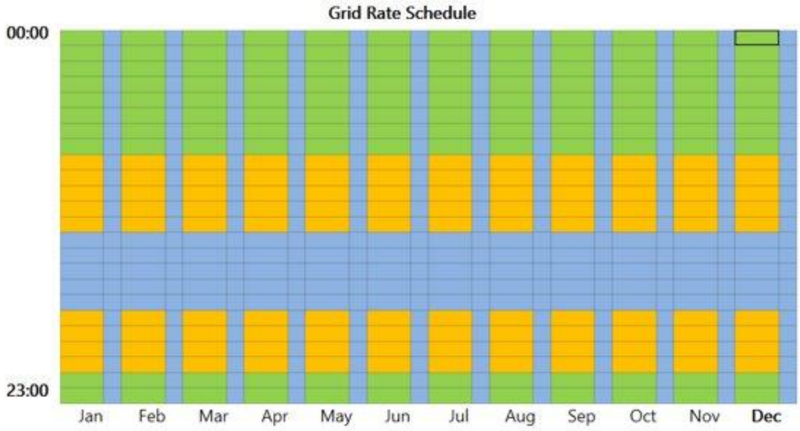


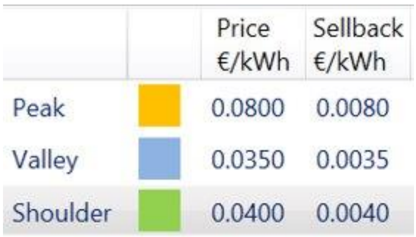
Figure 18. Production profiles vs energy demand.

The blue line is a real production profile of wind and the yellow is the PV production profile. The red boxes represent the periods H2GS will have to buy electricity, dominated by low PV and wind production and high prices. The green boxes represent periods it needs to be sold in, dominated by high PV and wind production and bottom prices.

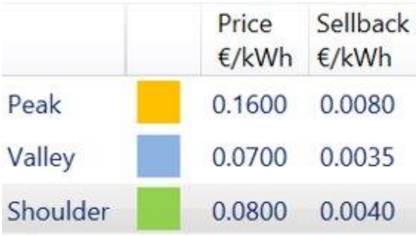
Modelling

To model this behavior, the average daily prices have been doubled to simulate the average peak prices (conservative approach). The same assumption is taken for sell-back prices. When there is over production of RES, the prices will drop, and have been assumed to be 1/10 of the purchase price of the average daily prices.





		Price €/kWh	Sellback €/kWh
Peak	🟧	0.0800	0.0080
Valley	🟦	0.0350	0.0035
Shoulder	🟩	0.0400	0.0040



		Price €/kWh	Sellback €/kWh
Peak	🟧	0.1600	0.0080
Valley	🟦	0.0700	0.0035
Shoulder	🟩	0.0800	0.0040

Figure 19. Grid rate schedule model 2, Average prices 2027 (left) vs Modelled prices 2027 (right).

The model nor H2GS have intention of selling back electricity to the grid when there are low-RES hours due to the stable demand of electricity from its plant.

4.4.3 Wave Energy

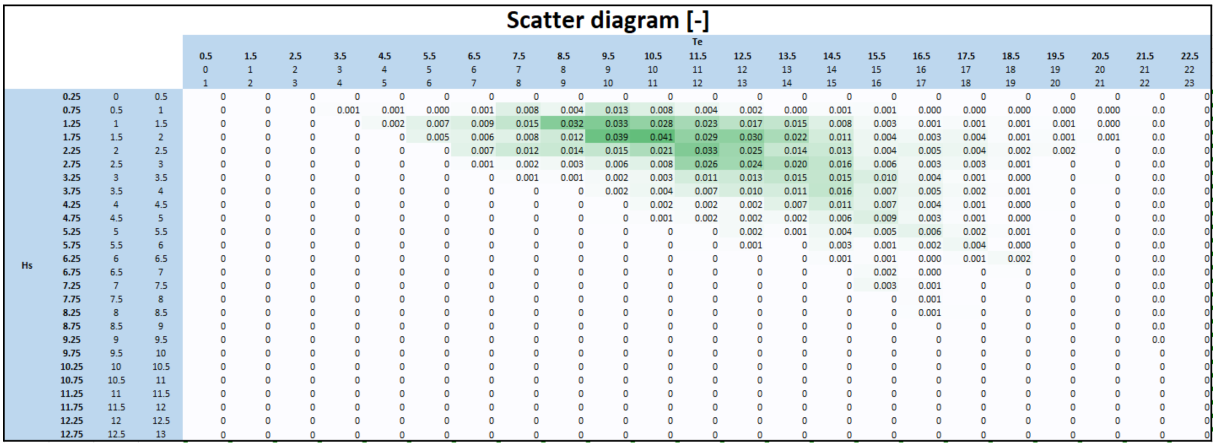
Location

The location chosen for the wave resource is located 20km offshore Viana do Castelo at the coordinates of 41°40'30"N 9°3'33"W and can be overviewed in Figure 14 and more in detail in Figure 24.

Resource

The wave resource is obtained from Copernicus Marine Service, the European Union´s Earth observation program. Specifically, the Atlantic–Iberian Biscay Irish-Ocean Wave Reanalysis [45]. This is a numerical model based on hindcasting that uses forecast data reanalyzed from satellite (ERA 5) and buoy data. It is a multi-year high-resolution wave reanalysis product with 5km horizontal resolution and hourly temporal resolution.

From these files, time-series of significant wave height (Hs) and the energy periods (Te) are obtained. The wave resource data is usually represented as a scatterplot of frequencies as shown in Figure 20.



Scatter diagram [-]

															Te											
				0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	0.25	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.75	0.5	1	0	0	0	0.001	0.001	0.000	0.001	0.008	0.004	0.013	0.008	0.004	0.002	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.0	0
	1.25	1	1.5	0	0	0	0	0.002	0.007	0.009	0.015	0.032	0.033	0.028	0.023	0.017	0.015	0.008	0.003	0.001	0.001	0.001	0.001	0.000	0.0	0
	1.75	1.5	2	0	0	0	0	0	0.005	0.006	0.008	0.012	0.039	0.041	0.029	0.030	0.022	0.011	0.004	0.003	0.004	0.001	0.001	0.001	0.0	0
	2.25	2	2.5	0	0	0	0	0	0	0.007	0.012	0.014	0.015	0.021	0.033	0.025	0.014	0.013	0.004	0.005	0.004	0.002	0.002	0	0.0	0
	2.75	2.5	3	0	0	0	0	0	0	0.001	0.002	0.003	0.006	0.008	0.026	0.024	0.020	0.016	0.006	0.003	0.003	0.001	0	0	0.0	0
	3.25	3	3.5	0	0	0	0	0	0	0	0.001	0.001	0.002	0.003	0.011	0.013	0.015	0.015	0.010	0.004	0.001	0.000	0	0	0.0	0
	3.75	3.5	4	0	0	0	0	0	0	0	0	0	0.002	0.004	0.007	0.010	0.011	0.016	0.007	0.005	0.002	0.001	0	0	0.0	0
	4.25	4	4.5	0	0	0	0	0	0	0	0	0	0	0.002	0.002	0.002	0.007	0.011	0.007	0.004	0.001	0.000	0	0	0.0	0
	4.75	4.5	5	0	0	0	0	0	0	0	0	0	0	0.001	0.002	0.002	0.002	0.006	0.009	0.003	0.001	0.000	0	0	0.0	0
	5.25	5	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0.002	0.001	0.004	0.005	0.006	0.002	0.001	0	0	0.0	0
	5.75	5.5	6	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0	0.003	0.001	0.002	0.004	0.000	0	0	0.0	0
Hs	6.25	6	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0.001	0.000	0.001	0.002	0	0	0.0	0
	6.75	6.5	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002	0.000	0	0	0	0	0.0	0
	7.25	7	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.003	0.001	0	0	0	0	0.0	0
	7.75	7.5	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0	0	0	0	0.0	0
	8.25	8	8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0	0	0	0	0.0	0
	8.75	8.5	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0
	9.25	9	9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0
	9.75	9.5	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	10.25	10	10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	10.75	10.5	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11.25	11	11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11.75	11.5	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12.25	12	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12.75	12.5	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

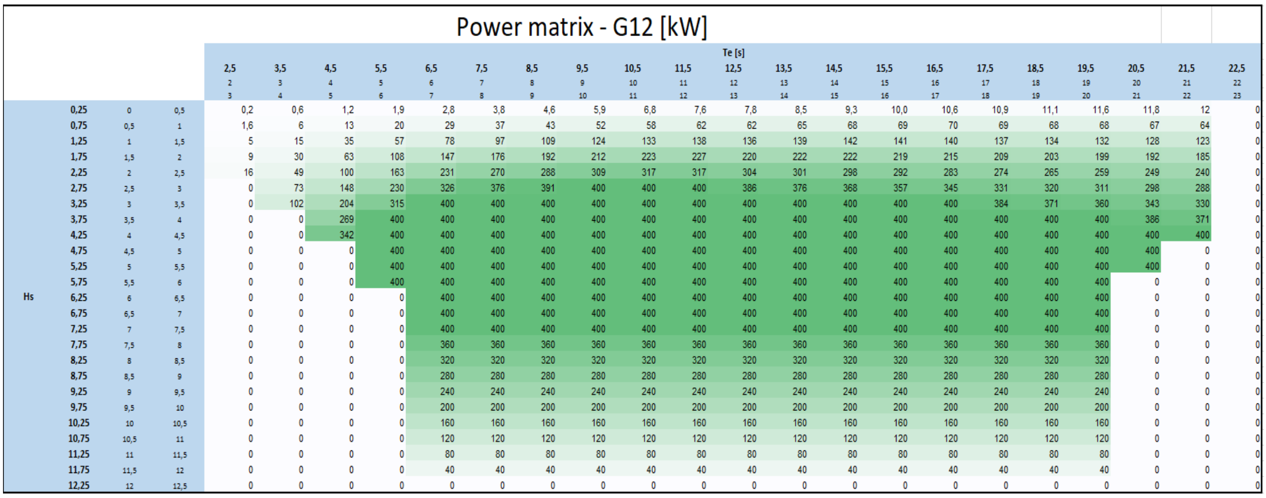
Figure 20. Scatter diagram Viana do Castelo.

Wave data from 2018 was used for Model 1 considered a representative year for the wave resource. For Model 2, data from 2019 was used due to matching time periods and limitation of wind data.

Technology

CPO´s generation 12 WEC has been used for this study. Its rated capacity is 400kW. As for wind turbines that follow a power curve to see the power output previously to losses, the WECs follow a power matrix. The power matrix for G12 is shown in Figure 21, and has been used for this study.

Disclaimer: The power matrix is the result of thorough analysis and simulations relying on certain assumptions. It will be updated site-specifically when tested on-site and with the evolution of the WECs designs, improving its reliability. It cannot be used as an official power calculator.



Power matrix - G12 [kW]

												Te [s]												
				2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	18,5	19,5	20,5	21,5	22,5
				2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
				3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	0,25	0	0,5	0,2	0,6	1,2	1,9	2,8	3,8	4,6	5,9	6,8	7,6	7,8	8,5	9,3	10,0	10,6	10,9	11,1	11,6	11,8	12	0
	0,75	0,5	1	1,6	6	13	20	29	37	43	52	58	62	62	65	68	69	70	69	68	68	67	64	0
	1,25	1	1,5	5	15	35	57	78	97	109	124	133	138	136	139	142	141	140	137	134	132	128	123	0
	1,75	1,5	2	9	30	63	108	147	176	192	212	223	227	220	222	222	219	215	209	203	199	192	185	0
	2,25	2	2,5	16	49	100	163	231	270	288	309	317	317	304	301	298	292	283	274	265	259	249	240	0
	2,75	2,5	3	0	73	148	230	326	376	391	400	400	400	386	376	368	357	345	331	320	311	298	288	0
	3,25	3	3,5	0	102	204	315	400	400	400	400	400	400	400	400	400	400	400	384	371	360	343	330	0
	3,75	3,5	4	0	0	269	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	386	371	0
	4,25	4	4,5	0	0	342	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0
	4,75	4,5	5	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0
	5,25	5	5,5	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0
	5,75	5,5	6	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0	0
Hs	6,25	6	6,5	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0	0
	6,75	6,5	7	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0	0
	7,25	7	7,5	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	0	0	0
	7,75	7,5	8	0	0	0	0	360	360	360	360	360	360	360	360	360	360	360	360	360	360	0	0	0
	8,25	8	8,5	0	0	0	0	320	320	320	320	320	320	320	320	320	320	320	320	320	320	0	0	0
	8,75	8,5	9	0	0	0	0	280	280	280	280	280	280	280	280	280	280	280	280	280	280	0	0	0
	9,25	9	9,5	0	0	0	0	240	240	240	240	240	240	240	240	240	240	240	240	240	240	0	0	0
	9,75	9,5	10	0	0	0	0	200	200	200	200	200	200	200	200	200	200	200	200	200	200	0	0	0
	10,25	10	10,5	0	0	0	0	160	160	160	160	160	160	160	160	160	160	160	160	160	160	0	0	0
	10,75	10,5	11	0	0	0	0	120	120	120	120	120	120	120	120	120	120	120	120	120	120	0	0	0
	11,25	11	11,5	0	0	0	0	80	80	80	80	80	80	80	80	80	80	80	80	80	80	0	0	0
	11,75	11,5	12	0	0	0	0	40	40	40	40	40	40	40	40	40	40	40	40	40	40	0	0	0
	12,25	12	12,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 21. Power matrix G12.

The power matrix is given at WECs terminals. For accurate estimates of the farm performance, the power matrix is multiplied by an efficiency factor, which takes into account hydrodynamic array interaction losses, auxiliary consumption, and electrical export losses. The total losses for the G12 are approximately 15%.

The array of WECs gather the power output to an offshore substation and is transported to land through an export cable which can be up to 132kV depending on the size of the farm, current highest voltage in offshore farms.

Financials

The economic figures behind the WEC are forecasted for the G12. For model 1 where the multi-use offshore farm is combined with wind, some costs are shared between technologies.

Disclaimer: These costs are calculated by CPO for specific-site conditions with a large number of variables and cannot be used as an official number for project costs. (E.g., Could be reduced if it is a 1GW wave farm).

Table 1. CPO Costs

	Stand-alone wave farm	Multi-use wave and FLOW farm
CAPEX [M€/MW]	2.8	2.6
OPEX [k€/MW/y]	77	69

4.4.4 Wind Energy

4.4.4.1 Model 1 Offshore wind

Location

The location of the floating wind farm is the same as the wave resource, where the WindFlaot Atlantic project is located, 41°40'30"N 9°3'33"W, Figure 14 shows the official Portugal grid system and its location, presented in a more local map in Figure 24.

Resource

The wind time-series were obtained from Copernicus Marine Service and post-processed by WavEC. Time-series go from 1993 to 2019. Data from 2018 has been used, considered a representative year for the wind resource. An annual trend of the wind speed is represented in Figure 22.

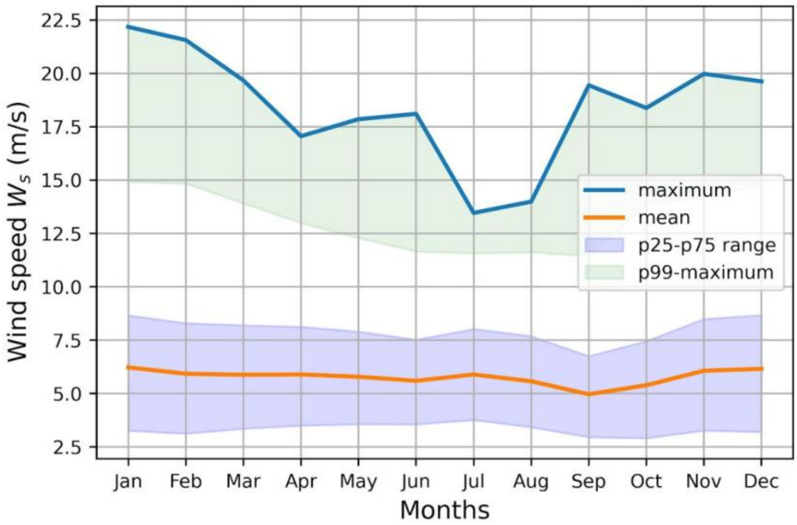


Figure 22. Wind speed trend at Viana – courtesy of WavEC.

The wind speed has been extrapolated to hub height, 150 meters. Wind direction is not considered in the power output calculation and the possible direction and wake effect losses are included in the total losses.

Technology

With the current trends of wind turbines growing in size with the years to optimize the power output, current developers are designing wind turbines up to 15MW for offshore wind farms. The wind turbine chosen is one preliminary designed by NREL together with DTU of this exact rated power [46]. It has a rotor diameter of 240 meters and is designed for a standardized 150m hub height. Its cut-in wind speed is 3m/s and 25m/s cut-out speed.

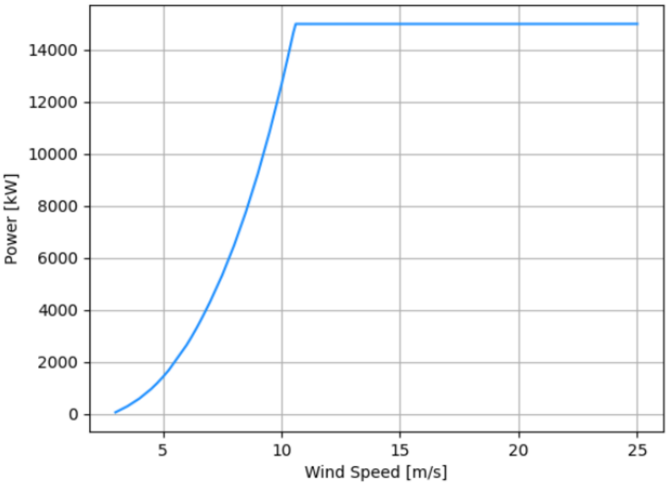


Figure 23. Power Curve NREL 15MW [47].

The total losses accounted for the wind farm is a standard number that reoccurs for offshore windfarms of 10%.

Financials

Projecting the costs for future wind turbines for 2027, (2030 numbers provided in most studies), is especially hard for floating wind with many factors to reduce the costs in the upcoming years, today being economically not viable without support mechanisms. The CAPEX for floating wind in 2030 ranges in different reports from 2M€ to 6M€ per MW [48]. Having chosen a 15MW turbine and expecting a rapid commercialization of this market and technology improvements in the sector, including shared electrical connections, a relatively low CAPEX has been chosen. OPEX is considered the same for the offshore farm.

Table 2. Floating wind costs 2030

	Offshore floating wind farm
CAPEX [M€/MW]	2.3
OPEX [k€/MW/y]	69

4.4.4.2 Model 2 Onshore wind

Location

For the onshore wind farm, an existing site of a wind farm, Carreço-Outeiro developed by Total Eren, has been selected north of Viana do Castelo, to simulate accurate site and conditions. It is located at coordinates of 41°43'52"N 8°49'48"W, as in the map below.

Figure 24. Renewable technology assets location.

Resource

The wind data was obtained from the web site renewable ninja [49], where weather data from global reanalysis models and satellite observations are used as source (NASA MERRA). They are obtained directly at hub height of 130m.

Technology

The wind turbine used for the onshore farm is the Vestas 8.0MW with a rotor diameter of 164m and a hub height of 130m. Currently installed offshore but projecting this capacity of wind turbine installation onshore by 2027. The cut-in and cut-out speed are 4 and 25m/s respectively.

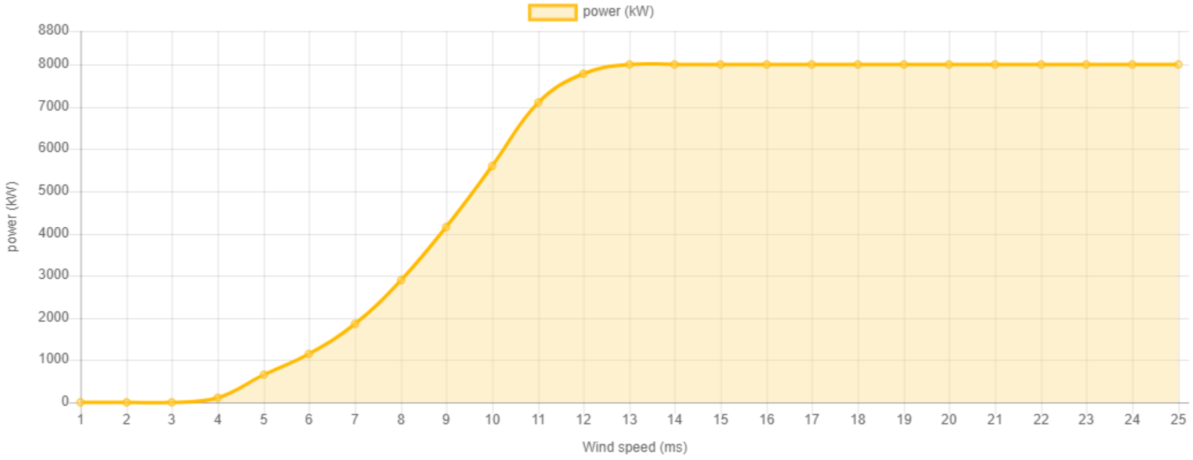


Figure 25. Vestas 8MW Power curve [50].

The total losses accounted for the wind farm is a standard number that reoccurs for windfarms of 10%.

Financials

Onshore windfarms are expected to reach the range of USD 800 – 1350 per kW [48]. Choosing an average value, also considering the increase of size and design in the wind turbines, and OPEX numbers decreasing by 30% from today's costs [51].

Table 3. Onshore wind costs 2030

	Onshore wind farm
CAPEX [M€/MW]	1.03
OPEX [k€/MW/y]	30

4.4.5 Solar Photovoltaics

Location

The location selected for the PV powerplant is selected south of Viana do Castelo due to an open and uninhabited area. It has been located at coordinates 41°39'34"N 8°48'59"W as shown in Figure 24.

Resource

The resource of the solar global horizon irradiation (GHI) has been used to calculate the flat panel PV array output. The time-series has been downloaded from NASA Prediction of Worldwide Energy Resource (POWER) database as average global solar radiation on the horizontal surface, expressed in kWh/m^2.

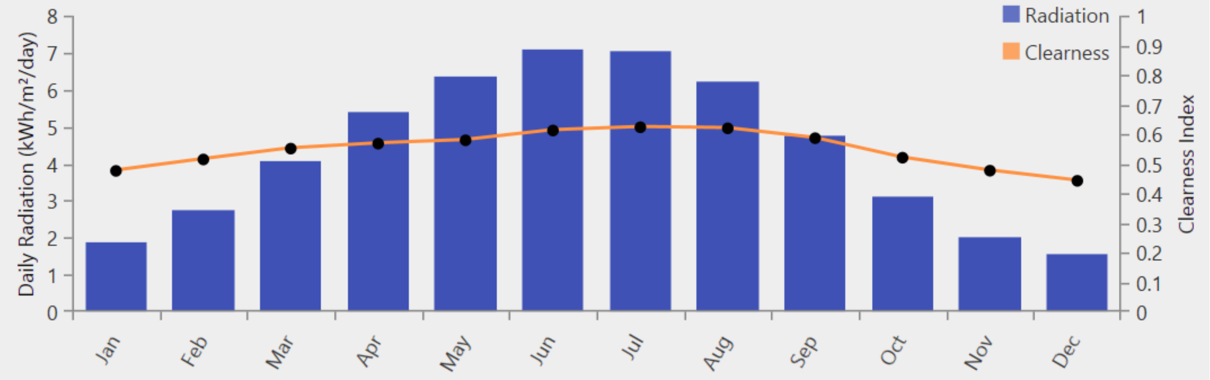


Figure 26. Average monthly radiation Viana.

Technology

A generic flat plate PV is used where the inverter is included directly in the PV system (efficiencies and costs). It has a derating factor of 80%.

Financials

Through IRENA´s report of PV costs in 2030 [52]:

Table 4. PV costs 2030

	PV power plant
CAPEX [M€/MW]	0.55
OPEX [k€/MW/y]	10

5 Results

5.1 Normalized study

A preliminary normalized study has been elaborated to analyze the technologies and the resources of the site, including a review of the stated properties of wave energy.

5.1.1 Capacity Factors

With the power performances and respective losses of each technology, together with the renewable energy resources, a first site of their performance can be measured in form of capacity factor (CF). This is the ratio of the electrical energy produced by the generating unit to the theoretical maximum output if it was producing at full capacity. The net capacity factor is the one including losses which is represented below for each model.

Table 5. Site CF per technology

Net CF	Wave	Wind	PV
Model 1 - 2018	0.57	0.37	0.17
Model 2 - 2019	0.56	0.34	0.17

The average monthly CF of model 1 and model 2 are shown to represent the seasonality effect of the renewable sources.

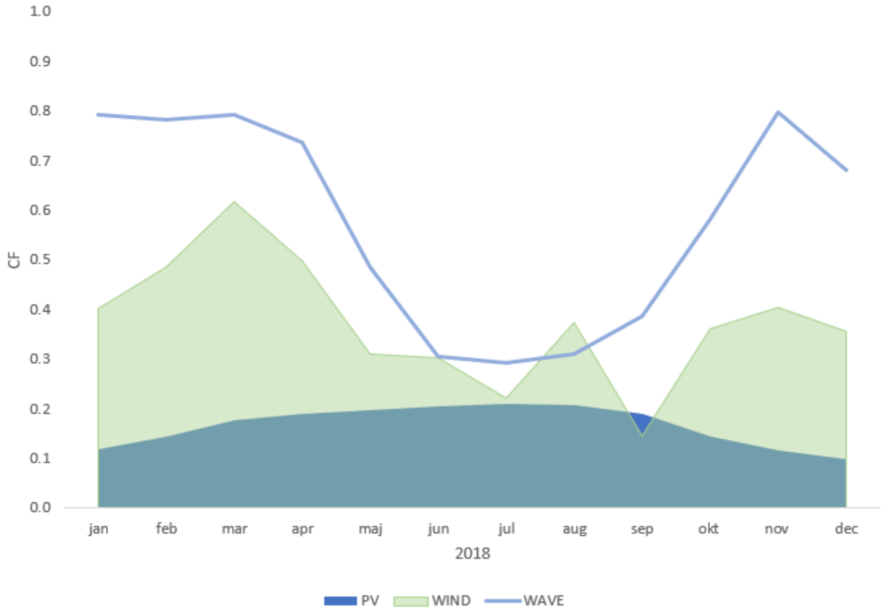


Figure 27. Normalized monthly average output per technology 2018.

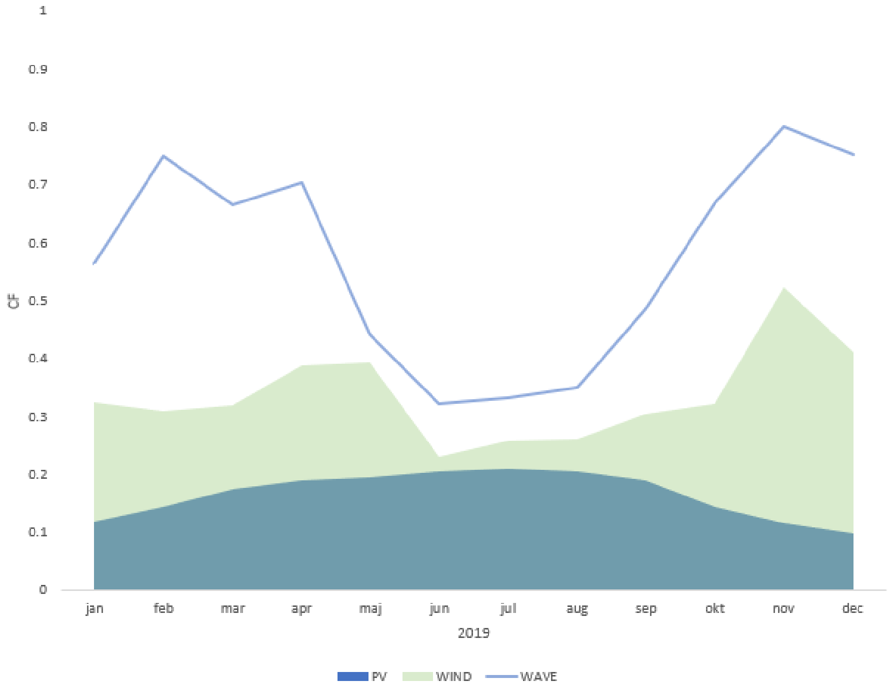


Figure 28. Normalized monthly average output per technology 2019.

The power output at substation after losses for 1 WEC in model 2 is represented in Figure 29.

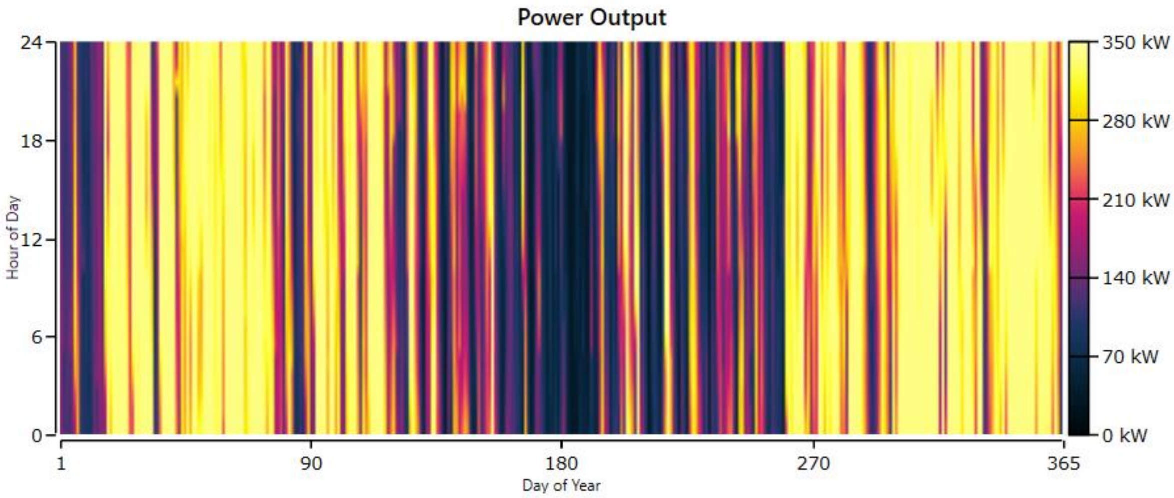


Figure 29. G12 Power Output - Model 2.

5.1.2 Technology LCOE

With the costs of each technology and the previously calculated CF, a preliminary site specific LCOE can be calculated for each technology as described in 4.1.4.

Table 6. LCOE per technology in each model

LCOE [€/MWh]	Wave	Wind	PV
Model 1 - 2018	55	84	35
Model 2 - 2019	61	37	35

5.1.3 Variability, predictability, and complementarity

As mentioned in the theory, wave energy´s main strengths are a low variability compared to wind and PV, it tends to be complementary to these resources and is a very predictable resource.

Complementarity

The complementary was studied on a shallow matter through numerical correlation with a coefficient of 0.36. The correlation can go from -1 to 1, where -1 means the power output has a perfect inverse correspondence, and 1 means they correspond perfectly, representing a kind of cannibalization effect. The correlation can be analyzed in more detail in the normalized two-week power output from Model 2 in Figure 30.

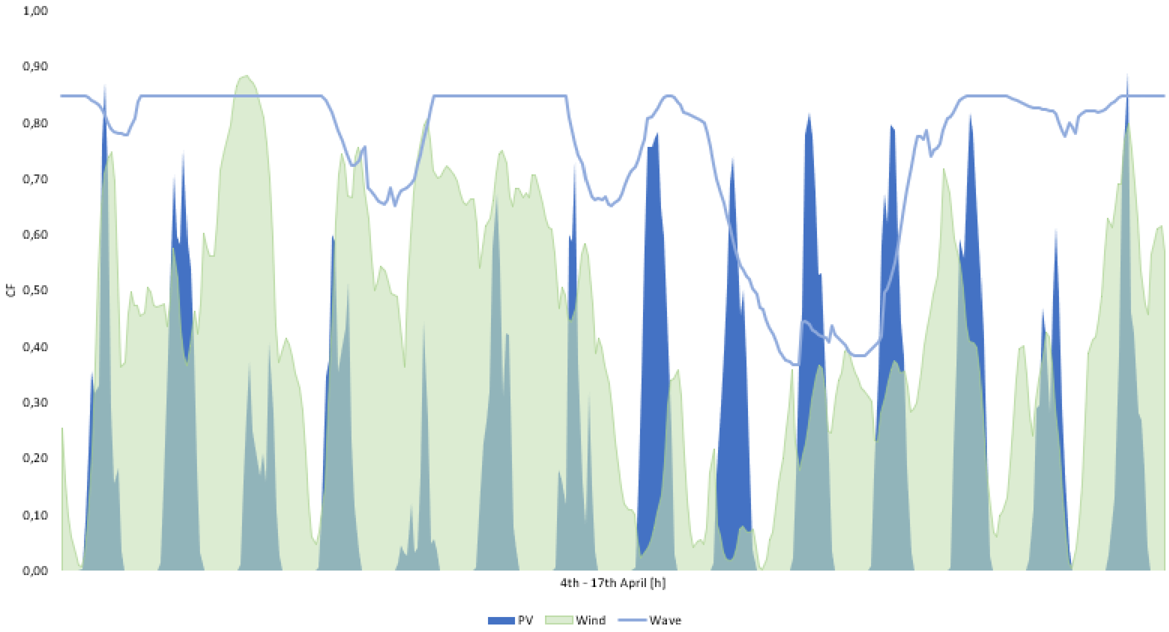


Figure 30. Two-week normalized production profile – Model 2.

The numerical correlation shows some kind of complementarity between the two sources but doesn’t give a very clear conclusion. The wave resource can be produced from local winds and be more “anti-correlated”, with a certain lag with the wind energy, but these waves are less energy dense than the waves originated far away in the oceans known as swells. Offshore locations west of the land have less complementarity between wind and wave than locations to the east [53].

These phenomena cannot be determined with exactitude by the production profile in Figure 30.

Variability

The variability was studied between Model 1´s wind and wave resources through its power output. The technologies used are the G12 WEC and the Vestas 8MW-164 wind turbine (from Model 2). An offshore farm with a 240MW capacity was assumed, where the ratio of wind-wave capacity has been modified in four scenarios.

Table 7. Scenarios for variability study

	Wind		Wave	
	%	#	%	#
Scenario 1	100	30	0	0
Scenario 2	80	24	20	120
Scenario 3	60	18	40	240
Scenario 4	50	15	50	300

In Figure 31, the whisker plot illustrates the four scenarios power output. The upper and lower lines represent the maximum and minimum production, whereas the cross shows the average electrical production. The box represents the upper quartile, the median and the lower quartile. This means respectively 75%, 50% and 25% of the values of the power output of the mixed offshore farm are beneath these values.

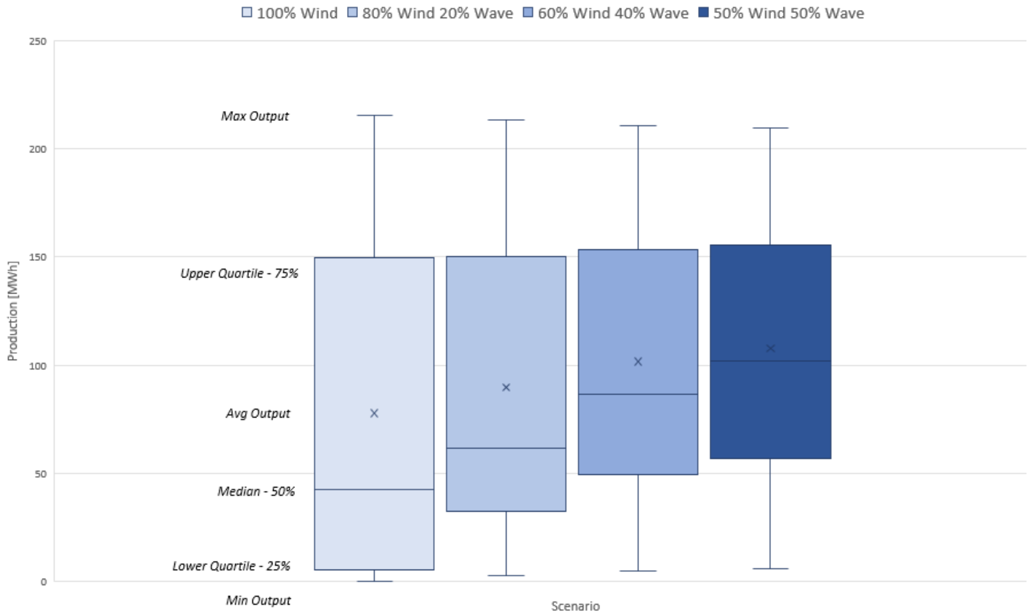


Figure 31. Whisker plots – 240MW Wind-Wave farm.

Even if the maximum power output decreases slightly by scenario, the average electrical output increases by nearly 40% from scenario only wind to 50-50 capacity of wind-wave. Moreover, the interquartile range, representative of the variability, decreases by a 30%.

The lower quartile increases significantly. Overall, it shows that the scenario with 50% wave have a less variable and higher average output of electricity.

5.2 Model 1

The result cases are ranked by the NPC classified into technology mixes. The optimal energy systems are shown below in Table 8 with the main KPIs, if the utilization rate of the electrolyser is 100%. The ETS applied in a no-allowance scenario are calculated with 120€/tCO_2. The system LCOE is calculated as explained in 4.1.4.2.

Case 8 is the reference case where the grid is the only electricity supplier with market pool prices from grid model 1.

Table 8. Model 1 KPIs - Optimal energy cases

Cases	PV [MW]	NREL15 [MW]	G12 [MW]	TOT [GW]	AEP [GWh]	NPC [B€]	LCOE [€/MWh]	Initial capital [B€]	Ren Pen [%]	CO2 (kt/yr)	ETS [M€/y]	Grid Buy [GW]	Grid Sell [GW]
1	4405	-	1177	5.6	12383	6.52	30	5.48	83%	301	36	1522	5145
2	4179	15	1179	5.4	12114	6.54	30	5.40	83%	299	36	1509	4863
3	12500	-	-	12.5	18251	6.93	19	6.88	44%	975	117	4926	14416
4	12125	120	-	12.1	18095	6.98	19	6.94	46%	930	112	4697	14032
5	-	-	1208	1.2	6113	7.41	53	3.14	69%	538	65	2719	72
6	-	60	1214	1.3	6335	7.46	53	3.29	70%	519	62	2621	195
7	-	1110	-	1.1	3622	9.00	65	2.53	41%	1017	122	5138	0
8	-	-	-	-		9.66	70	0.00	0%	1734	208	8760	0

Case 1 constituted by 4.4GW PV and 1.2GW wave is the energy system that supplies the demand with the lowest net present cost, covering an 83% of the load with the renewable assets. Two series of its production compared to the flat demand is shown in

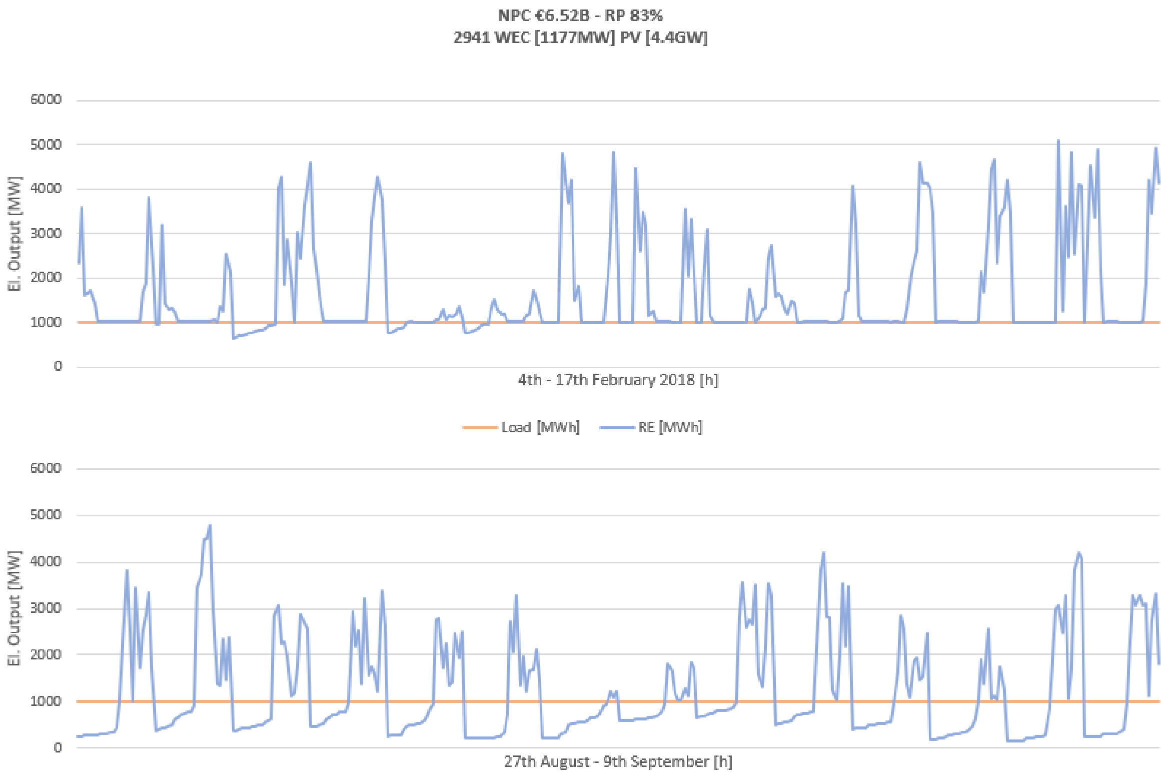


Figure 32. When the power curve from the renewable technologies is below the demand, electricity is purchased from the grid, a 17% of the total demand.

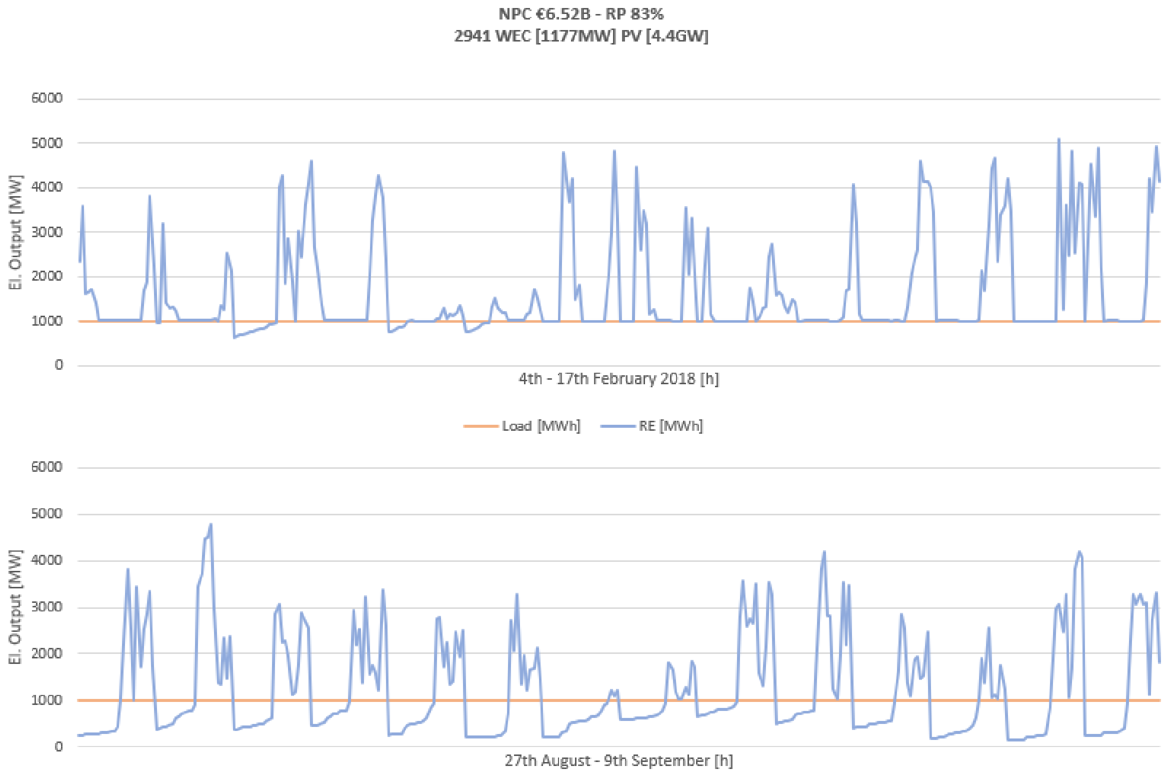


Figure 32. Case 1 Production profile.

In order to obtain a higher renewable penetration and cover the total demand with the renewable assets by a 90%, a pareto frontier analysis is performed in Figure 33. The red mark represents the previous shown case 1. The green mark represents the case with the lowest NPC to reach 90% of renewable penetration, case E. It consists of an installed capacity of 5.2GW PV, 0.75GW wind and 1.2GW wave.

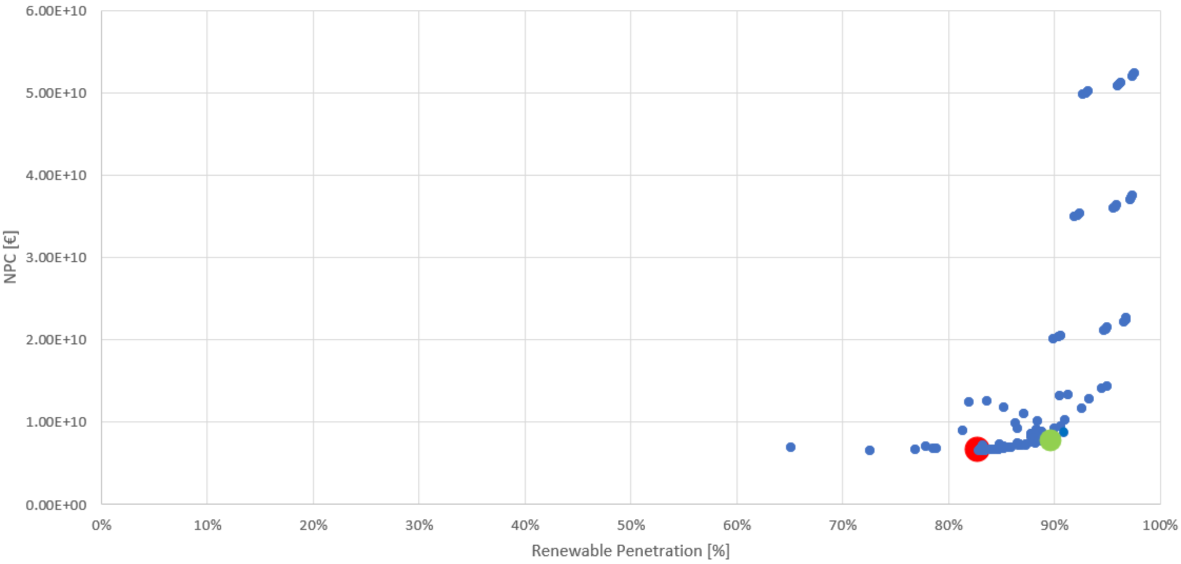


Figure 33. Pareto frontier model 1

In Table 9 the KPIs for case E are shown, it assumes there is a 100% utilization of the load where electricity is purchased from the grid when the full demand is not met. Successively, H2GS could choose to sell electricity in periods where the electrolyser is under maintenance or other reasons. H2GS could also avoid buying electricity from the grid and reach 90% utilization, in this way the emissions and the ETS penalties would be deducted.

Table 9. Case E, KPIs

Cases	PV [MW]	NREL15 [MW]	G12 [MW]	NPC [B€]	LCOE [€/kWh]	Initial capital [B€]	Ren Pen [%]	CO2 (kt/yr)	ETS [M€/y]
E	5231	750	1254	7.71	28	7.84	90%	197	24

The most representative cases modelled can be found in Annex 1.

5.3 Model 2

5.3.1 100% Utilization

As in model 1, the result cases are ranked by the NPC classified into technology mixes. The optimal energy systems are shown below in Table 10 if the utilization rate of the electrolyser is 100%.

The system LCOE is calculated as explained in 4.1.4.2. The number of devices installed is shown between brackets in the capacity of the technology.

Table 10. Model 2 KPIs - Optimal energy cases

Cases	PV	WT 8MW	CPO 0.4MW	TOT	AEP	NPC	LCOE	Initial Capital	Ren. Pen	CO2	ETS	Grid Buy	Grid Sell
	[GW]	[GW(#)]	[GW(#)]	[GW]	[GWh]	[B€]	[€/kWh]	[B€]	[%]	[kt/yr]	[M€/y]	[GW]	[GW]
1'	1.2	1.7 (216)	0.54 (1343)	3.4	9509	8.36	47.8	3.94	82%	315	38	1592	2340
2'	1.4	2.5 (310)	-	3.9	9358	8.42	46.5	3.30	76%	421	50	2125	2723
3'	-	1.8 (229)	0.76 (1909)	2.6	9249	9.05	52.2	4.05	80%	349	42	1761	2250
4'	1.3	-	1.18 (2969)	2.5	7824	9.25	60.1	4.08	78%	385	46	1946	1010
5'	-	3 (378)	-	3.0	8952	9.39	51.4	3.10	70%	523	63	2644	2836
6'	-	-	1.34 (3359)	1.3	6702	10.13	70.0	3.81	72%	492	59	2485	427
7'	2.9	-	-	2.9	4259	12.86	80.5	1.60	33%	1165	140	5881	1380
8'	-	-	-	-	-	16.68	120.9	0.00	-	1734	208	8760	0

The optimal energy system obtained is constituted by the three technologies; 1.2GW PV, 1.7GW wind and 0.54GW wave. It has a renewable penetration of 82% covered of the electrolyser's demand. A production profile of case 1' is shown in Figure 34.

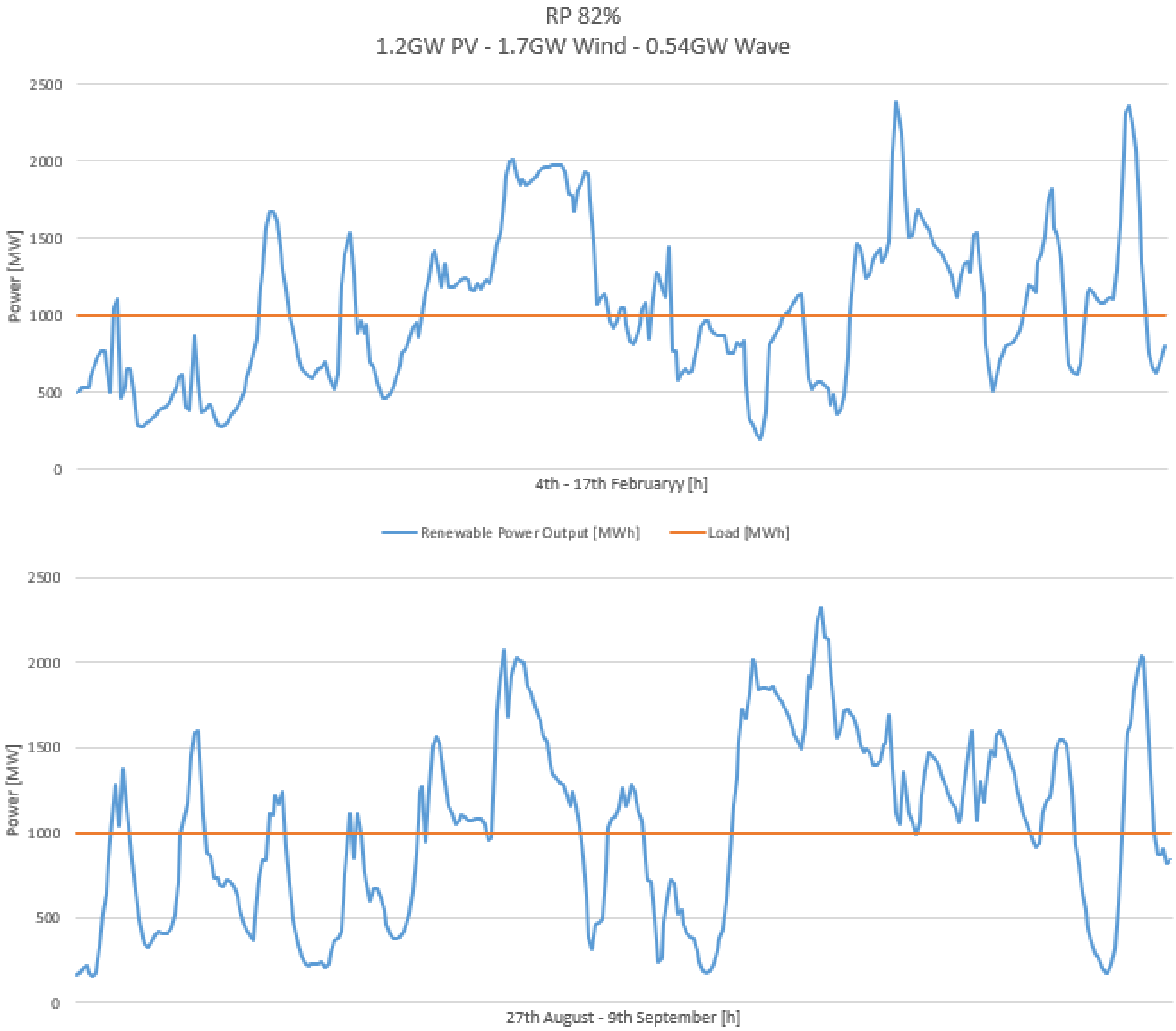


Figure 34. Case 1' Production profile.

All cases modelled production profiles, together with compared KPIs, can be found in Annex 2.

5.3.2 90% Utilization

H2GS demand is to reach 90% utilization of the electrolyser. Therefore, a pareto frontier with the renewable penetration and the NPC has been created. This allows to see all the simulated cases and choose between tradeoffs. Two cases reaching 90% of renewable penetration have been selected from the full simulation series, one with the lowest NPC (Case C, green mark) and one with the lowest NPC where wave is absent (Cade D, red mark).

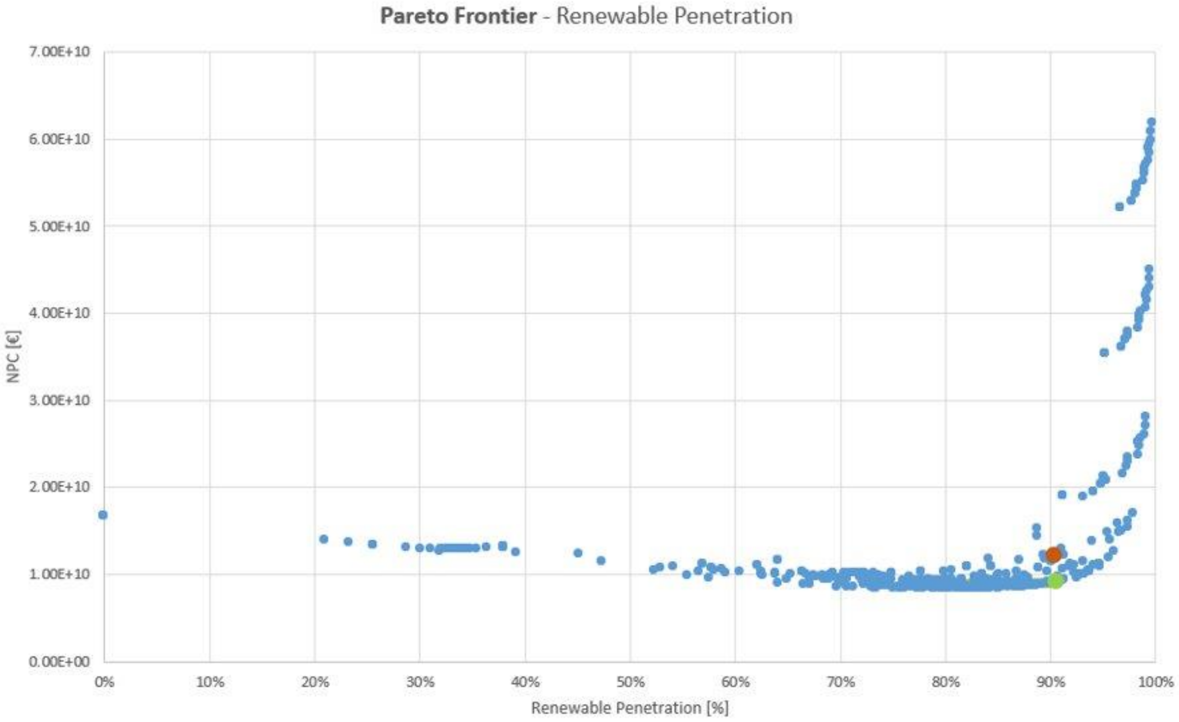


Figure 35. Pareto frontier Model 2.

There are cases with higher renewable penetration that can be considered, but at extensive costs. Cases C and D are summarized below assuming there is no electricity purchased from the grid. For these cases the effective LCOE has been used as in 4.1.4.3. The NPC also is recalculated without electricity costs and ETS penalties.

Table 11. Model 2 KPIs - Case C and D

Cases	PV	WT 8MW	CPO 0.4MW	TOT	AEP	NPC	LCOE	Initial Capital	Load Covered	CO2	ETS	Grid Buy	Grid Sell
	[GW]	[GW(#)]	[GW(#)]	[GW]	[GWh]	[B€]	[€/MWh]	[B€]	[%]	[kt/yr]	[M€/y]	[GW]	[GW]
C	1.4	2.1 (257)	0.96 (2407)	4.5	12886	7.55	71	5.59	91%	0	0	0	4947
D	1.7	6.7 (833)	-	8.4	22182	10.00	96	7.75	90%	0	0	0	14348

Both cases production profiles are represented in Figure 36, where the green area above the flat demand curve represents the electricity sold to the grid according to the prices of grid model 2.

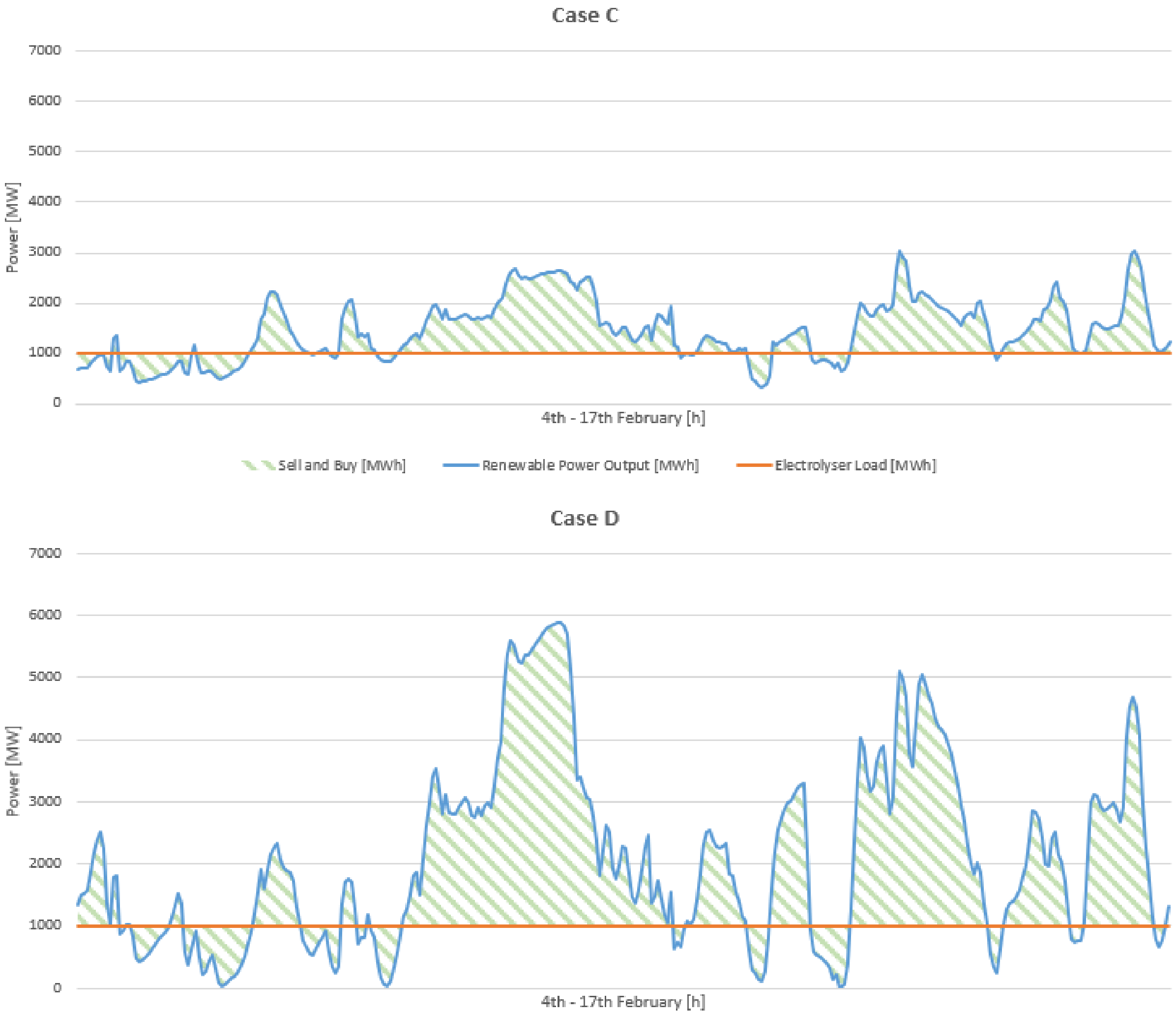


Figure 36. Production profile case C and D.

5.3.3 Product Output

Taking case C as reference for this parallel case study, a total yearly production of 7972GWh is delivered to H2GS´s facility. With previous assumptions from 4.4.1.2, the PEM electrolyser is able to produce hydrogen stably from the electricity supply. With this electricity covering the electrolysers demand and 1.7 million $m^3$of water, a total of 185386 tons of H_2 can be produced yearly.

This would translate into 3.7 million tons of green steel per year with previous assumptions. Within the range published by Iberdrola and H2GS [54].

6 Discussion

Previously it was proved that wave energy has a higher capacity factor than wind and sun in the site of Viana do Castelo with the chosen technologies. This is due to the stable wave resource compared to wind which has more hours with low or non-wind resource. An additional factor is the optimal power matrix provided of CPOs G12 which manages through its control system to operate at a higher load in hours of lower wave resource. Its lower variability gives its production profile a property of a base load and the average electrical output increases compared to the wind technologies studied.

Regarding the complementarity, it can be seen through the time series some correlation between wind and wave, where a combination of both resources can achieve a higher output than one technology by itself. A longer period would be required to obtain more detailed conclusions.

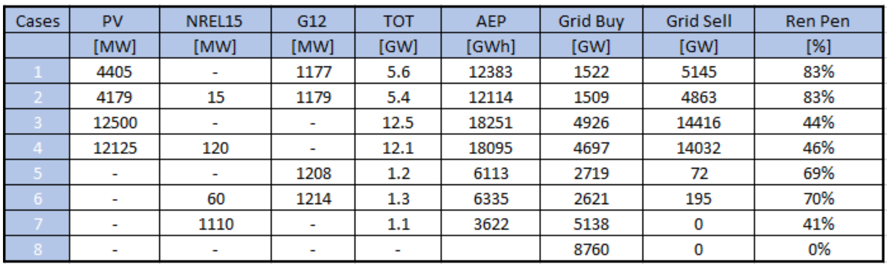
The LCOE of PV is the lowest by itself, followed by wind and wave. These renewable technologies have been developed and industrialized for decades and have a low margin of improvement compared to wave energy which aims to reach 50€/MWh in the next decade. Even though, this study aims to measure the value of wave energy's electricity, therefore the technology LCOE does not determine the outcome of the project.

6.1 Model 1

It is important to remember now that the optimal cases are obtained through lowest NPC, these are the costs of the renewable assets through their lifetime, grid sales and purchases, and the ETS penalties.

At first glimpse, two conclusions can be taken from the Table 12 below. Firstly, the wind energy doesn't participate in the optimal cases with just one turbine in the case with the three technologies. This is due to a combination of the costs of the wind assets and their production profile. When it stands alone it gets the optimal capacity according to the costs of the system, but don't install over capacity and thereby a low, almost equivalent to the CF, renewable penetration. Secondly, it is observed through cases 3 and 4 where the PV capacity is over 10GW, that the grid model 1 creates cases where the sale of electricity rules over the selection process. The sale of electricity becomes the main drive. Out of the 18TWh produced yearly, with an electrolyser demand of 8.8TWh, almost an 80% of the renewable electricity produced is sold to the grid. This results in the load covered by less than 50% of the renewable electricity produced.

Table 12. Electricity KPIs Model 1



Cases	PV	NREL15	G12	TOT	AEP	Grid Buy	Grid Sell	Ren Pen
	[MW]	[MW]	[MW]	[GW]	[GWh]	[GW]	[GW]	[%]
1	4405	-	1177	5.6	12383	1522	5145	83%
2	4179	15	1179	5.4	12114	1509	4863	83%
3	12500	-	-	12.5	18251	4926	14416	44%
4	12125	120	-	12.1	18095	4697	14032	46%
5	-	-	1208	1.2	6113	2719	72	69%
6	-	60	1214	1.3	6335	2621	195	70%
7	-	1110	-	1.1	3622	5138	0	41%
8	-	-	-	-		8760	0	0%

Model 1 shows that floating offshore wind with this production profile is not yet viable for commercial projects without any financial support and don’t give us a clear view of the benefits of a combination of renewable resources to cover a base load demand.

6.1.1 Sensitivity Analysis

To analyse wind energy’s cost in detail, a sensitivity analysis was performed with its CAPEX.

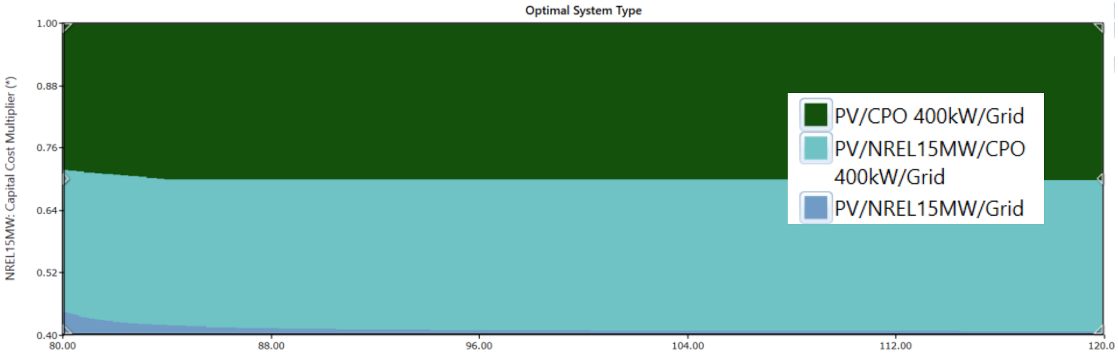


Figure 37. Sensitivity analysis wind CAPEX with ETS.

The sensitivity analysis shows the optimal model configuration by technology mix for different CAPEX percentages of wind energy versus the ETS penalties. It doesn’t give the detail of the configuration, but it can be seen that after a 70% of the Wind CAPEX, wind energy starts including in the optimal case. This is 1.6M€/MW for floating offshore which is not probable to be reached in the upcoming decade.

Therefore, model 2 will be the reference model to address the main research questions.

6.2 Model 2

6.2.1 100% Utilization

From model 2, a summarized Table 13 is presented where the electrical data is collected. The case with the lowest NPC includes the three renewable assets. The grid sales are around a 20% of the total annual energy production, similar to the grid purchases, adapting better to the electricity demand of the electrolyser, not selling electricity for the purpose of obtaining a better financial outcome. Therefore, the total installed capacities are in normal ranges to be able to cover 70 to 80% of the load.

Table 13. Electricity KPIs Model 2

Cases	PV [GW]	WT 8MW [GW(#)]	CPO 0.4MW [GW(#)]	TOT [GW]	AEP [GWh]	Grid Buy [GW]	Grid Sell [GW]	Ren. Pen [%]
1'	1.2	1.7 (216)	0.54 (1343)	3.4	9509	1592	2340	82%
2'	1.4	2.5 (310)	-	3.9	9358	2125	2723	76%
3'	-	1.8 (229)	0.76 (1909)	2.6	9249	1761	2250	80%
4'	1.3	-	1.18 (2969)	2.5	7824	1946	1010	78%
5'	-	3 (378)	-	3.0	8952	2644	2836	70%
6'	-	-	1.34 (3359)	1.3	6702	2485	427	72%
7'	2.9	-	-	2.9	4259	5881	1380	33%
8'	-	-	-	-	-	8760	0	-

Case 1’ representing the three technologies and case 2’, with the traditional renewable technologies, are compared to case 8’ with only electricity providing form the grid through the main KPIs.

In Figure 38 the emission reduction is represented, directly proportional with the renewable penetration. At the right-side axis, the equivalent emission penalties are represented. The emissions are reduced by an 82% in case 1’ and 76% in case 2’.

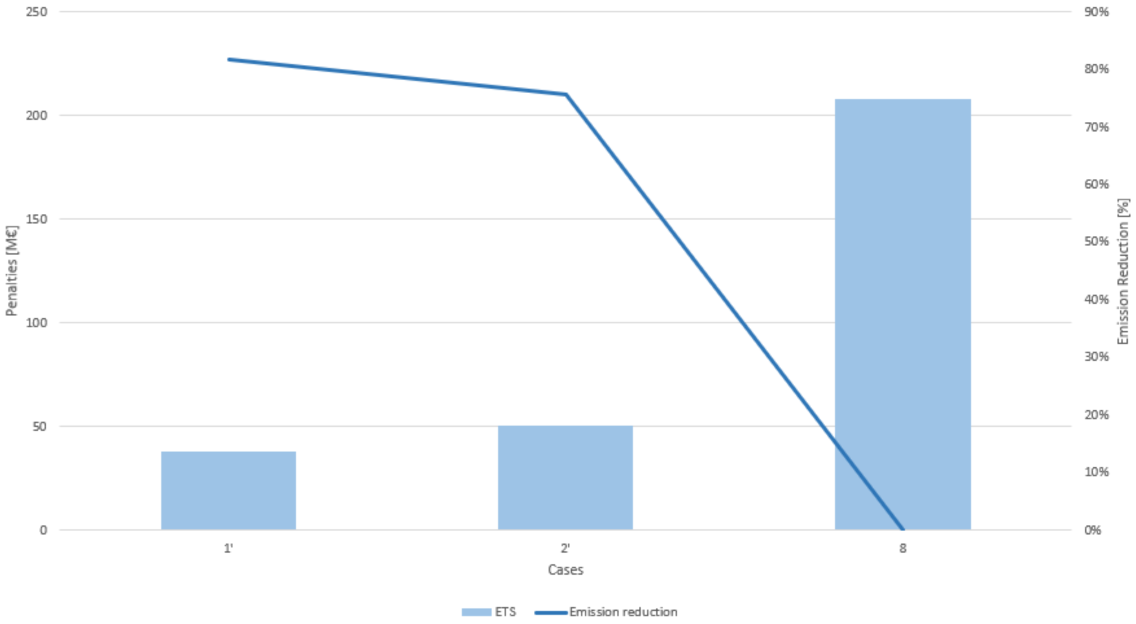


Figure 38. Emission reduction vs ETS penalties.

For the economical comparison, the average grid prices have been applied to calculate the NPC and LCOE of Case 8’ in Table 14. These can be seen in 4.4.2.2, which LCOE increases due to the emission penalties. The system LCOEs make a positive LCOE for the system compared to the base system.

Table 14. Financial KPIs Model 2

Cases	NPC	LCOE	Initial Capital	CO2	ETS	Ren. Pen
	[B€]	[€/kWh]	[B€]	[kt/yr]	[M€/y]	[%]
1'	8.36	47.8	3.94	315	38	82%
2'	8.42	46.5	3.30	421	50	76%
8	9.98	72.3	0.00	1734	208	0%

6.2.2 90% Utilization

Case C and D are the cases with lowest NPC to reach a 90% renewable penetration. These cases can be referred as a solution to H2GS demand with an energy system with and without wave energy. The electricity production is summarized in Table 15.

Table 15. Electricity KPIs 90% Utilization

Cases	PV	WT 8MW	CPO 0.4MW	TOT	AEP	Load Covered
	[GW]	[GW(#)]	[GW(#)]	[GW]	[GWh]	[%]
C	1.4	2.1 (257)	0.96 (2407)	4.5	12886	91%
D	1.7	6.7 (833)	-	8.4	22182	90%

The total installed capacity needed is reduced by a **46%** when introducing wave energy in the case as represented in Figure 39, covering practically the same amount of the electrolysers demand.

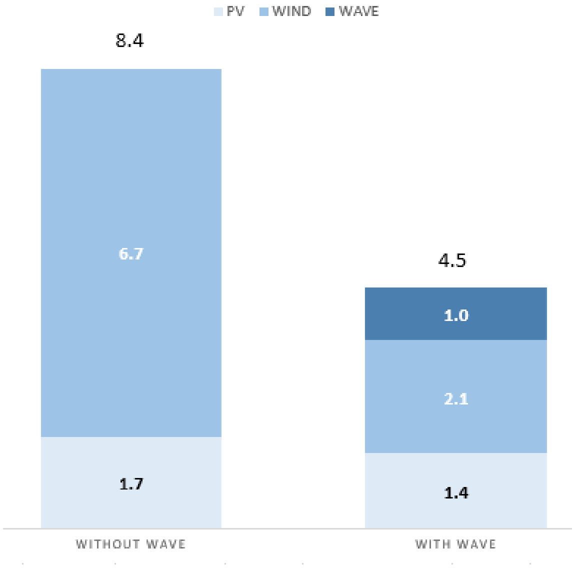


Figure 39.Capacity mix to deliver 90% utilization of electrolyser.

Additionally, the costs are also reduced due to this capacity requirements, Table 16. The effective LCOE which represents the value of the electricity delivered to the load is reduced by a 26%. The NPC is also reduced by a **24.5%** as well as the initial capital for the renewable energy assets.

Table 16. Financial KPIs 90% Utilization

Cases	NPC	LCOE	Initial Capital
	[B€]	[€/MWh]	[B€]
C	7.55	71	5.59
D	10.00	96	7.75

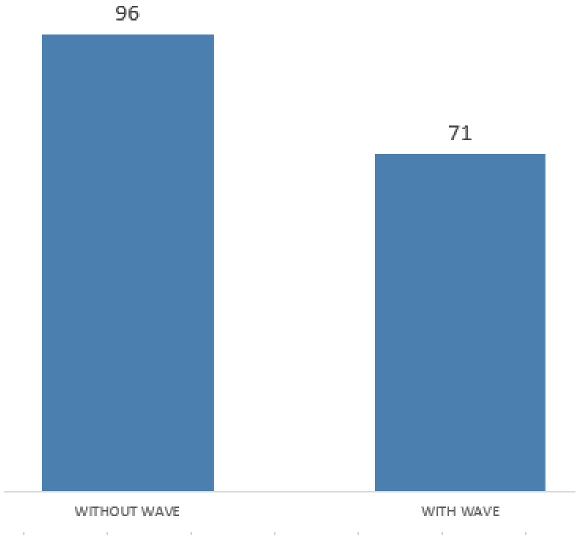


Figure 40. Effective LCOE to deliver 90% utilization of electrolyser.

Lastly, the variable of the electricity price when bought or sold is the most difficult to predict and model. The amounts of electricity sold are shown in Table 17, equal to overcapacity.

Table 17. Electricity sold by case C and D

Cases	AEP	Grid Buy	Grid Sell
	[GWh]	[GW]	[GW]
C	12886	0	4947
D	22182	0	14348

In Figure 36 the production profiles were presented and the energy that is sold to the grid is highlighted in green above the line of flat demand. The total amount sold in case D is almost three times more than in case C. This financial benefits of the over-production of electricity are a variable income in function of the electricity market price.

The reduction in required RE over-capacity makes the project financials less dependent of sales of over-capacity to the grid, where the technological and geographical similarities of the production profiles of case D with the overall market, entails a low selling price.

By meeting demand with dedicated RE farms to 91% utilization, less electricity is needed to be purchased from the grid if to be run at 100% utilization, making the H2 projects less dependent on volatile future electricity market price.

This translates into an important risk reduction for the project.

6.2.3 Sensitivity analysis

A sensitivity analysis was carried out with the costs entailed to CPO's G12 with the ETS penalties. It's observed that even if the costs increase, wave energy will be included in the optimal energy system if the ETS reaches 120€/ton of CO_2, due to its stable and complementary power output.

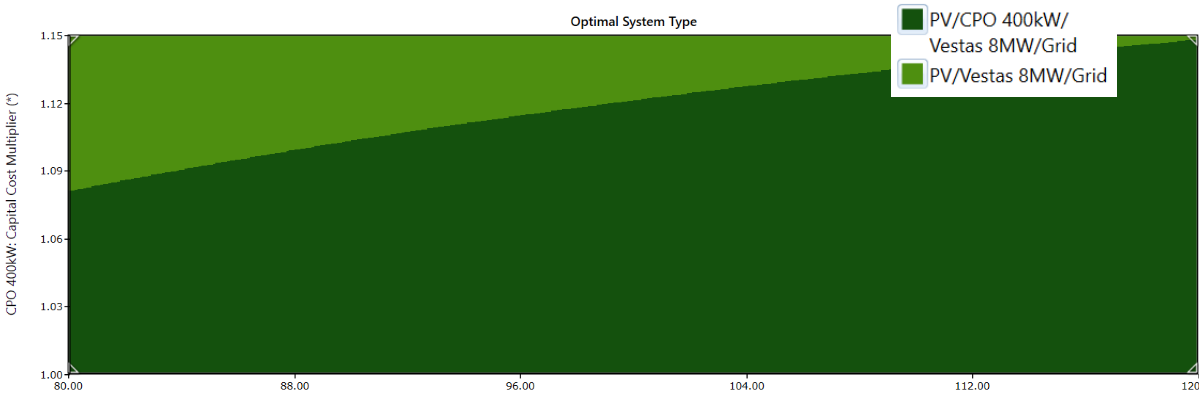


Figure 41. Sensitivity analysis CPO costs vs ETS penalties.

6.2.4 H2GS Business case

H2GS business case to cover 90% of the electrolysers load is found to be feasible technically with an installed capacity of 4.5GW of PV, wind, and wave energy. The results suggest that including wave in the energy system provides a reduction in the total installed capacity of 46%, due to the combination of the resources, enabling a greener and more reliable supply, bringing down the total costs.

This reduction makes the project financials less dependent of sales of over-capacity to the grid, where the technological and geographical similarities of the production profiles of a case with just wind and PV with the overall market, entails a low selling price. By meeting demand with dedicated RE farms to 91% utilization, less electricity is needed to be purchased from the grid, if to be run at 100% utilization, making the H2 projects less dependent on volatile future electricity market price. This translates into an important risk reduction for the project.

Additionally, the capacity reduction benefits any land space constraint, more security in the supply chain, and other factors related to the volume installed.

The effective LCOE which is believed to represent most accurately the value of the electricity to a project through its lifetime, is also reduced by a 26%. The complementary production profile of wave covering hours with low traditional renewable sources, increases wave energy´s value based on the simple principle of supply and demand. This term is referred to as a higher capture price.

Wave energy can play a key role supporting industries with a need for a base load and this project could be scalable to similar cases. Wave energy makes a major contribution towards 24/7/365 Carbon Free Electricity System, by significantly increasing the renewables penetration for a given installation capacity.

An interesting topic to be raised is if the water obtained as a by-product of the electrolysis in form of steam, could be recycled due to the vast amounts needed. In some cases, it is used as a heat to facilitate the process of steel production downstream, but it should be studied if it could be condensed further on and reused in the electrolyser, closing a cycle which would improve substantially the environmental side of these giga-projects.

Storage in form of batteries, would be a good support to have more control over the load coverage during emergency periods. This would be a positive post study for this business case. On the other hand, hydrogen storage for these vast volumes is counterproductive due to its dimensions. But a deeper analysis could be done according to demands.

The model is believed to represent faithfully an energy system that aims to supply H2GS´s demand. On the other hand, the power generation sources can always become smoother with real measured data and further corrections. As well as the grid model could use real time data from a representative year to show a more precise relation with the grid. Other aspects that can be taken into account are electricity constraints not discussed in this project, as voltage limitations, frequency stability, etc.

CPO is on the way to a bankable and scalable product where LCOE levels are aimed to reach competitive numbers by the end of the decade without financial support tools. Innovative renewables and marine energy within, have an ambitious role in most countries energy roadmaps which will support the industrialization of wave energy amongst other.

In the policy aspect, the additionality plan did not come through as the Parliament voted against it, arguing it would hold back the development of green hydrogen projects, (14th September 2022). The temporarily matching changed to quarterly and the renewable energy supply must be local. Probably the additionality rule would have speeded up the development and installation of renewable baseloads. On the other hand, the additionality rules, mainly hourly matching electricity, is still the only path towards the full decarbonization of the steel industry. The EU will just legislate it more gradually in order not to harm the green hydrogen development in Europe.

Currently, there is a great boost regarding hydrogen development worldwide, it is important in its road map to include who are going to be the main users, where are they going to be located and what it will be used for to be able to address and scale up the hydrogen system properly. This “local” project is a good example that answers all these questions and has a mindful application.

7 Conclusion

In our current energy transition to reach a zero-carbon scenario, the steel industry is one of the hardest sectors to abate, due to its high energy demand and the need for carbon for its synthesis. It has been proven that through changing the process, the carbon can be substituted with hydrogen obtaining the same results. However, to be able to fully decarbonize the system, the hydrogen must come from a renewable source at a constant supply. Currently the optimal way is through electrolysis powered by renewable electricity. Wave energy is believed to be a supportive renewable resource to the intermittence of wind and solar production.

Therefore, a site-specific case for H2GS in the north of Portugal was analysed. The aim was to study the technical and financial benefits, of supplying a 1GW electrolyser plant at a high load factor, when adding wave into the energy mix. For the plant to be financially feasible (electrolyser and downstream steel production) it has to run for 8000h a year, equivalent to a 90% utilization of the electrolyser, fed by renewable sources.

As software support, HOMER, an optimizer tool of energy systems, was used. Two models were run through simulations. The first one is composed by a mixed wind-wave offshore farm and an onshore solar plant in parallel with a grid model divided into hourly ratings. In the second model, the floating wind was substituted with an onshore wind farm and the grid model was optimized to match the behaviour of the overall energy system.

The results for model 1 suggest that the high costs of floating wind in relation to its power output, leads to an exclusion of its technology for the optimal cases. Some optimal cases were selected due to their good performance selling electricity back to the grid, leading to massive deployment of PV. Due to these drivers that modelled the results, the combination of different renewables to cover a base load demand where not represented, leading to different conclusions.

For model 2, the main aim is to reach a 90% utilization, delivered by renewable technologies. The findings indicate that the total installed capacity can be reduced by a 46% when including wave into the energy mix with the provided power matrix, going from 8.4GW needed, to only 4.5GW. This translated directly into a reduction in the total costs. The LCOE of the system for this case, which accounts for the costs of the renewable assets and the sales to the grid, is decreased by a 26%.

This reduction in both capacity and AEP, still meeting the plant´s demand, makes the project financials less dependent of sales of over-capacity to the grid, where the technological and geographical similarities of the production profiles of a case with just wind and PV with the overall market, entails a low selling price. By meeting demand with dedicated RE farms to 90% utilization, less electricity is needed to be purchased from the grid, if to be run at 100% utilization, making the H2 projects less dependent on volatile future electricity market price. This translates into an important risk reduction for the project.

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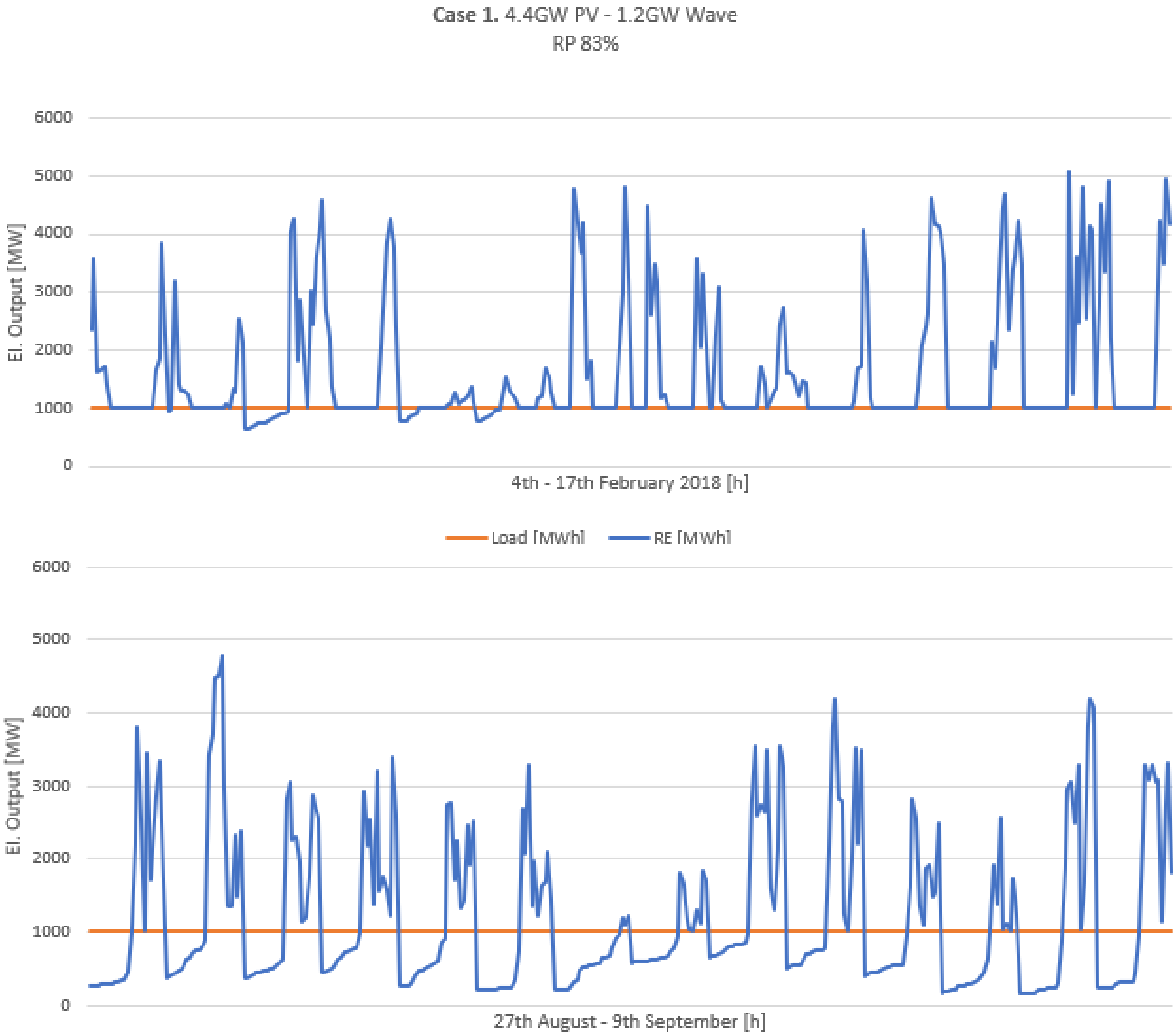
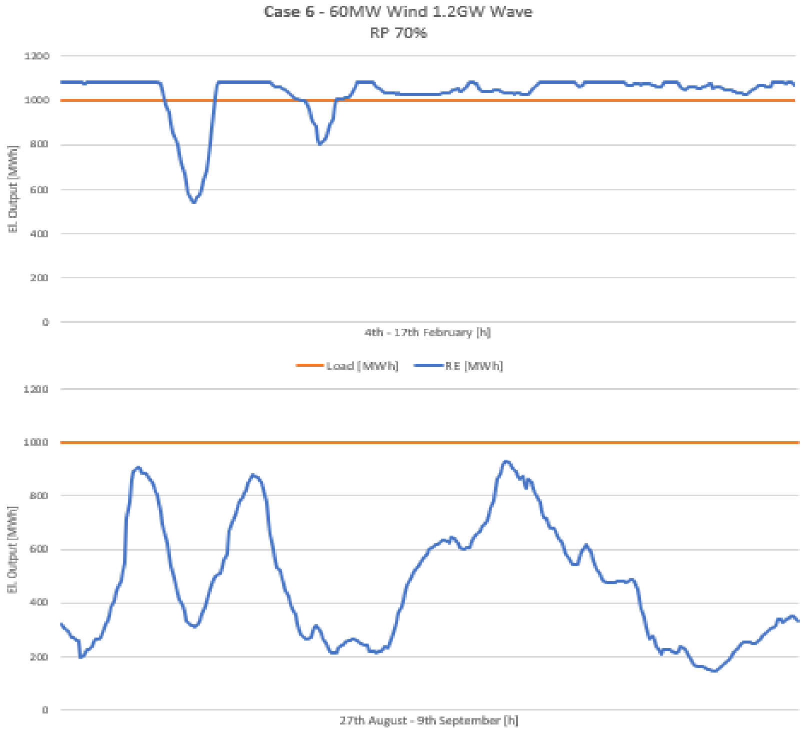
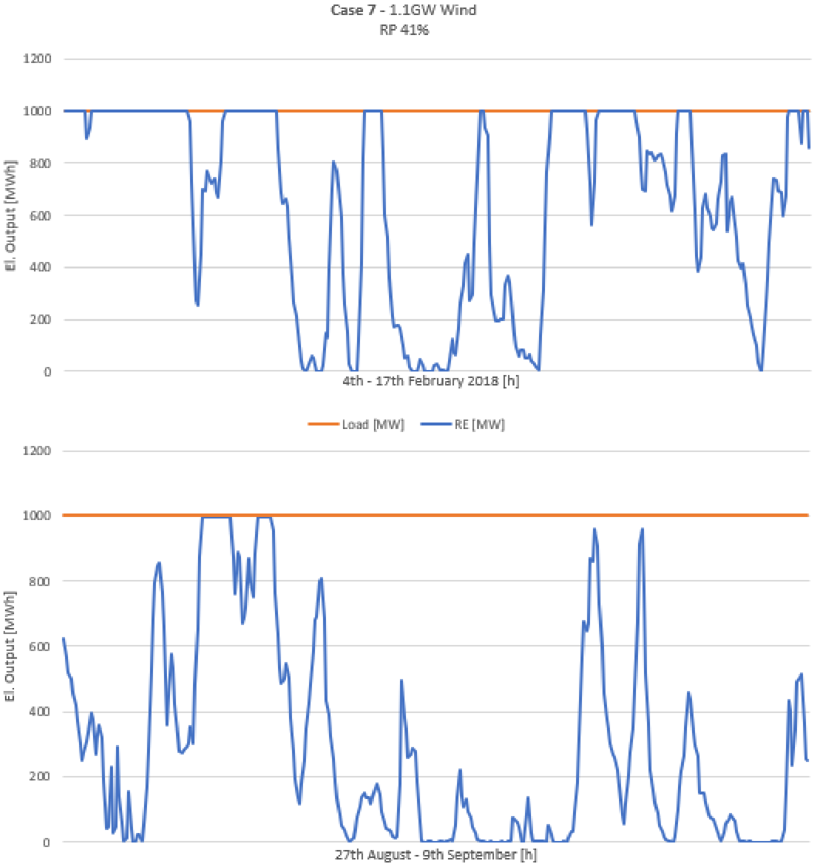
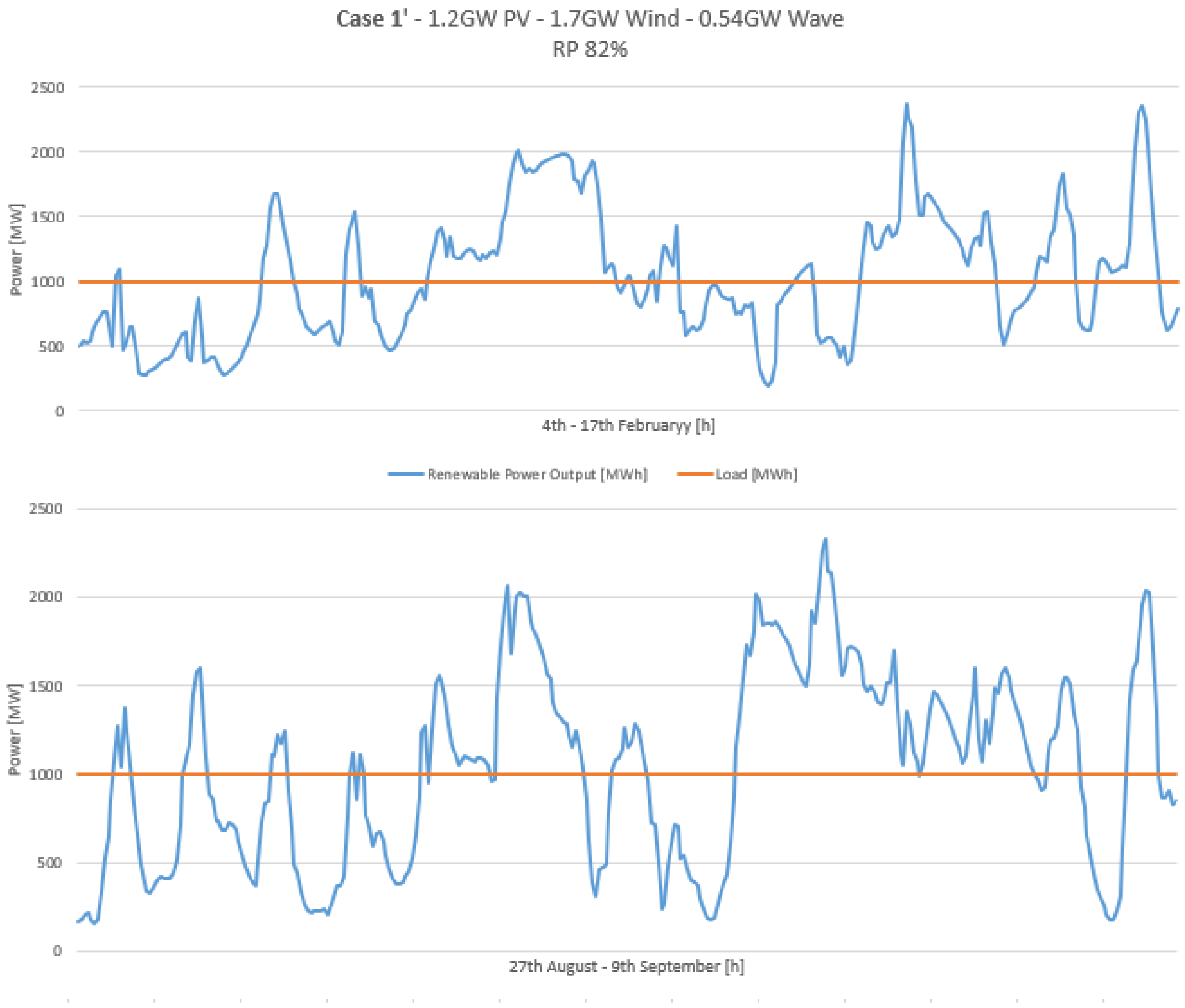
9 Annex 1 – Model 1

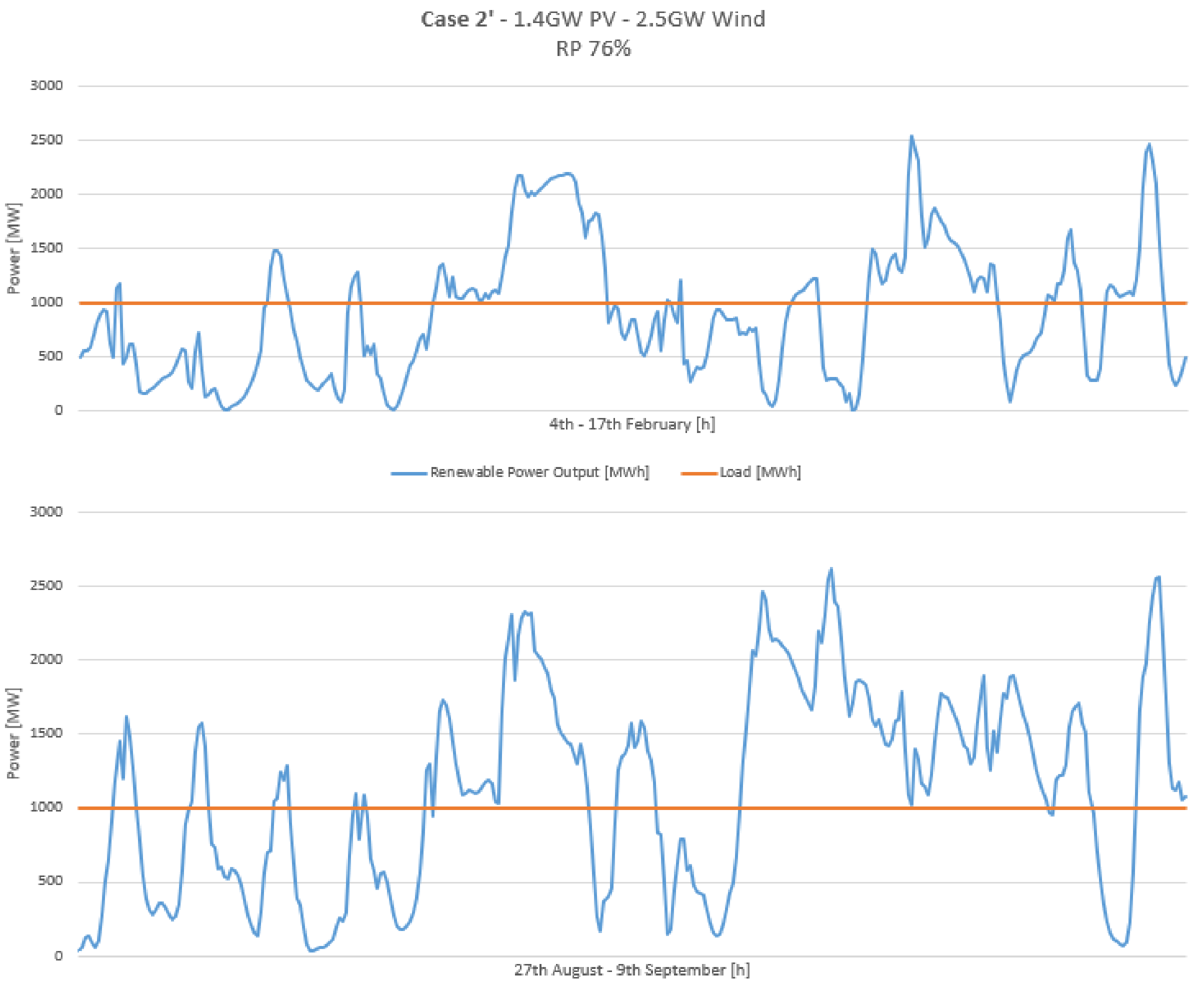


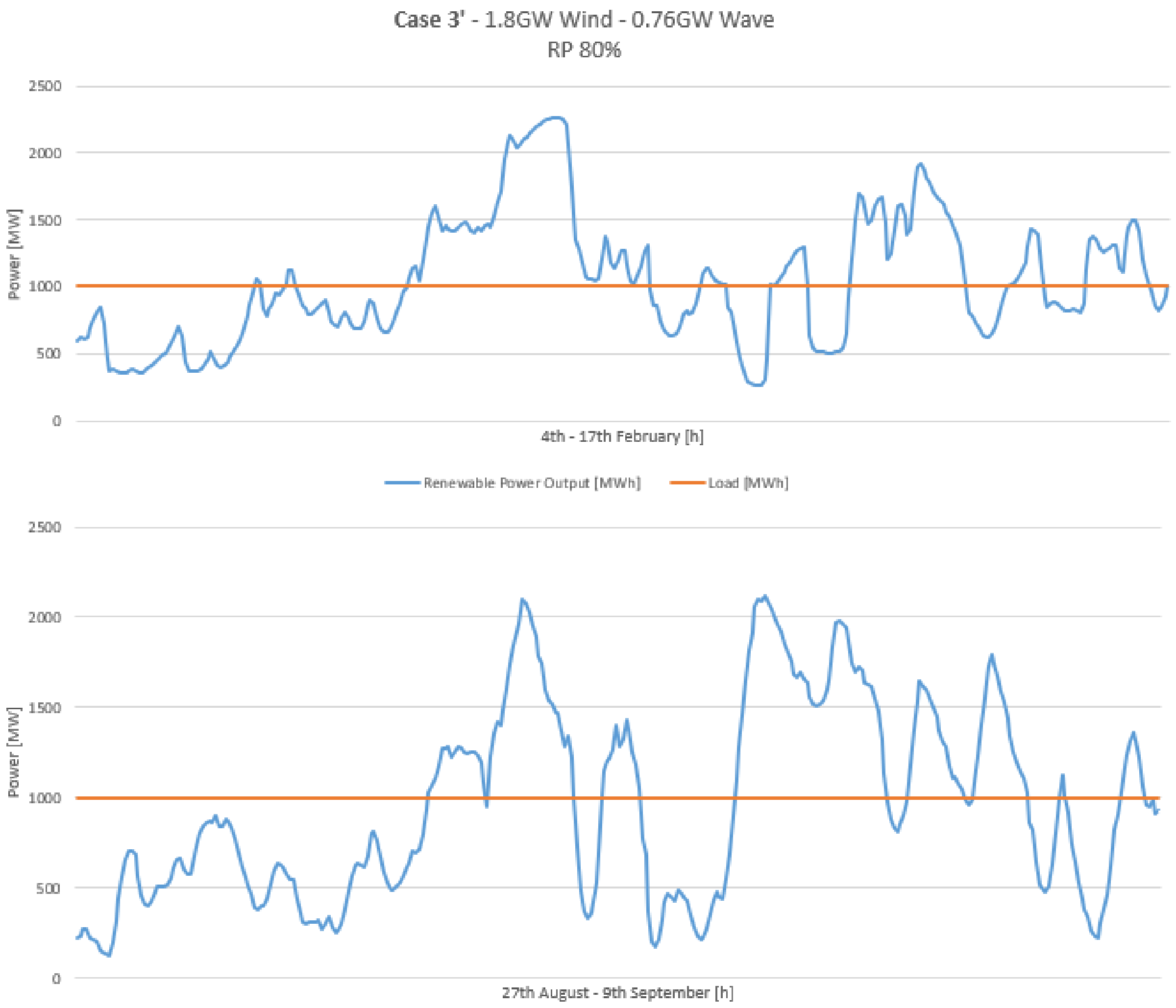

Case 6 - 60MW Wind 1.2GW Wave
RP 70%
1200
1000
800
600
400
200
0
El. Output [MWh]
4th - 17th February [h]
Load [MWh]
RE [MWh]
1200
1000
800
600
400
200
0
El. Output [MWh]
27th August - 9th September [h]

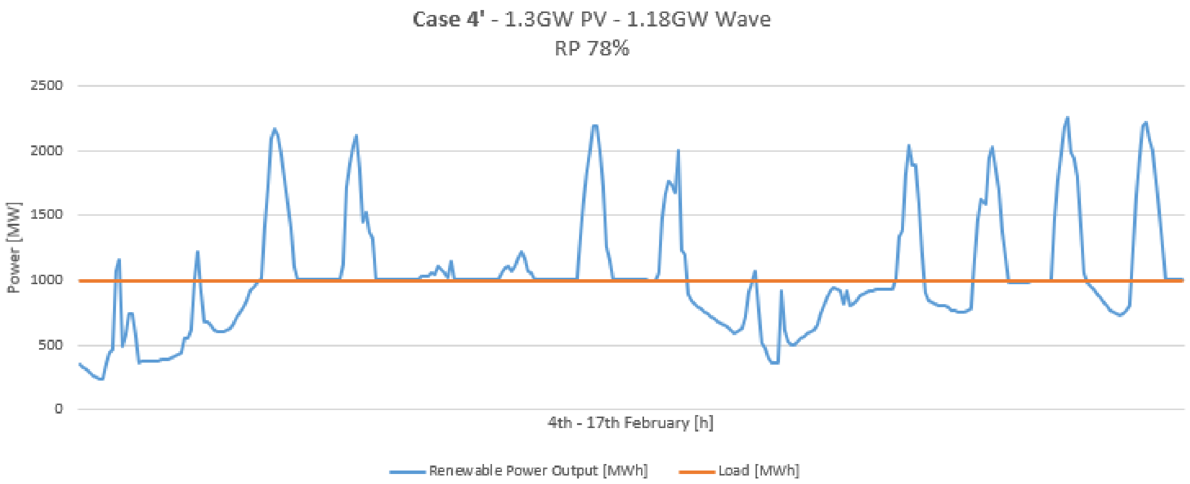

Case 7 - 1.1GW Wind
RP 41%
1200
1000
800
600
400
200
0
El. Output [MWh]
4th - 17th February 2018 [h]
Load [MW]
RE [MW]
1200
1000
800
600
400
200
0
El. Output [MWh]
27th August - 9th September [h]

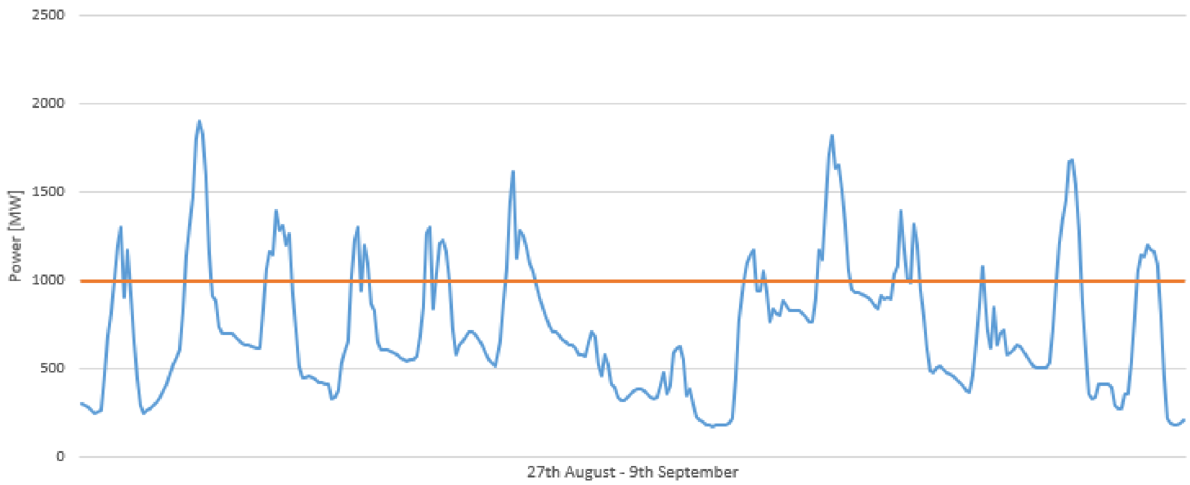
10 Annex 2 – Model 2

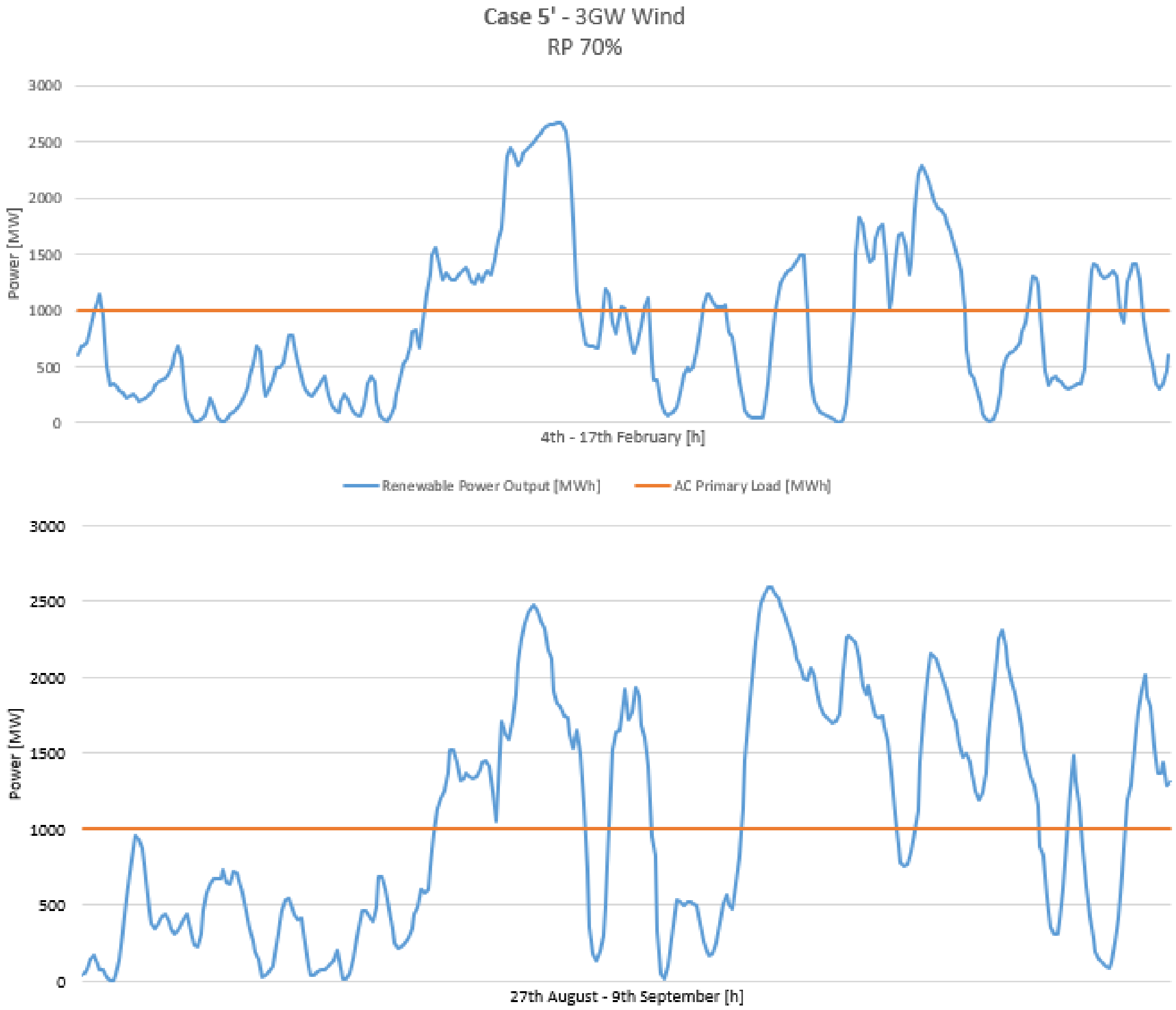


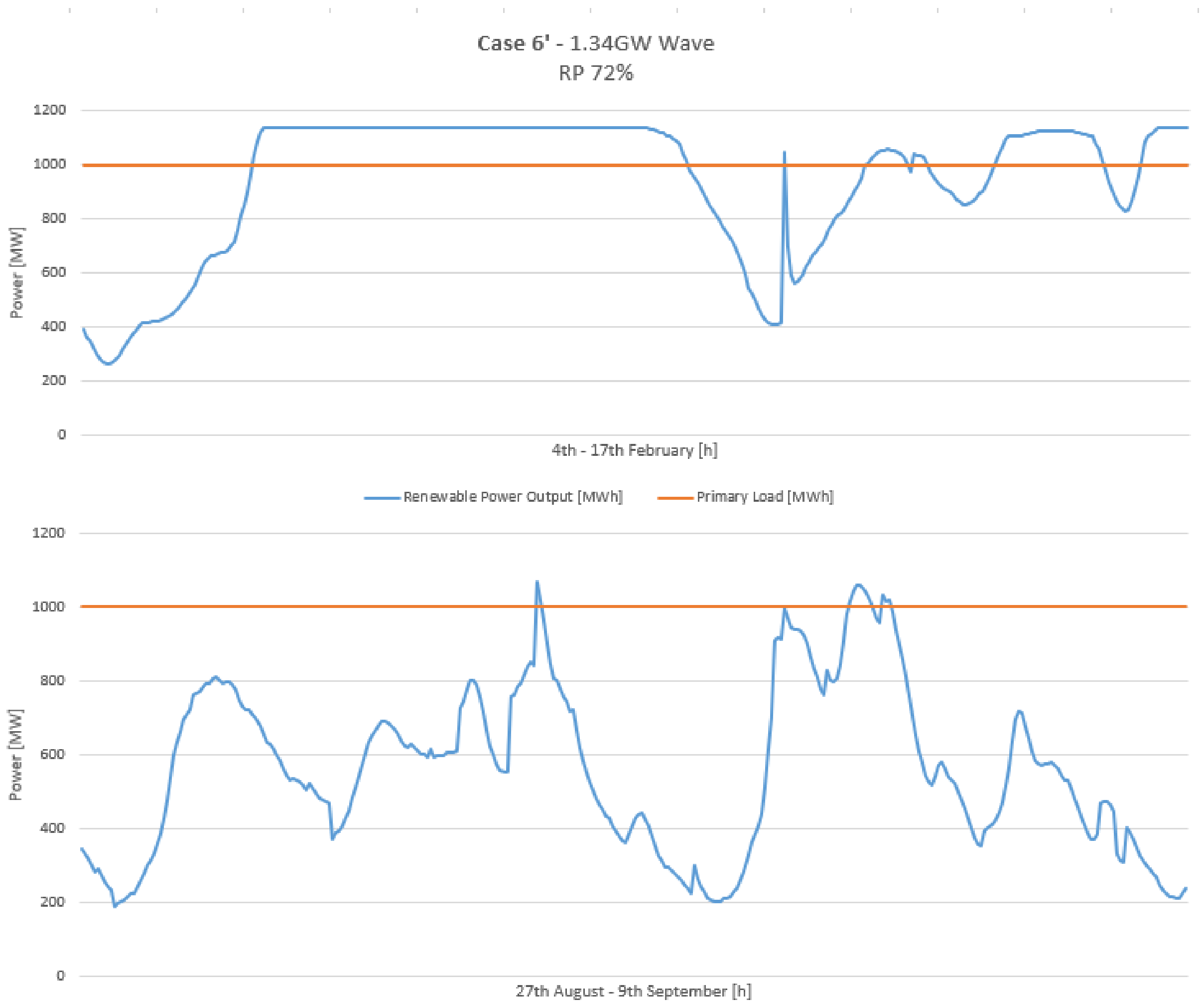

Case 2' - 1.4GW PV - 2.5GW Wind
RP 76%
3000
2500
2000
1500
1000
500
0
Power [MW]
4th - 17th February [h]
Renewable Power Output [MWh]
Load [MWh]
3000
2500
2000
1500
1000
500
0
Power [MW]
27th August - 9th September [h]

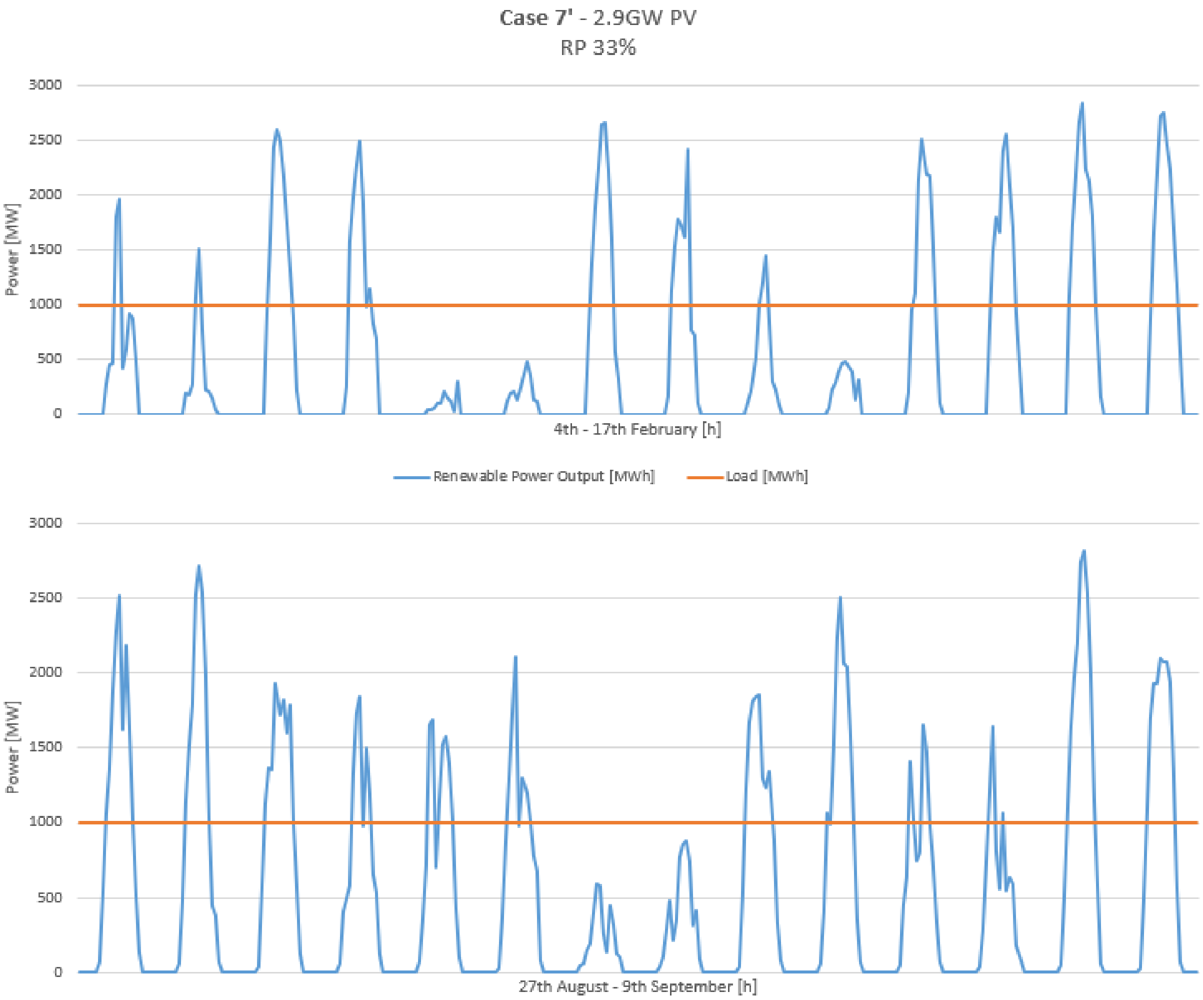

Case 3' - 1.8GW Wind - 0.76GW Wave
RP 80%
Power [MW]
2500
2000
1500
1000
500
0
4th - 17th February [h]
Renewable Power Output [MWh]
Load [MWh]
Power [MW]
2500
2000
1500
1000
500
0
27th August - 9th September [h]

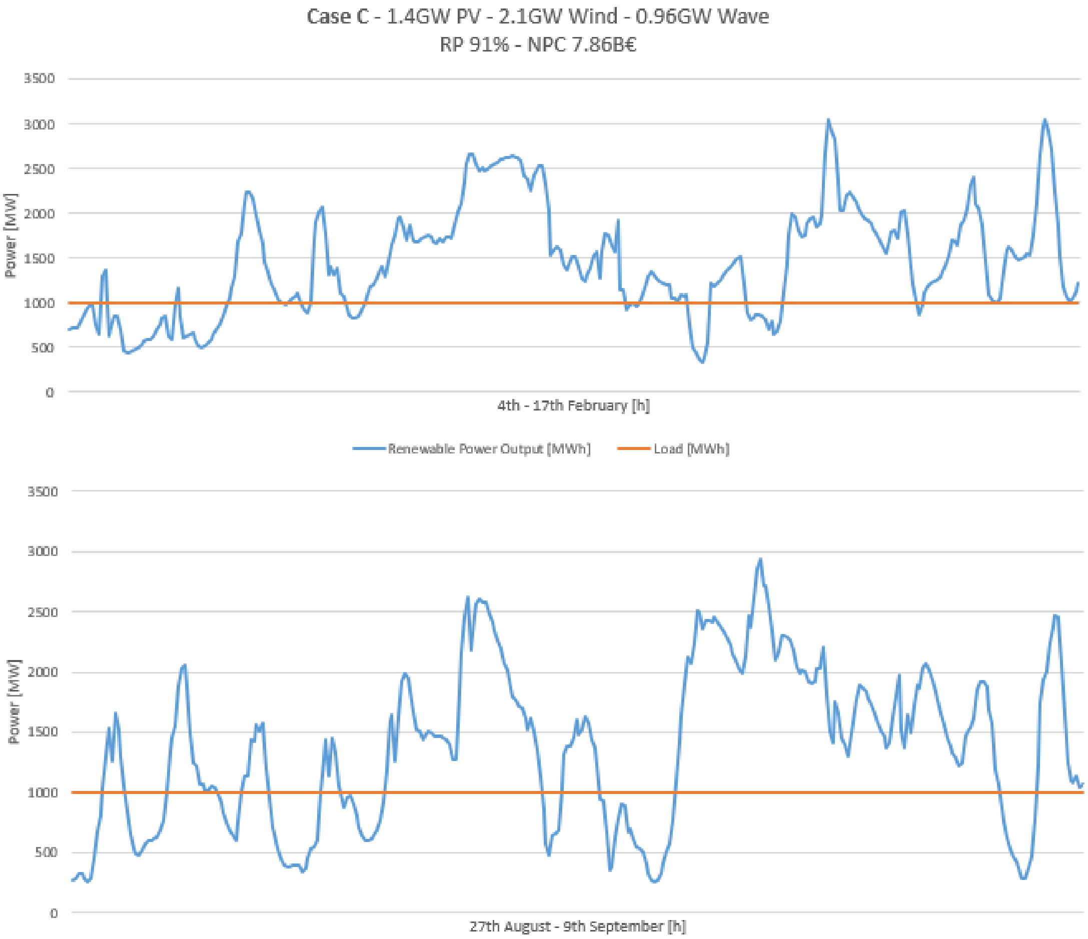

Case 4' - 1.3GW PV - 1.18GW Wave
RP 78%
Power [MW]
2500
2000
1500
1000
500
0
4th - 17th February [h]
Renewable Power Output [MWh]
Load [MWh]

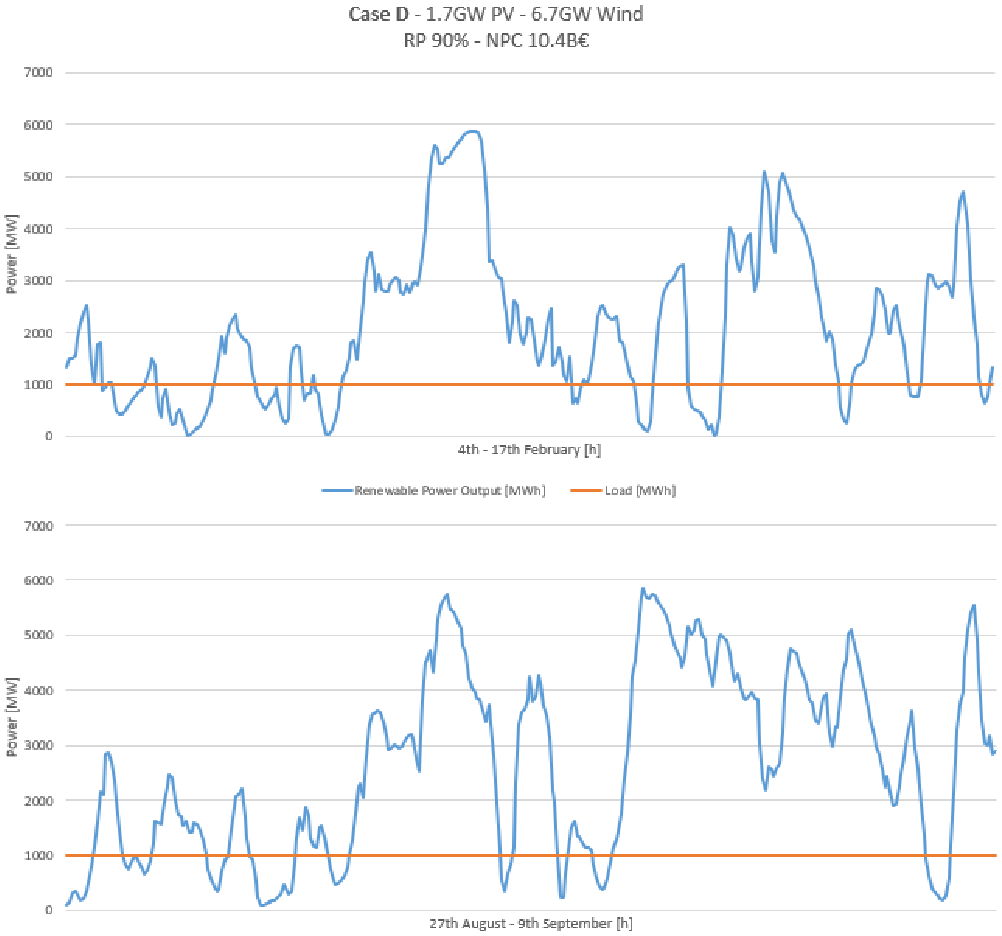

Power [MW]
2500
2000
1500
1000
500
0
27th August - 9th September


Case 5' - 3GW Wind
RP 70%
3000
2500
2000
1500
1000
500
0
Power [MW]
4th - 17th February [h]
Renewable Power Output [MWh]
AC Primary Load [MWh]
3000
2500
2000
1500
1000
500
0
Power [MW]
27th August - 9th September [h]

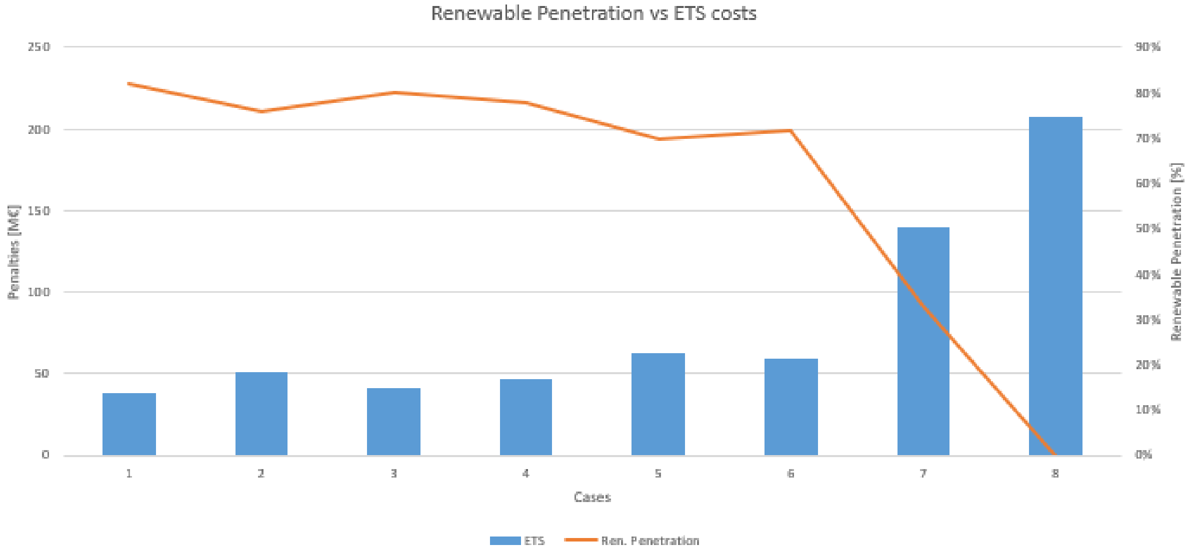

Case 6' - 1.34GW Wave
RP 72%
Power [MW]
1200
1000
800
600
400
200
0
4th - 17th February [h]
Renewable Power Output [MWh]
Primary Load [MWh]
Power [MW]
1200
1000
800
600
400
200
0
27th August - 9th September [h]

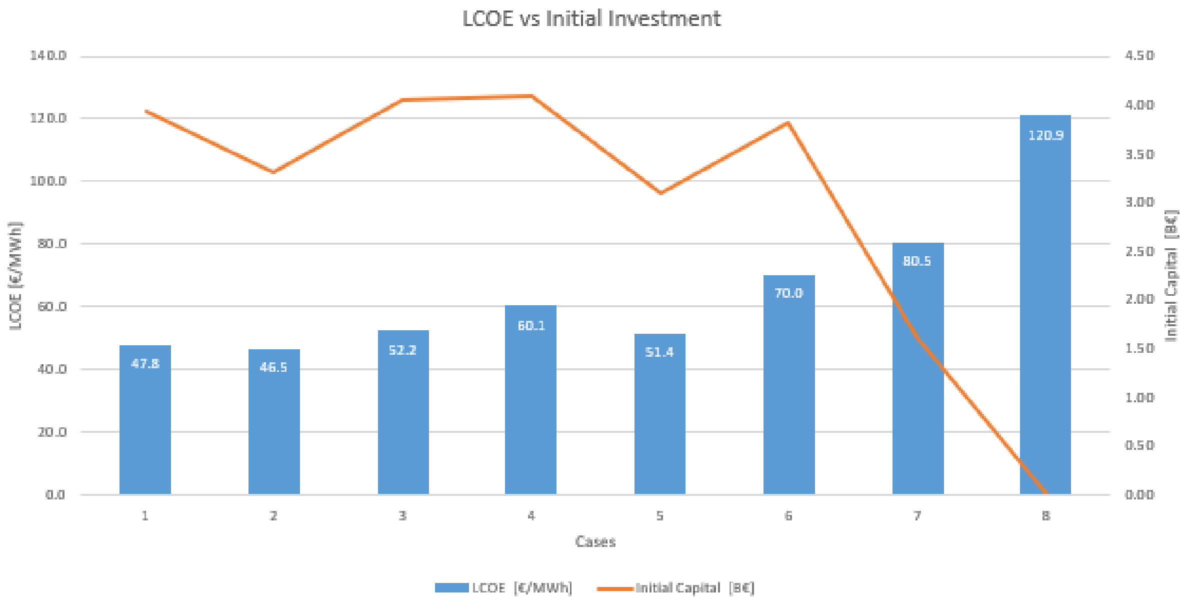

Case 7' - 2.9GW PV
RP 33%
3000
2500
2000
1500
1000
500
0
Power [MW]
4th - 17th February [h]
Renewable Power Output [MWh]
Load [MWh]
3000
2500
2000
1500
1000
500
0
Power [MW]
27th August - 9th September [h]

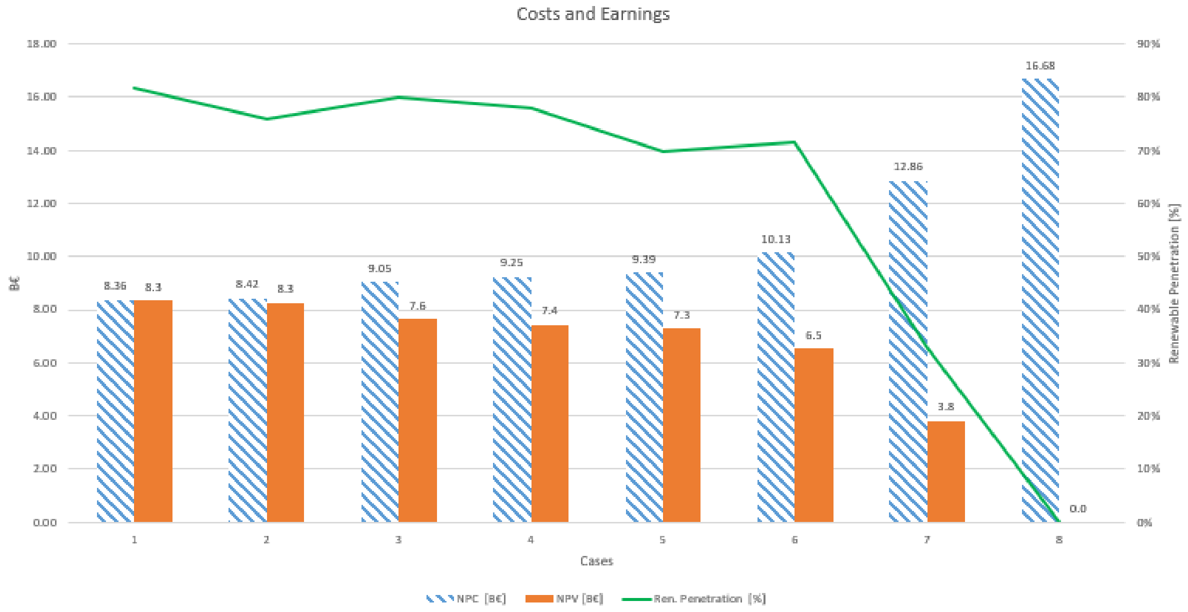

Case C - 1.4GW PV - 2.1GW Wind - 0.96GW Wave
RP 91% - NPC 7.86B€
3500
3000
2500
2000
1500
1000
500
0
Power [MW]
4th - 17th February [h]
Renewable Power Output [MWh]
Load [MWh]
3500
3000
2500
2000
1500
1000
500
0
Power [MW]
27th August - 9th September [h]



KPI summaries




LCOE vs Initial Investment
LCOE [€/MWh]
Initial Capital [B€]
Cases
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
1
2
3
4
5
6
7
8
47.8
46.5
52.2
60.1
51.4
70.0
80.5
120.9
LCOE [€/MWh]
Initial Capital [B€]


Costs and Earnings
B€
Renewable Penetration [%]
Cases
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
1
2
3
4
5
6
7
8
8.36
8.3
8.42
8.3
9.05
7.6
9.25
7.4
9.39
7.3
10.13
6.5
12.86
3.8
16.68
0.0
NPC [B€]
NPV [B€]
Ren. Penetration [%]