UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

THE EU RENEWABLE ENERGY FINANCING MECHANISIM FROM A HOST PROJECT PERSPECTIVE – AN APPROACH THROUGH AN ACADEMIC CASE STUDY

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Madrid, July 2023

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Summary

The objective in this Thesis is two-folded:

- On the one hand, to review and analyze the Renewable Energy Financing Mechanism (REFM), which allows a Member State to meet their renewable target by investing in a third EU “Host” country. The Host country receives in exchange a percentage of the associated renewable production statistics to also meet its own target.
- On the other hand, to model this mechanism from the point of view of the Host country, so as to provide a tool for the decision-making process. That is, to decide whether or not to be the counterpart of this regional mechanism. A toy case example is shown.

The Renewable Energy Financing Mechanism

The European Commission established the Renewable Energy Financing Mechanism (REFM) to incentivize and support the development of renewable energy projects. Through this mechanism, Member States could make voluntary financial contributions to support new renewable energy projects in EU countries interested in hosting such projects. In exchange, these Contributing member States would receive the statistics from the projects in their own national renewable energy targets.

According to the REFM Regulation, 80% of renewable energy generated by REFM-supported installations will be statistically allocated and distributed to contributing Member States, with the remaining 20% going to hosting Member States. However, the Commission may propose deviations from 50% to 100% for the contributing Member State and from 0% to 50% for the host Member State: To balance interest from participating Member States and ensure effective competition, to avoid that the call to participate in the mechanism results in little or no support, and to account for the potential costs that host Member States may incur.

The idea behind the mechanism is that contributor Member States can access cost-effective RES potential with resulting support savings and that hosting Member States can add RES capacities beyond the quantities triggered by national support schemes without incurring direct support costs, as the contributing Member States fully pay for these expenditures.

A modeling approach of REFM from the Host country perspective

To the author best knowledge, there are not public analyses about under which circumstances the REFM could be in the Host capacity best interest. This is precisely the gap that is addressed in this Thesis with the following approach:

- First, the cost that takes to the host country to achieve the RES targets without participating in the REFM has been quantified. This approach simulates a fully competitive short-term market while minimizing electricity supply and new investment costs subject to constraints *(Model I).*
- Then**,** another model has been developed in which two key factors of the mechanism are accounted for: (i) the percentage of share of the statistical benefits that is set and (ii) the cost that the Host country would bear as a consequence of increasing its renewable penetration (e.g. network reinforcements and losses).

A toy case example is used to illustrate the approach and also to validate the proposed model.

Foreword

To my tutors, my sincere gratitude for your support and guidance throughout the completion of this thesis. Your valuable input and insights have greatly contributed to the final outcome.

To my friends and family, your belief in my abilities and encouragement have been instrumental in helping me navigate the challenges of this project. I am truly thankful for your presence and unwavering belief in my potential.

Thank you for being an essential part of this journey and for standing by me throughout.

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Chapter 1. INTRODUCTION

1.1. THE NEED FOR RENEWABLES

According to the International Energy Agency [1], the global electricity demand grew by 6% in 2021. It was the largest ever annual increase in absolute terms (over 1500 TWh) and the largest percentage rise since 2010 after the financial crisis. As well, this same agency in its well-known report 'World Energy Outlook' (from now on, WEO) in 2021 [2] has predicted that, even in the least ambitious scenario, current and announced policies will push electricity demand up by almost 30% from 23.300 TWh in 2020 to almost 30.000 TWh by 2030 and to 42.000 TWh by 2050, almost 80% above today's level.

This increase is due to, among other factors such as the increase in population or the improvement in general of life conditions, the need of electrifying the demand, which is the process of replacing fossil fuels with electricity in all sectors, especially road transport, heating in buildings and industrial processes. By electrifying the demand, the use of technologies that emit CO_2 and other greenhouse gases decreases, which is the main step towards the objective of end with global warming.

However, if the demand increases, supply should do so too, and, of course, to be coherent with the purpose of demand electrification, the energy produced should be generated by alternative technologies to fossil fuels, clean and non-polluting, which leads us to renewable energy sources. But are renewable energy sources that necessary? Do they present other advantages compared to other technologies? Do they bring with themselves other benefits apart from the CO_2 emission reduction? Why do we need them?

To answer these questions, one could travel back to 2015 to learn about the Paris Agreement, which is a legally binding international treaty on climate change, adopted by 196 Parties in Paris, on December 12, 2015 [3]. The Paris Agreement is a milestone in the climate change process because, for the first time, a binding agreement brings all countries together in common cause to undertake ambitious efforts to combat climate change and adapt to its effects. Thus, the Paris Agreement aims to prevent the increase in the average global temperature of the planet from exceeding 2ºC compared to pre-industrial levels and also seeks to promote additional efforts that make it possible for global warming to not exceed 1.5ºC. In this way, the Agreement includes the greatest possible ambition to reduce the risks and impacts of climate change throughout the world incorporating, as well, all the elements to achieve this objective.

However, according to the last published WEO [2], more needs to be done to move beyond the announced pledges towards a pathway that would actually limit global warming to 1.5 °C, and one of these measures is the doubling of solar PV and wind deployment relative to the Announced Pledge Scenario. Therefore, one could then agree that renewable deployment is crucial to fulfill the Paris Agreement's objectives and, consequently, help mitigate the global warming effects.

That's for sure the most popular advantage of renewable energy, but of course not the only one. Another reason why renewable energy is needed is because the world population increases almost linearly each year [4]. To supply all these increasing demands, fossil fuels cannot just be relied on, as these are finite and sooner or later will run out. On the contrary, clean energies are inexhaustible, so no matter how much they are exploded, they do not run out.

Besides, apart from infinite, renewable energy in one of its forms (wind, sun, water, organic matter…) can be found in any part of the planet, while fossil fuels' location is nothing but uniform around the world. On the contrary, the reserves of these types of energy sources are distributed among very few countries:

For instance, the Middle East accounted for 40.3% of the total world proved gas reserves in 2020 and the Commonwealth of Independent States (CIS) for 30.1%, as it can be seen in Figure 1. Other example is oil, as 80.4% of the world's proven reserves are property of the Organization of the Petroleum Exporting Countries (OPEC), composed just by 13 countries [6].

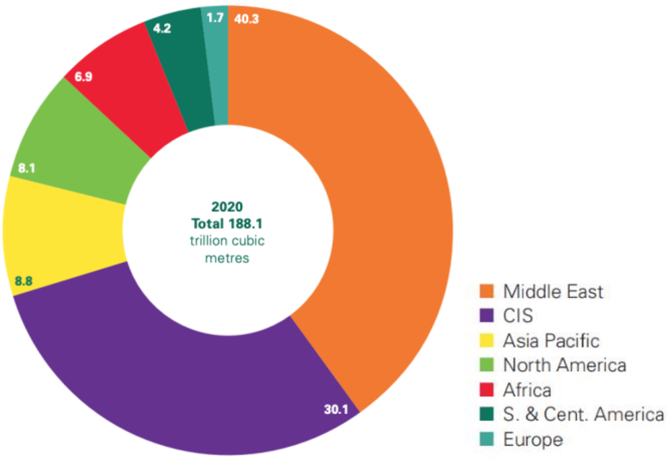


Figure 1. Distribution of proved gas reserves in 2020 © BP [5]

Using fossil fuels increases energy dependency, defined as the amount of primary energy that a country needs to import in order to supply itself, whether in the form of heat, electricity or for transportation. Therefore, it is the dependence that a country has on the outside to be able to obtain all the energy that it consumes. A high energy dependence has great consequences such as, but not limited to, instability in the energy supply (since the dependence on other countries to obtain part of the energy consumed by a country can generate alterations in the energy supply since it is not solely under the control of the importing country), or direct effects on the economy (due to the fact that energy dependence on foreign sources causes the economy to suffer continuous fluctuations in the price of energy, which generates instability in energy costs. As a consequence, this energy dependency can trigger a deficit in the trade balance of the countries). Therefore, the use of renewable energy sources can guarantee security of supply and price stability [7].

Moreover, this availability makes renewable energy the only type of source that cities in middle- and low-income countries can have access to.

Finally, the last reason to support the need of renewable energies is to help the energy mix to be diversified. Each energy source (thermal, solar, hydro, etc.) has its own particular operational characteristics:

- Some of them are more flexible, such as hydraulic energy sources or combined cycles, and therefore can vary their production quickly, so they are technically appropriate to answer to demand variation or to unexpected unit failures, while others are not, for example, nuclear energy. However, combined cycles contaminate, and that is a more than reasonable motive to try and not use it.
- Some of them have low variable costs (while high fixed costs), such as nuclear energy, so having it as a base technology (one that produces a fixed quantity for a large number of hours) is operationally effective. Renewable energies are also operationally cheap as their fuel, as it has been mentioned, comes from natural sources and is inexhaustible, but, as it will be discussed, grants or other kind of support policies have been used to give them competitive advantage as they were novel, and therefore not profitable, compared to former technologies.

Consequently, one can conclude that renewable energies make up for the shortcomings of conventional energy sources. But, to the question: can all generation of a country be composed of renewable sources? Not now, as renewable generation is intermittent (without rain, sun, and wind it cannot be generated) and batteries are not yet competitive enough to storage the energy needed to use it in other moments. However, including them in the mix can help to alleviate demand increase, lower the costs and, of course, reduce unwanted emissions.

1.2. SUPPORT MECHANISMS FOR RENEWABLE ENERGY SOURCES

Up to this point, one cannot deny that renewable energy sources of electricity (from now on, RES-E) are necessary in the energy mix. However, they have traditionally faced significant barriers to growth, since, as the technology was novel and therefore, not mature enough, it has had high capital costs and risk to a market and regulatory structure designed to accommodate conventional fossil-fuel based generators was perceived by investors.

Policymakers have long recognized that, in order to boost their deployment and eventually compete in the energy market, RES-E have needed to be promoted with specific support policies. Of course, as a matter of fact, the learning curves of these technologies show that, especially wind but also solar photovoltaic (from now on, PV) one day may be fully competitive without needing any economic aid, but, for now, mechanisms that limit investor risk, so they promote the construction of RES-E, are still necessary. However, the design of these policies is not that simple, and in fact, it has led to major debates between experts in the field, that question themselves up to what extent support mechanisms broader objectives for creating competitive electricity markets, as often they conduct to market distortions [8].

The clearest one is the resulting negative prices in the spot market: As renewables have low variable costs (close to 0€/MWh), they have incentive to keep running offering low prices or even negative ones as they will be receiving subsidies anyway. Therefore, other technologies that physically can't turn off their production, such as nuclear or coal ones, have to offer negative prices to, so as to be included in the mix, as the costs of stopping the production are greater than the payment to produce.

Other effect in longer them is the composition of the mix: if renewables are paid more than necessary, the efficient signal for the system will be to over-invest in renewables, which is not a good idea as long as batteries are not well developed, because, for instance, at night solar is not available, and fast-ramping technologies have to be dispatched at higher costs than usual, ending up with a more expensive price for energy.

These and other ones demonstrate that developing efficient support policies for RES-E is not that easy, and researchers have designed several of them trying to adjust to a competitive market. In chapter 2 these will be developed thoroughly by performing a review of the state of the art associated with the policies that have been implemented worldwide.

In summary, as it has been seen, mitigating the negative impacts of climate change is one of the greatest challenges facing humanity today, and one of the main strategies in the fight against climate change is to reduce greenhouse gas emissions produced in the generation of electricity. In this sense, different policies have been implemented in the electricity markets with the aim of encouraging the generation of renewable-based electricity and/or reducing greenhouse gas emissions produced by fossil technologies. In general, these policies can be based on a price given by the market, based on providing incentives or penalties depending on the type of technology with which electricity is generated and/or different combinations of both mechanisms. Considering the particular characteristics that electricity markets present, different policies have been used in the integration of renewable energy generation in electricity systems. This is the case of the EU Renewable Energy Financing Mechanism (REFM).

The European Commission established the REFM to incentivize and support the development of renewable energy projects to reduce emissions by 55% and increase renewable energy's share of the power mix to at least 32% by 2030. Through this mechanism, member States could make voluntary financial contributions to support new renewable energy projects in EU countries interested in hosting such projects. Contributors and hosting Member States participating in the scheme will be able to include part of the statistics from the projects in their own national renewable energy targets. The renewable energy allocated to contributing and host Member States is the renewable energy generated by the installations supported with the mechanism for an implementation period defined in the calls for proposals.

The 2017 bilateral agreement between Lithuania and Luxembourg is an example of statistical transfer. In this agreement, Lithuania transferred a certain amount of renewable energy production between 2018 and 2020 to assist Luxembourg in meeting its 2020 national renewable energy targets [9]. Luxembourg and Estonia have implemented a similar mechanism too [10]. These experiences will be developed further (See 2.5.4 International Experiences).

According to Article 27 of the REFM Regulation [11], 80% of renewable energy generated by REFM-supported installations will be statistically allocated and distributed to contributing Member States, with the remaining 20% going to hosting Member States. The REFM aggregates all RES statistics transferred to it and distributes them to contributing countries based on their financial participation in the mechanism. However, the Commission may propose deviations from 50% to 100% for the contributing Member State and from 0% to 50% for the host Member State in three cases:

1. To balance interest from participating Member States and ensure effective competition.
2. The call to participate in the mechanism could result in little or no support.
3. When there are potential costs that host Member States may incur.

The main goal of the REFM is to enable EU countries to collaborate more closely in the adoption and promotion of renewables to meet both individual and collective renewable energy targets more easily [12]. The idea behind the mechanism is, on the one hand, that contributor Member States can access cost-effective RES potential with resulting support savings. On the other hand, hosting Member States can add RES capacities beyond the quantities triggered by national support schemes without incurring direct support costs, as the contributing Member States fully pay for these expenditures. However, one of the main challenges of the REFM is that this mechanism could reduce the RES potential to be exploded at a national level and make it difficult to achieve its renewable energy targets in the long term [13]. Moreover, it is still unclear under which circumstances the REFM could adversely affect hostings.

1.3. MOTIVATION AND OBJECTIVES

In this context, it has been found that methodologies to **identify propitious scenarios for a Member State acting as a host in a REFM** still need to be proposed. In this Thesis, this gap is addressed and **the impact that the REFM could have on renewable energy deployment in hosting countries is discussed**.

Therefore, the objectives are:

- To describe REFM and similar mechanisms that are discussed today in the electricity sector, as well as the international experience implementing similar mechanisms.
- To propose a methodology and to develop an academic case study to identify propitious scenarios for a host to participate in the REFM, where investment, price and welfare of the of the REFM are analyzed in detail, according to the established percentages of participation and the adaptation cost incurred in the mechanism.
- To draw conclusions derived from the numerical results.

1.4. STRUCTURE OF THE REPORT

The report will be divided into five main chapters:

- The first one accounts for the introduction, in which the problem has been briefly discussed and the motivation and objectives have been presented.
- The second one shows a review of the state of the art associated with the policies that have been implemented worldwide, making special emphasis in describe REFM and its characteristics.
- The third one displays the methodology followed to program a test system in which to develop the academic case study previously explained. In this one, the case studies are introduced, and the key performance indexes used are described.
- The fourth one explains the results obtained.
- Finally, in the fifth one the conclusions are highlighted.

Chapter 2. STATE OF THE ART

The mechanisms studied in this thesis and briefly explained in this chapter will be the main four types of support schemes that exist in Europe, according to [14], which are: Feed-in tariffs (FiTs), Feed-in premiums (FiPs), Green Certificates and Grants. As well, there is a final section explaining the new renewable energy financing mechanism of the European Union and the international experiences of implementing it. This novel mechanism basically consists of a tender between Member States willing to deploy renewable energy sources in their country and Member States disposed to enable a budget to improve their RES statistics. It is object of study as it can be combined with the former support schemes.

2.1 FEED-IN TARIFFS

A FiT is an energy supply policy focused on supporting the development of new renewable energy projects by offering long-term purchase agreements for the sale of renewable energy electricity [15]. These purchase agreements are typically offered within contracts ranging from ten to twenty-five years and are extended for every kilowatt-hour (kWh) of electricity produced [16].

The payment levels offered for each kWh is independent from the market price, offering a guaranteed payment for a predetermined period of time, and can be differentiated to better reflect actual project costs by: technology type and/or fuel used, size of the installation (total capacity), quality of the resource at the particular site or value of generation to the market utility (based on the particular project location). Moreover, there can be bonus payments created to target specific goals and encourage certain types of choices and behaviors on the part of the developer, such as:

High-efficiency systems, use of particular waste streams, repowering (for example, replacing older wind turbine models, or hydro sites, with newer, larger, or more efficient ones), specific ownership structures (for instance, community-owned), use of innovative technologies, and vintage of installation (where a bonus is awarded if a project is installed before a certain date). Thus, FiTs have an extremely diverse and complex set of design choices from which policymakers can choose. While not all design options need to be used, it is clear that multiple policy goals can be targeted simultaneously. Therefore, FiTs can be designed to achieve a variety of goals, to be transparent to investors and renewable energy developers alike (thus lowering investment risk), and to uphold a high level of cost efficiency by matching FiT payments closely to levelized generation costs [17].

Besides, policy designers can also adjust the payment levels for several different reasons, such as, but not limited to, decline for installations in subsequent years, which will both track and encourage technological change [18], track inflation annually, encourage certain choices or address other factors. Figure 2 shows an example of the payment of a FiT.

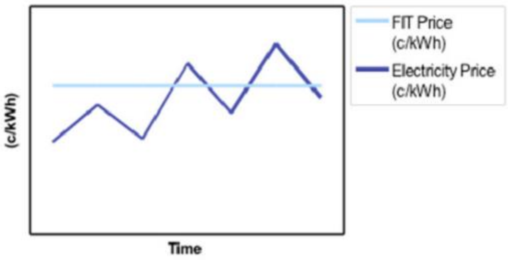


Figure 2. Example of the payment of a FiT © NREL [17]

Generally, FiTs have three advantages [19]:

- They guarantee grid access, meaning energy producers will have access to the grid.
- They offer long-term purchase agreements.
- They offer guaranteed, cost-based purchase prices, meaning that energy producers are paid in proportion to the resources and capital expended in order to produce the energy.

Also, anyone with the ability to invest is eligible for a feed-in tariff, including but not limited to homeowners, business owners, federal, state, and local government agencies; private investors; utilities or nonprofit organizations.

FiT payments have demonstrated a higher level of cost efficiency compared to FiPs, and have created, on average, lower risk, and more transparent market conditions for RE development [18]. Also, more European countries choose FiTs over FiPs [17].

2.2 FEED-IN PREMIUMS

FiPs are basically feed-in tariffs that in which FiT payments, instead of being fixed, can be offered as a premium, or bonus, above the prevailing market price [20]. In this market-dependent model, the payment level is directly tied to the electricity market price, rewarding renewable energy developers when market prices increase, and potentially penalizing them when they drop. Figure 3 shows an example of the payment of a FiP.

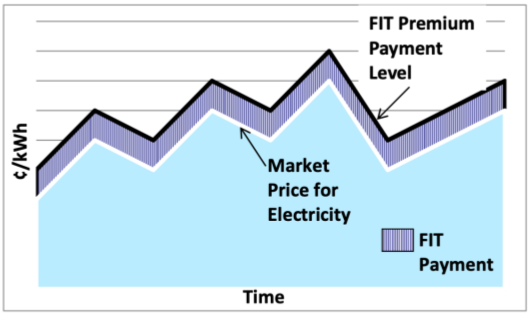


Figure 3. Example of the payment of a FiP © NREL[17]

The premium payment can be designed to achieve two objectives: represent the environmental value added of RE (environmental and/or societal attributes) or to better approximate RE generation costs.

Similar to the FiTs, FiPs can be differentiated to allow for a more cost-based payment level for each technology type, fuel type, and project size. Many of the design choices can apply to FiPs. However, some different considerations apply, as the total revenues of the project depend not only on the premium but also on the market price.

For example, the FiPs can be **constant or sliding:** Constant premium policies provide a non-variable adder on top of the spot market price, while **sliding** premiums vary with the market price. In these last ones, payment **"caps"** and **"floors"** are introduced on either the total premium amount or on the total payment amount. These options will be developed next [17].

2.2.1 CONSTANT FEED-IN PREMIUMS

Constant FiPs create an incentive to generate electricity in times of high demand and when market prices are high. The high spot prices, combined with a fixed adder on top, tend to encourage supply when it is needed most. The higher payments may be understood as a compensation for the added market risk. However, this result in higher average payment levels when electricity prices increase, which creates windfall profits to RE developers and puts upward pressure on policy costs. In addition, this model does not consider that electricity prices can decline, which causes projects with high up-front capital costs to struggle with revenues insufficient to cover project costs [17]. This uncertainty over future revenue streams creates an additional risk for the investor, who is likely to increase the equity returns and the debt interest rates, which increases the marginal costs [21].

2.2.2 SLIDING FEED-IN PREMIUMS

To alleviate the problems created by the Constant FiPs, FiP payments that vary based on market price were created. In this approach, as the market price increases, the premium amount can be designed to decline (and vice versa) to minimize windfall profits [17]. There are four examples:

2.2.2.1 Caps (maximum payment) and floors (minimum payments) on the total premium amount

To the basis of sliding FiPs (if average electricity market prices increase, the premium paid declines) a floor price is added, below which the combined revenues of the premium price and the market price cannot drop, which provides added investment security. In this way, the premium slides between an upper and a lower range in response to changes in the spot market price.

Example: A cap price is set at 70 €/MWh, that means that, if electricity market prices drop below that level, the premium must ensure that minimum payment level, so 70 €/MWh is the maximum premium payment that can be done, which will happen if electricity prices are 0€. As the electricity "pool" price increases, the premium amount declines until this price rises until 80€/MWh, to the point where the premium offered falls to zero (floor price) and RE developers receive just the spot market price.

This model represents a potential solution to the problem of under- or overcompensation that could result from constant FiPs. A premium that varies between two limits creates stability and provides protection for ratepayers on the upper end, while helping provide revenue security to investors through a minimum floor payment on the lower end [17]. However, it remains challenging to establish what the "correct" caps and floors should be, and to adjust them over time if technology costs change. Furthermore, if just the premium amount is capped, the total payment received by RE developers is still able to track the spot market when electricity prices increase, this means that they could be still receiving windfall profits when electricity prices are high.

2.2.2.2 Caps and floors on the total payment amount

This approach consists of capping the entire allowable payment amount. This provides a way of limiting the total payment, while still allowing it to vary within a range sufficient to obtain profitability.

This is one way of ensuring that revenues remain within a range sufficient to encourage investment, while securing the hedge benefit of renewable energy resources if electricity prices increase. The floor can offer a guarantee that project revenues will not drop below a certain specified level, which increases transparency and diminishes risks for RE developers and investors, while the cap limits the problem of overcompensation and reduce the overall costs for ratepayers. However, this approach poses some challenges. While a floor provides protection against the risks of downward electricity price movements, a cap may be perceived as an arbitrary tax on renewable energy developers because it awards them a lower payment level than is available on the spot market [21].

Therefore, a cap on the total allowable payment amount may reduce the total number of investors, by reducing the potential upside gains that could result from electricity price increases. This could also be considered a discriminatory policy design because amortized fossil fuel generators with low marginal production costs can still receive the spot market prices, while RE producers could not.

2.2.2.3 Spot Market Gap Model

This model offers a total guaranteed payment level. This provides revenue certainty for the RE developer. However, instead of having the FIT payment cover the total amount, the sliding FIT payment only covers the difference between the guaranteed payment level and the average spot market price, as it can be seen in Figure 4. This means that the premium payment varies based on the electricity price. Unlike other FiP policies, RE developers receive a guaranteed total price for their output [22].

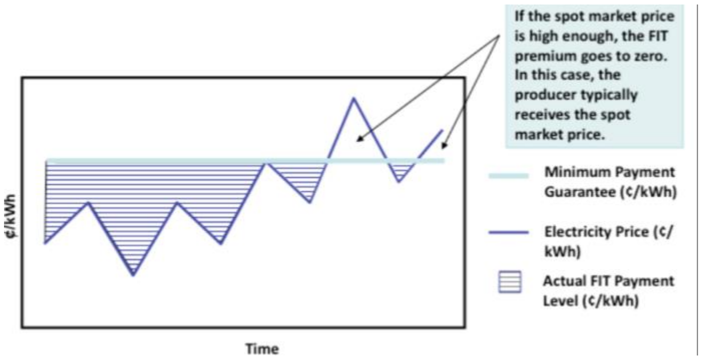


Figure 4. Spot Market Gap Model representation © NREL [22]

The spot market gap model has some benefits [22]:

- If the minimum payment is assured, it provides investors with price certainty.
- It provides a more transparent format for the calculation of policy costs: By offering a premium on top of the market price, any upward pressure on overall electricity prices that is directly caused by the FiP can be quantified.
- This approach can help limit policy costs, because no payment is awarded if the spot market price increases above the guaranteed payment level.

- This methodology is simpler than applying both a cap and a floor to the premium payment level *(See 2.2.2.1 Caps (maximum payment) and floors (minimum payments) on the total premium amount),* because there is a floor to the total payment amount (which is good for investors), and yet the project can take advantage of high spot prices.

However, similar to the sliding premium model with caps and floors on the total premium amount, that they could be still receiving windfall profits when electricity prices are high.

2.3 GREEN CERTIFICATES

A green certificate scheme is a market-based support mechanism designed to provide RES technologies with an additional income to the market revenue by selling previously awarded certificates to an obliged party. Basically, it is a tradable asset which proves that electricity has been generated by a renewable energy source. It is volume driven with a particular renewable target, usually set as a RES-share in final consumption or explicitly in volume of produced electricity. Within the scheme, market participants (typically suppliers and producers or grid operators) are given a duty to annually buy electricity certificates. The number of certificates that one is obliged to buy corresponds to the value of the mandatory renewable quota established for the current year, multiplied by the quantity of electricity (MWh) supplied annually to the final consumers. This will create a demand for certificates, without prejudice that a supplier can increase this quota on a voluntary basis. Producers will earn an income from selling certificates, in addition to the income they receive from the sale of electricity. This is intended to make it profitable for investors to invest in new electricity generation from renewable energy sources. Also, for businesses, this has commercial benefits, as it improves reputation and provides a competitive edge in a society in which awareness and the importance of environmental impacts are ever increasing [23].

However, certificates cannot be transferred between the European markets, as opposed to emission certificates, so the total market size is often small and trading rather illiquid.

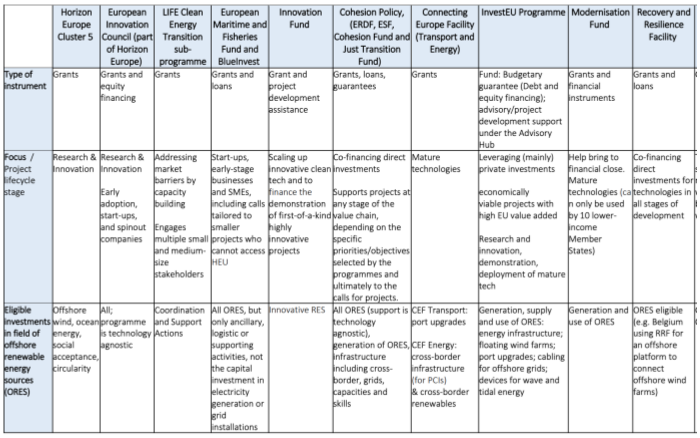
This is one of the reasons why compliance markets for green certificates have lost popularity in recent years [24].

2.4 GRANTS

Grants are direct financial contributions from public budget (for instance, the European Union budget) subject to centralized management awarded by way of a donation to third-party beneficiaries engaged in activities that serve with policies aligned with the grant. Grants fall into two broad categories: Grants that finance actions intended to help to achieve an objective that forms part of a policy or operating grants that finance the operating expenditure of a body pursuing an aim of general interest or an objective that forms part of a policy. Grants are based on the costs actually incurred by the beneficiaries for carrying out the activities in question, and the results of the action remain the property of the beneficiaries [25].

As an example, the EU Innovation Fund is a grant that provides around 38 B€ of support over 2020-2030, aiming to bring to the market industrial solutions to decarbonize the EU and support its transition to climate neutrality. This fund supports up to 60% of the relevant costs of projects [26]. A brief description of other EU funding programs can be found in Table 1.

Table 1. Overview of EU funding programs © European Commission [26]



	Horizon Europe Cluster 5	European Innovation Council (part of Horizon Europe)	LIFE Clean Energy Transition sub-programme	European Maritime and Fisheries Fund and BlueInvest	Innovation Fund	Cohesion Policy, (ERDF, ESF, Cohesion Fund and Just Transition Fund)	Connecting Europe Facility (Transport and Energy)	InvestEU Programme	Modernisation Fund	Recovery and Resilience Facility
Type of instrument	Grants	Grants and equity financing	Grants	Grants and loans	Grant and project development assistance	Grants, loans, guarantees	Grants	Fund: Budgetary guarantee (Debt and equity financing); advisory/project development support under the Advisory Hub	Grants and financial instruments	Grants and loans
Focus / Project lifecycle stage	Research & Innovation	Research & Innovation Early adoption, start-ups, and spinout companies	Addressing market barriers by capacity building Engages multiple small and medium-size stakeholders	Start-ups, early-stage businesses and SMEs, including calls tailored to smaller projects who cannot access HEU	Scaling up innovative clean tech and to finance the demonstration of first-of-a-kind highly innovative projects	Co-financing direct investments Supports projects at any stage of the value chain, depending on the specific priorities/objectives selected by the programmes and ultimately to the calls for projects.	Mature technologies	Leveraging (mainly) private investments economically viable projects with high EU value added Research and innovation, demonstration, deployment of mature tech	Help bring to financial close. Mature technologies (can only be used by 10 lower-income Member States)	Co-financing direct investments for technologies in all stages of development
Eligible investments in field of offshore renewable energy sources (ORES)	Offshore wind, ocean energy, social acceptance, circularity	All; programme is technology agnostic	Coordination and Support Actions	All ORES, but only ancillary, logistic or supporting activities, not the capital investment in electricity generation or grid installations	Innovative RES	All ORES (support is technology agnostic), generation of ORES, infrastructure including cross-border, grids, capacities and skills	CEF Transport: port upgrades CEF Energy: cross-border infrastructure (for PCIs) & cross-border renewables	Generation, supply and use of ORES: energy infrastructure; floating wind farms; port upgrades; cabling for offshore grids; devices for wave and tidal energy	Generation and use of ORES	ORES eligible (e.g. Belgium using RRF for an offshore platform to connect offshore wind farms)

2.5 THE NEW RENEWABLE ENERGY FINANCING MECHANISM

Apart from the national binding RES targets, the EU has stablished that by 2030 at least 32% in gross final energy consumption of the EU has to come from RES. To this end, it has created several instruments, one of which is the new renewable energy financing mechanism.

The mechanism is basically a pooled cross-border cooperation auction, where Member States cooperate on a multilateral basis, that works as follows: There are different kinds of Member States [27] [28]:

- **Contributing Member States:** make voluntary financial contributions to the mechanism in exchange of obtaining the RES statistics, but do not get RES installed in their country. The rationale to participate for them would be to access cost-effective RES with resulting support cost savings compared to national deployment, and that they may experience lower transaction costs compared to the individual cooperation mechanisms.
- **Hosting Member States:** allow the RES to be installed in their country, so they get the benefit from having RES installed without having to bear the costs, but do not get the benefit from the statistics. They transfer the RES target statistics back to the mechanism which then redistributes them to the contributing Member States according to their contribution.
- **Mixed Member States:** Member States can participate both as a contributing or hosting country.

However, parts of the statistics may be redistributed back to the host Member States to account for costs such as grid integration.

Finally, it is worth mentioning that an installation participating in this mechanism is not eligible for support in a national support scheme.

2.5.1 FUNCTIONING OF THE MECHANISM

Member States make voluntary financial contributions to the mechanism. The mechanism then implements a RES tender and thereby determines support levels and allocates support to projects in host Member States. The host Member States transfer the RES target statistics from these RES installations back to the mechanism which then redistributes the RES statistics to the contributing Member States according to their share in the financial contributions used in the respective tender round. The RES statistics are thus pooled per tender round. Figure 5 shows an overview of the basic functioning of the mechanism [28].

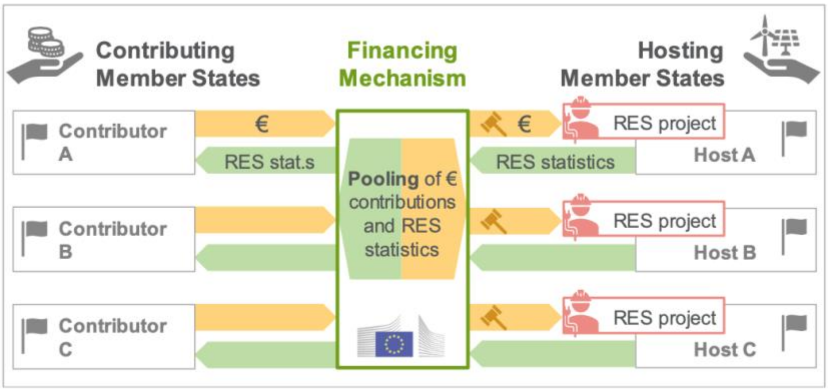


Figure 5. Overview of the basic functioning of the EU RES financing mechanism © Aures II [28]

2.5.1.1 Financial Instruments Considered

The mechanism can be provided with:

- **Repayable support:** financial instruments such as, but not limited to, low-interest loans, junior loans, guarantees, among others.
- **Non-repayable support:** grants, feed-in premiums, or investment support. The source are voluntary financial contributions from Member States.
- **Funding from other European Union funds:** such as Connecting Europe Facility.

However, just the non-repayable forms of support will be the focus, as they directly trigger RES investments, and which result in the transfer of RES Statistics.

2.5.1.2 Types of Auctions

The auctions can be:

- **Technology-neutral:** It maximizes cost-effectiveness of RES support. This approach includes the option to allocate support across the sectors electricity, transport and heating and cooling or to allocate support across technologies but within each sector (end-use specific). However, if they are introduced across sectors, the comparability of bids between sectors may be difficult as the value of each kWh in the heating sector is lower than the one in the electricity sector.

  Furthermore, if all the technologies bid, the technology with the lowest specific investment cost would win, regardless of how much energy it produces, resulting in higher costs per energy unit and increased uncertainty regarding energy output.
- **Technology-specific:** targets specific technologies. It may focus on technologies which are the most acceptable to the participating Member States. It may support less mature technologies and thus their market entry, even though it still triggers least-cost deployment per technology. While it does not introduce competition neither between technologies, nor sectors, it may avoid the issues found in the technology-neutral approach.
- **Project-specific**: are selected on a least-cost basis. In the case of selection between different projects and sites, the lowest bid per type of project or the best cost-benefit ratio would be the deciding factor.

2.5.2 BENEFITS AND BARRIERS OF MEMBER STATES TO PARTICIPATE

In this section, the benefits and barriers of the Member States to participate are described.

2.5.2.1 Contributing Member States

BENEFITS

- To receive RES statistics
- To save costs: the likeliness of effectively accessing cheap RES potentials in other Member States is higher when using the mechanism rather than relying on individual cooperation mechanism.
- To benefit from better credit rating, decreasing the cost of support
- To benefit from reduced transaction costs, given that it does not require a negotiation of support schemes, allocation of costs and benefits and contracts.
- To ensure that they comply with RES targets.
- To fulfil the condition of the Commission of partially opening their support schemes for installations abroad.
- In case some circumstances make national RES deployment more challenging, such as negative trends in local planning and permitting or macroeconomic developments.

BARRIERS

- A barrier to participate may be the lack of political acceptance: the idea of supporting RES deployment outside a country while missing the benefits of domestic RES deployment, is not accepted globally. The remedies are to explore the benefits and to communicate them clearly or to participate in a mixed role.

2.5.2.2 Hosting Member States

BENEFITS

- To comply with the Paris Agreement, that requires, among other things, a decarbonization of the energy system. This may be particularly relevant in Member States which have to replace existing capacities in the short term, because of a planned coal phase-out or because aging energy conversion assets have to be replaced.
- Triggers additional investment in the respective Member State and has positive employment effects.
- Reduces greenhouse gas emissions, and statistics regarding them.
- Decreases import dependency.
- Improves air quality.
- Could be used to foster political cooperation with other Member States
- Benefit from free direct support costs.

BARRIERS

- Tenders implemented by the mechanism make use of a host country's RES deployment potential. Potential sites are no longer available for national deployment.
- Member States may experience system integration costs (grid reinforcement/extension or re-dispatch costs)
- Hosts may experience transaction costs related to setting up the legal and administrative framework and carrying out related tasks (monitoring and communicating the production data).
- These barriers may limit public acceptance. These barriers can be addressed through updates of planning instruments and by adequate communication strategy.

2.5.2.3 Mixed Role

To overcome the barriers to participating as a contributing Member State (political resistance against financing RES deployment abroad) or to be a truly cost-effective approach: contributing financially without an ex-ante determination of plant locations would allow for the most cost-effective RES deployment throughout the European Union. An EU-wide auction as implemented by the EU RES financing mechanism deepens the market integration approach of RES support, as it works across borders.

As it has been seen in this section, there are benefits and barriers to participate in the mechanism, both as a Host Country, and as a Contributing Member State. This thesis will help to discover that the barriers and benefits will depend on the percentages defined to the statistics' transfers.

2.5.3 ALLOCATION OF COSTS AND BENEFITS

In this section, a discussion on how to allocate the costs and benefits will be presented.

2.5.3.1 Determination of the size of contributions

The process of determining the size of the contributions is subject to these conditions:

- Member States should have the sufficient acquisitive power as the European Commission cannot pre-finance Member States' contributions.
- Member States must know the budgetary implications of the participation in a specific tender round before committing.
- The exact level of support is only known once the tender has taken place.
- The tender results depend on the level of participation both of contributing and hosting Member States.

These conditions require to establish **ex-ante a ceiling price.** For each tender, the Commission may calculate a maximum price per MWh (or per MW per technology) and share it with the Member States before the commitment, so they know that that will be the maximum that they will have to pay in the worst case.

As estimating a maximum price is only possible once both the level of supply and demand are known, an iterative process per round is applied:

- Based on the Expressions of Interest, the Commission gathers information on the aggregated potential for a specific technology of all hosting Member States.
- It is used to determine a range of potential support costs that would result from a tender. Since the final result depends on the level of demand, an indicative maximum price for a low, medium, and high tender volume will be derived from the cost-supply curve. These are communicated to Member States.
- Considering the maximum prices, interested contributing Member States are asked to provide information on their intended financial contribution to the mechanism in terms of budget, capacities, and generation.
- Based on this information, a maximum price is determined.

2.5.3.2 Allocation of statistical benefits

The attribution of statistical benefits should be done according to the actual contributions made. To provide predictability and transparency, the rules on the allocation of the statistical benefits must be known prior to the binding commitments of the contributing Member States. For instance, the statistical benefits can either be transferred to the mechanism over the lifetime of support or the lifetime of the installation. The options for the allocation of the statistical benefits are:

- To allocate them **entirely to the contributing Member States**: this is simple and transparent and applies equally to all participants of the mechanism. It is clear and provides incentives for making contributions to the mechanism. However, if no statistical benefits remain with the host country, the incentive for hosting Member States is reduced.

- To **split part of the benefits to the hosting Member States**: This is fair because:
    - Hosting Member states bear costs despite not contributing to the support payments (system integration of additional RES capacities and grid connection of individual projects).
    - Hosting Member States give up part of their domestic RES potential, which in the long term may lead to higher domestic costs of RES deployment.
    - It increases the incentive to participate as a host. The more participants, the better the functioning of the mechanism, the cheaper the auction and the more attractive to contribute.

The splitting rule has an impact on the maximum price, as well as on the final price. The higher the share retained by the hosting Member States, **the more support needs to be paid per RES benefit transferred to the mechanism.** Inside of this second option, a lot of alternatives can apply:

- To apply a **flat-rate approach** to all cases (e.g., 20% of statistical benefits attributed to hosting Member States). However, that case may be rejected for individual cases, which need more flexibility. This rate could change or not per tender round.
- A **more flexible and tailored approach**. The following criteria may be reflected:
    - **Maturity of the technology:** for less mature technologies, the share of support payments will be higher. Therefore, contributing Member States bear a relatively higher share of the costs. In these cases, the statistical benefits for the hosts should be smaller.
    - **Likelihood of having a very low auction result:** if auctions result in low bids (technologies are mature or competition is high), contributing Member States bear low support costs. In these cases, the statistical benefits for the hosts should be greater, as the host provides low-cost sites to the mechanism and the project could have been built domestically at very low support costs as well. Auction results cannot be predicted, but past auction results in the participating host Member States can be used as an indicator for the likelihood of having a very low auction result.

  - **Impact of technology on system integration costs:** The higher the impact of the technology in the system integration costs, the higher the benefits for hosting Member States. This depends on factors of the energy system and regulatory conditions.
  - **Preferences of Member States:** The split needs to be a compromise, based on the Member States' feedback.

Perhaps Member States may prefer to determine individual target attribution splitting, instead of defining a splitting rule that applies equally to all participating countries.

The advantages of letting hosting Member States to determine their own individual target attribution split are:

- **Increase the attractiveness** to participate as a hosting country and thereby increase the availability of low-cost potential offered to the mechanism: host countries have flexibility in defining a central aspect of the terms and conditions of their participation. As a result, the mechanism may also be more attractive to contributing Member States.
- **Avoids all participating Member States have to agree on one rule**

The disadvantages are:

- **It can be seen as unfair**, especially by those hosting Member States that retain a lower share
- **Adds complexity to the tender:** bids would need to be adjusted to the same denominator when making the bid decision.
- **The projects awarded may not be those with the lower costs:** To ensure that bids are compared on equal terms, all bids must be compared on the basis of "€/MWh transferred to the mechanism". This requires adjusting the bids according to the splitting rule of the country in which the projects will be located. For example, a bid from country A with a splitting rule of 80/20 would be divided by 0.8 and a bid from country B with a splitting rule of 70/30 would be divided by 0.7.

However, the projects awarded may not be those with the lowest support costs. Projects with a lower need for support but located in a host country with a less “favorable” splitting rule (e.g. 70/30) may lose to projects that require more support but are located in a host country with a splitting rule that grants more RES statistics to the contributors (e.g. 80/20). Thus, from a system’s perspective, this can result in sub-optimal result in terms of cost-efficiency.

- **It can add an administratively determined element that has an impact on the competitiveness.**
- The **incentive for potential contributing Member States to participate may be reduced**, depending on the share.

Right now, the regulation of the mechanism (2020/1294 of 15 September 2020 on the Union renewable energy financing mechanism [11]) states in its article 27 that the renewable energy generated by installations supported by the mechanism shall be statistically allocated pursuant to Directive (EU) 2018/2001 and shall be distributed as follows: 80 % to contributing Member States and 20 % to host Member States. However, the Commission may propose to deviate from the that distribution and to allocate the energy to contributing and host Member States within a range going from 50 % to 100 % for the contributing Member State, and from 0 % to 50 % for the host Member State, where the total allocation for both contributing and host Member States amounts to 100 %. This modification from the 80%-20% base scenario shall be based on these criteria:

- The **likelihood of the call to attract a balanced interest** from contributing Member States and host Member States to ensure effective competition in the call for proposal;
- The **likelihood of the call to result in no or little support** being disbursed by the mechanism;
- The **potential costs**, including system integration costs, which the host Member States may incur.

In sum, a uniform splitting rule per auction round for all participating Member States appears to be the preferred option, clear before they enter a binding commitment. Allowing for individual splits per host Member States should only be considered if deviating views by the Member States cannot be accommodated otherwise. Finally, bids need to be adjusted to ensure that the award decision is based on "€/MWh transferred to the mechanism".

This tesis will help to propose a methodology to identify propitious scenarios for a host to participate in the REFM based on the distribution of the allocation of the statistical benefits.

2.5.4 INTERNATIONAL EXPERIENCES

Before the creation of the mechanism, which was regulated in the (EU) 2020/1294 of 15 September 2020 on the Union renewable energy financing mechanism [11] in September 2020, there had been some examples of other renewable energy mechanisms that required collaboration between member States.

This was the case of Germany and Denmark, who held in 2016 the first cross-border PV auction [29]. This allowed photovoltaic installations in Denmark to participate in a German auction competing with photovoltaic installations from Germany. However, this action required that the electricity was physically imported from Denmark into Germany.

This was a great step towards the collaboration of States in collaborating to achieve targets, but it was not until 2017 that happened the first agreements on statistical transfer of renewable energy amounts. This was the case of Lithuania and Luxembourg in 2017 [9]. It was the first ever cooperation agreement on the statistical transfer of renewable energy amounts. It was agreed as Luxembourg achieved a 5% renewable energy share in its gross final energy consumption in 2015, being its national target 11% whereas Lithuania achieved a share of 25.75%, being its national target 23%. The agreement stipulated that Lithuania would transfer a certain amount between 2018 and 2020 to help Luxembourg fulfil its 2020 national renewable energy target.

Approximately a month later, Luxembourg signed the second ever agreement on statistical transfers of renewable energy, this time collaborating with Estonia [30], willing to fulfil its 2020 target, taking advantage of Estonia, which in 2015 achieved a share of 28.6% of renewable energy in its gross final energy consumption, when its national target was 25%. The agreement stipulated that Estonia would transfer a minimum volume of renewable energy target amounts in 2018 and 2020 but also included the option for additional transfers in the future. In contrast, the revenues received by Estonia from Luxembourg were used to finance projects in the areas of renewable energy or energy efficiency.

Finally, in 2023 has been the first time two countries have agreed to commit to take part in the REFM [31]. These two countries have been Finland and Luxembourg. Luxembourg will participate as a contributing Member State, contributing 40M€ to the mechanism. Finland will participate as a host country, allowing solar PV projects located in its territory with a total capacity of up to 400MW to take part in the tender. This cross-border tender for renewable energy has taken form of a call for proposals, which was opened on 18 April. This call will be open for six months, after which the European Climate Insfrastructure and Environment Executive Agency (CINEA) will evaluate the competing offers and will award the successful projects on the basis of the lowest bid price until the budget is used up [32].

As for now just two countries have taken part in this novel mechanism, one of the strengths of this thesis is that it will help countries decide under which circumstances will be paid off to participate in the REFM.

Chapter 3. METHODOLOGY

As it has been mentioned Section 2.5, hosting member states face several challenges when participating in the mechanism:

- First, as a result of the tenders implemented by the mechanism, hosting members waves to exploit part of the RES potentials and obtain all the possible statistical benefits of the project.
- Second, hosting Member States may experience system integration costs due to grid reinforcements and increased re-dispatched costs.
- Third, hosts may face some legal and administrative framework costs related to RES generation data management issues.
- Fourth, achieving public and political acceptance of acting as a host could be challenging for the reasons mentioned earlier.
- Fifth, future deployment of RES for hosting State Members could become more difficult because of the reduction of the capacities and locations of cost-effective RES projects to achieve the national targets.
- Sixth, future deployment of RES for hosting members could become less attractive for investors because of the sagging in electricity prices produced by the new entries of near-zero cost technologies. Moreover, this could lead to implementing support policies for future RES obligations faced by other programs that could be even more expensive at the national level than investing without appeal to the REFM

In this thesis, the focus will be put into this last challenge. Specifically, the impact of REFM on future support measures needed by host Member States to achieve RES targets will be investigated.

One Member State would participate in the REFM as a host under one of two conditions: On the one hand, participating in the mechanism allows the Member State to achieve the RES targets at a lower cost than if it does not participate. And on the other hand, if the cost of attaining the RES goals is higher than the Member State can bear. This Thesis assumes that Member States can face the acquired commitments. Therefore, a Member State will participate in the mechanism if it reduces the cost of achieving the RES targets.

Considering the above, our methodology consists in the following steps:

First, we quantify the cost that takes to the host country to achieve the RES targets without participating in the REFM. This approach simulates a fully competitive short-term market while minimizing electricity supply and new investment costs *(Model I).*

Then**,** we propose an approach to identify, depending on the percentage of share of the statistical benefits that is set, the maximum and minimum cost that a host country would bear to participate in the REFM. That is, that produce a lower cost for the system than calculated in the first step while obtaining the optimal mix capacity of renewable energy available for REFM projects on host territory, and giving profit to the plants already installed *(Model II).*

Finally, we evaluate the impact of the percentage of share of the statistical benefits on RES development and support needs from other fundings than REFM. The support needs from other fundings are the investment costs of the RES that the market revenues or the REFM cannot cover.

Therefore, several scenarios are proposed to be analyzed in an academic study case. In all the scenarios, investment, price, adaptation costs and number of plants installed are analyzed in detail. In the first case study, the generation planning to meet the RES target without considering REFM has been performed. This will provide the host country the necessary tools to assess whether to participate in the mechanism or not under different circumstances.

In this chapter, the models will be explained.

3.1 DESCRIPTION OF THE ELECTRICITY MARKET MODEL

The model used is an Electricity Market Model based on the Mixed Integer Linear Programming (from now on, MILP) prototype that is a modification of the one programmed by Javier García González, a researcher from the IIT[1].

The original one was first created with the aim of providing the system operator with the necessary tools to enable it to determine the optimal operating generation mix hourly, as well as the decisions to start-up and shut-off thermal units, so as to meet system demand at a minimum cost, bearing in mind long-term guidelines, maintaining a suitable level of reliability, and guaranteeing compliance with system constraints [33]. Also, the model provided the operating and marginal cost forecasting.

However, this one is modified to, being provided expansion costs of solar and wind production technologies, as well as the targets to be attained in a certain period of time, return when and how much to invest in these technologies. Another important modification is that now the GAMS programming program is relaxed. This means that the variables that usually could take just the values of 1 and 0, can now have intermediate values. This approach is valid for cases where generators are highly aggregated, like in this study case in which 13 generators have been used to model one fictitious country.

The code is provided in Anex I. Code for Model I.

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[1] Instituto de Investigación Tecnológica (https://www.iit.comillas.edu/)

3.1.1 MODEL ASSUMPTIONS

The most relevant model assumptions are:

- The temporal structure is divided into periods (p).
- The construction of a generator is expected to last one period, and it just can be performed in the first period.
- The grid is not included in the model (single node approach).
- Uncertainty is not considered (deterministic approach).
- Just solar and wind are considered as RES to simplify the model.

3.1.2 VARIABLES

Considering that the indexes are "t", for thermal units, "p" for hourly periods, "h" when referring to hydro river basin and "g" for generators, the variables of the model are defined below:

$d_p = system\ demand\ at\ central\ bus\ in\ period\ p\ [MW]$

$\overline{q_t}, \underline{q_t} = \ gross\ maximum\ and\ minimum\ power\ of\ the\ thermal\ units\ [MW]$

$k_t = in - house\ consumption\ factor\ [p.u]$

$\alpha_t = Linear\ term\ of\ the\ input - output\ curve\ [\frac{Th}{MWh}]$

$\beta_t = Fix\ term\ of\ the\ input - output\ curve\ [\frac{Th}{h}]$

$\gamma_t = \ Start - up\ fuel\ consumption\ [Th]$

$\theta_t = Shutdown\ fuel\ waste\ [Th]$

$f_t = Fuel\ price\ [€/kTh]$

$o_t = Operation\ \&\ Maintenance\ variable\ cost\ [\frac{€}{MWh}]$

$rs_t, rb_t = Ramp\ rate\ limits\ (up\ and\ down)\ \left[\frac{MW}{h}\right]$

$\overline{q_h}, \underline{q_h} = \ gross\ maximum\ and\ minimum\ power\ of\ the\ hydro\ units\ [MW]$

$\overline{w_h}, \underline{w_h} = \text{ maximum and minimum energy in the reservoir}[MW]$

$\overline{b_h} = \text{ maximum pumping power } [MW]$

$\eta_h = Efficiency\ of\ the\ pumping - turbine\ cycle\ [p.u]$

$i_{hp} = \ Natural\ inflows\ in\ period\ p\ [MWh]$

$k_h = In - house\ consumption\ factor\ [p.u]$

$flu_{hp} = Run - of - river\ generation\ in\ period\ p\ [MW]$

$q_p = Power\ generated\ in\ period\ p\ [MW]$

$q'_p = \ Power\ produced\ above\ the\ minimum\ stable\ load\ in\ p\ [MW]$

$u_p = Commitment\ state\ in\ p$

$y_p = Startup\ decision\ at\ the\ beginning\ of\ period\ p$

$z_p = Shutdown\ decision\ at\ the\ beginning\ of\ period\ p$

$q_{hp} = Power\ generated\ in\ period\ p\ [MW]$

$s_{hp} = Spillages\ in\ period\ p\ [MW]$

$b_{hp} = Pumping\ consumption\ in\ period\ p\ [MW]$

$w_{hp} = Energy\ storage\ in\ the\ reservoir\ at\ the\ end\ of\ period\ p\ [MWh]$

$c^{pns} = Non\ served\ energy\ cost\ [\frac{€}{MWh}]$

$wg_p = wind\ generation\ [MW]$

$sg_p = solar\ generation\ [MW]$

$pns_p = Non\ served\ energy\ [MW]$

$pwind_p = Power\ due\ to\ expansions\ of\ wind\ turbines\ [MW]$

$psolar_p = Power\ due\ to\ expansions\ of\ solar\ panels\ [MW]$

$XX_p = Accumulated\ number\ of\ wind\ units\ installed\ up\ to\ period\ p\ [-]$

$YY_p = Accumulated\ number\ of\ solar\ units\ installed\ up\ to\ period\ p\ [-]$

$c_{expw} = cost\ of\ expansion\ of\ wind\ units\ (investment\ cost)[€/plant]$

$c_{exps} = cost\ of\ expansion\ of\ solar\ units\ (investment\ cost)[€/plant]$

$datw_{exp} = capacity\ of\ each\ wind\ unit\ that\ it\ is\ installed\ [MW]$

$dats_{exp} = capacity\ of\ each\ solar\ unit\ that\ it\ is\ installed\ [MW]$

$capw_{exp} = capacity\ installed\ in\ the\ initial\ instant\ of\ wind\ turbines\ [MW]$

$caps_{exp} = capacity\ installed\ in\ the\ initial\ instant\ of\ solar\ units\ [MW]$

$P = percentage\ of\ generated\ energy\ that\ has\ to\ be\ renewable\ according\ to\ the\ EU\ 2030\ targets\ \ [-]$

3.1.3 OBJECTIVE FUNCTION

$$Min \sum_{p} [c^{pns} \cdot pns_p + \sum_{t} \left[f_t \cdot \left[\beta_t \cdot u_{tp} + \gamma_t \cdot y_{tp} + \theta_t \cdot z_{tp} + \alpha_t \cdot \frac{q_{tp}}{k_t} \right] + o_t \cdot \frac{q_{tp}}{k_t} \right] + c_{expw} \cdot XX_{pfin} + c_{exps} \cdot YY_{pfin} (0)$$

The objective function is represented in equation (0). It shows that the aim of the problem is to minimize the operational cost, including the penalization of the non-served energy, as well as the future investments made. The concept of "non-served power" is introduced to avoid potential infeasibilities and will be highly penalized in the objective function

3.1.4 CONSTRAINTS

The model is subject to the following constraints:

- **Supply-demand balance:** it must be satisfied in every period of the scheduling horizon

$$\sum_{t} q_{t,p} + \sum_{h} (q_{h,p} - b_{h,p}) + wg_p + sg_p + pns_p + \sum_{g} pwind_p + \sum_{g} psolar_p = d_p \quad (1)$$

- **Spinning reserve:** to maintain a reliable supply of electricity, provisions must be made to ensure a level of backup generation. The difference between the current level and the maximum output power is the spinning reserve.

$$\sum_{t} (u_{tp} \cdot k_t \cdot \overline{q_t} - q_{tp}) \geq rod_p \ \ (2)$$

- **Thermal units:** the power of a thermal unit is modelled as a minimum stable load plus an extra. That incremental power can only go from 0 to the difference from the maximum to the minimum thermal capacity

$$q_{tp} = u_{tp} \cdot k_t \cdot \underline{q_t} + q'_{tp} \quad (3)$$

$$q'_{tp} \leq u_{tp} \cdot k_t \cdot (\overline{q_t} - \underline{q_t}) \quad (4)$$

- **Maximum output power** (of thermal and hydro units, respectively)

$$q_{hp} \leq k_h \cdot \overline{q_h} \ (5)$$

$$b_{hp} \leq \overline{b_h} \quad (6)$$

- **The minimum load of the hydro-plants** is the run-of river production, and the pumping consumption cannot be negative.

$$q_{hp} \geq flu_{hp} \ (7)$$

$$b_{hp} \geq 0 \quad (8)$$

- **Water balance equations:** the existing water at the end of every period in the reservoir is what it is there at the end of the previous period minus what it has been decided to release and spill plus the energy pumped plus the inflows. w* refers to the water level at the end of the week.

$$w_{hp} = w_{h,p-1} - [q_{hp} + s_{hp} - \eta_h \cdot b_{hp}] + i_{hp} \quad (9)$$

$$w_{hp} \leq \overline{w_{hp}} \ (10)$$

$$w_{hp} \geq \underline{w_{hp}} \quad (11)$$

$$w_{hp} = w_h{}^* \quad (12) \quad \forall h, p = p_{168}$$

- **Logic coherence startup-commitment-shutdown:** the variable u_{tp} shows whether the unit is producing or not, y_{tp} shows that the plant has been turned on and z_{tp}, on the contrary, shows that the plant has been turned off. To guarantee the consistency between start-ups and shut downs, this equation is written

$$u_{t,p-1} = u_{tp} - y_{tp} + z_{tp} \quad (13)$$

- **Ramp rates:** These constraints, also known as load gradient constraints, limit the variations in power output in two consecutive periods. The ramping up constraint is formulated in equation (14) and the ramping down constraint in equation (15).

$$q'_{tp} - q'_{tp-1} \leq rs_t \quad (14)$$

$$q'_{t,p-1} - q'_{t,p} \leq rb_t \quad (15)$$

- **Expansion:** Restriction of the expansion in time: the units, if installed, can only be installed in period 1.

$$XX_{gp} = XX_{g(p-1)} \quad (16)$$

$$YY_{gp} = YY_{g(p-1)} \quad (17)$$

- **Production and expansion relationship:** relationship between the production and the accumulated expansions up to a period. It corresponds to a percentage of the total production to conserve the wind or solar dynamic of the existing generation.

$$pwind_p = \frac{datw_{exp}}{capw_{exp}} \cdot wg_p \cdot XX_p \quad (18)$$

$$psolar_p = \frac{dats_{exp}}{caps_{exp}} \cdot sg_p \cdot YY_p \quad (19)$$

- **Renewable energy target:** Equation that emulates the target set by the EU in 2030, that obliges that at least **30%** in gross final energy consumption of the EU has to come from RES. Because electricity accounts for just one third of final energy consumption [34] it could be assumed that for the EU to reach the target, more than 30% of the electricity demand must be generated by RES. This PERCENTAGE (P) will be defined after.

$$\sum_{p}(pwind_p + psolar_p + wg_p + sg_p + \sum_{h}(q_{h,p} - b_{h,p})) \geq P \cdot \sum_{p} d_p \ (20)$$

3.2 DESCRIPTION OF THE REFM MARKET MODEL

As it has been said in the beginning of this section, in the **second step,** we propose an approach to identify the lower percentage of share of the statistical benefits that produce a lower cost than calculated in the first step while obtaining the optimal mix capacity of renewable energy available for REFM projects and other fundings on host territory.

To do so, another model is programmed. There are just subtle differences between this model and the Electricity market model: new variables are added, and the objective function and the constraints are subtly modified.

The code is provided in Annex II. Code for Model II.

3.2.1 VARIABLES

The new variables of the model with respect to the electricity market model are defined below:

$$pcmsw_p = Power\ due\ to\ expansions\ of\ wind\ turbines\ by\ the\ contributing\ member\ states\ [MW]$$

$$pcmss_p = Power\ due\ to\ expansions\ of\ solar\ panels\ by\ the\ contributing\ member\ states\ [MW]$$

$$XX\_CMS_p = Accumulated\ number\ of\ wind\ units\ installed\ up\ to\ period\ p\ by\ contributing\ member\ states\ [$$

$$YY\_CMS_p = Accumulated\ number\ of\ solar\ units\ installed\ up\ to\ period\ p\ by\ contributing\ member\ states [$$

$$S = percentage\ of\ statistics\ that\ the\ host\ country\ will\ add\ to\ theirs\ [-]]$$

$$Acost = Cost\ to\ bear\ to\ adapt\ power\ plants\ intalled\ by\ the\ CMS\ to\ the\ grid\ [€/plant]$$

3.2.2 OBJECTIVE FUNCTION

$$Min \sum_p [c^{pns} \cdot pns_p + \sum_t \left[f_t \cdot \left[\beta_t \cdot u_{tp} + \gamma_t \cdot y_{tp} + \theta_t \cdot z_{tp} + \alpha_t \cdot \frac{q_{tp}}{k_t}\right] + o_t \cdot \frac{q_{tp}}{k_t}\right] + c_{expw} \cdot XX_{pfin} + c_{exps} \cdot YY_{pfin} + Acost \cdot (XX\_CMS_{pfin} + YY\_CMS_{pfin}) \quad (21)$$

The objective function is represented in equation (21). It shows that the aim of the problem is to minimize the operational cost, including the penalization of the non-served energy, as well as the future investments made. The greatest difference between this model and the first one, is that there is an adaptation cost considered to take into account the costs that the host-country will bear because of the installation of a renewable energy source from the contributing member State (See 2.5.3.2 Allocation of statistical benefits).

3.2.3 CONSTRAINTS

The complete REFM market model is shown in this section, for easy reference. The model is subject to some of the constraints of the prior model (equations 2 to 19), while some others that are modified (supply-demand balance equation – 22 and the renewable energy target equation – 27), and new ones that are included (equations from 23 to 26) added:

- **Supply-demand balance:** it must be satisfied in every period of the scheduling horizon

$$\sum_t q_{t,p} + \sum_h (q_{h,p} - b_{h,p}) + wg_p + sg_p + pns_p + \sum_g pwind_p + \sum_g psolar_p + \sum_g pcmsw_p + \sum_g pcmss_p = d_p \quad (22)$$

- **Spinning reserve:** to maintain a reliable supply of electricity, provisions must be made to ensure a level of backup generation. The difference between the current level and the maximum output power is the spinning reserve.

$$\sum_t \left(u_{tp} \cdot k_t \cdot \overline{q_t} - q_{tp}\right) \geq rod_p \quad (2)$$

- **Thermal units:** the power of a thermal unit is modelled as a minimum stable load plus an extra. That incremental power can only go from 0 to the difference from the maximum to the minimum thermal capacity

$$q_{tp} = u_{tp} \cdot k_t \cdot \underline{q_t} + q'_{tp} \quad (3)$$

$$q'_{tp} \leq u_{tp} \cdot k_t \cdot \left(\overline{q_t} - \underline{q_t}\right) \quad (4)$$

- **Maximum output power** (of thermal and hydro units, respectively)

$$q_{hp} \leq k_h \cdot \overline{q_h} \ (5)$$

$$b_{hp} \leq \overline{b_h} \quad (6)$$

- **The minimum load of the hydro-plants** is the run-of river production, and the pumping consumption cannot be negative.

$$q_{hp} \geq flu_{hp} \ (7)$$

$$b_{hp} \geq 0 \quad (8)$$

- **Water balance equations:** the existing water at the end of every period in the reservoir is what it is there at the end of the previous period minus what it has been decided to release and spill plus the energy pumped plus the inflows. w* refers to the water level at the end of the week.

$$w_{hp} = w_{h,p-1} - \left[q_{hp} + s_{hp} - \eta_h \cdot b_{hp}\right] + i_{hp} \quad (9)$$

$$w_{hp} \leq \overline{w_{hp}} \ (10)$$

$$w_{hp} \geq \underline{w_{hp}} \quad (11)$$

$$w_{hp} = {w_h}^* \quad (12)$$

- **Logic coherence startup-commitment-shutdown:**

$$u_{t,p-1} = u_{tp} - y_{tp} + z_{tp} \quad (13)$$

- **Ramp rates:**

$$q'_{tp} - q'_{tp-1} \leq rs_t \quad (14)$$

$$q'_{t,p-1} - q'_{t,p} \leq rb_t \quad (15)$$

- **Expansion:** Restriction of the expansion in time: the units, if installed, can only be installed in period 1.

$$XX_{gp} = XX_{g(p-1)} \quad (16)$$

$$YY_{gp} = YY_{g(p-1)} \quad (17)$$

$$XX\_CMS_{gp} = XX\_CMS_{g(p-1)} \quad (23)$$

$$YY\_CMS_{gp} = YY\_CMS_{g(p-1)} \quad (24)$$

- **Production and expansion relationship:** relationship between the production and the accumulated expansions up to a period. It corresponds to a percentage of the total production to conserve the wind or solar dynamic of the existing generation.

$$pwind_p = \frac{datw_{exp}}{capw_{exp}} \cdot wg_p \cdot XX_p \quad (18)$$

$$psolar_p = \frac{dats_{exp}}{caps_{exp}} \cdot sg_p \cdot YY_p \quad (19)$$

$$pcmsw_p = \frac{datw_{exp}}{capw_{exp}} \cdot wg_p \cdot XX\_CMS_p \quad (25)$$

$$pcmss_p = \frac{dats_{exp}}{caps_{exp}} \cdot sg_p \cdot YY\_CMS_p \quad (26)$$

- **Renewable energy target:** The target set by the EU in 2030 obliges that at least **30%** in gross final energy consumption of the EU has to come from RES. Because electricity accounts for just one third of final energy consumption [34] it could be assumed that for the EU to reach the target, at least 75% of the electricity demand must be generated by RES.

$$\sum_p (pwind_p + psolar_p + wg_p + sg_p + \sum_h (q_{h,p} - b_{h,p})) + S \cdot (pcmsw_p + pcmss_p)) \geq P \cdot \sum_p d_p \ (27)$$

Chapter 4. DISCUSSION

Up to this point, the issue studied has been described and the models that are going to be used to represent the scenarios have been presented. In this section, first the input data for the electricity market model is introduced. Then, the results of this first model will be explained. After, the REFM model initial data will be shown, and the cases will be described. Finally, the outcome will be analyzed. Therefore, the objective of this chapter is to describe the simulations performed and examine and compare the results obtained, to set the base of the conclusions of this thesis.

4.1 THE ELECTRICITY MARKET MODEL

The objective of this section is to present the input data of the case study, as well as the results of the Electricity Market Model. The obtained results will be contrasted with the results of the REFM Market Model.

4.1.1 INPUT DATA

Toy-Scenario

The input data for this scenario can be found in Table 2, Table 3 and Table 4.

Table 2. Initial parameters for the generators of the toy-scenario

Generator	α [MTh/GWh]	ß [MTh/h]	γ [MTh]	θ [MTh]	Rs [GW/h]	Rb [GW/h]	f [k€/MTh]	o [k€/GWh]	qmax [GW]	qmin [GW]
Nuclear	1	0	3	3	3.585	3.585	3.5	1.2	3.585	2
Lignite	3	0.015	2	0.2	0	0	8	2.4	0	0
Subbitumin	2.6	0.03	2	0.2	0.232875	0.232875	8.5	1.8	0.3845	0.0769
Bituminous	2.3	0.035	1.4	0.14	0.2176875	0.2176875	8	1.2	0.2455	0.0491
Anthracite	2.2	0.06	1.9	0.19	0.6226875	0.6226875	7	1.2	2	0.4
CCGT	1.3	0.09	1.1	0.11	0.334125	0.334125	20	1.2	13.125	2.5
Fueloil	2.1	0.08	0.07	0.007	0.6733125	0.6733125	23	1.2	2	0.4
Gas	2	0.09	0.11	0.011	0.405	0.405	20	2	0.5745	0.1149
Hydro reservoir					0	0			8.547	0
Hydro run-of-river					0	0			0	0
Hydro pump					0	0			1.6655	0
Wind					0	0			12.1112	0
Sun					0	0			9.27	0

Table 3. Initial data for the toy-scenario

Generator	uo [-]	mode [-]	bmax[GW]	wmax [GWh]	w0 [GWh]	wmin [GWh]	wfin [GWh]	k [-]	rend [-]
Nuclear	1	1						1	
Lignite	1	1						1	
Subbitumin	1	2						1	
Bituminous	1	2						1	
Anthracite	0	2						1	
CCGT	0	2						1	
Fueloil	1	3						1	
Gas	0	3						1	
Hydro reservoir			0.1	5000	3000	1000	2975	1	1
Hydro run-of-river								1	
Hydro pump			0.2	30	15	0	15	1	1
Wind	1	1							
Sun	0	1							

Table 4. Input costs and capacities for the model

Cost of unsupplied energy [€/MWh]	180
Cost of expansion (wind) [k€/plant]	1000
Cost of expansion (solar) [k€/plant]	1000
Capacity of each unit of wind generator [GW]	0.4
Capacity of each unit of solar generator [GW]	1
Installed capacity of wind energy in the initial instant [GW]	12.1112
Installed capacity of solar energy [GW]	9.27
PERCENTAGE [-]	0.75

Therefore, as it can be observed in Table 4, it costs the same to install a wind power plant as a solar power plant (1000k€/plant). However, a wind power plant will have 0.4GW of capacity (2500k€/GW), whereas a solar generation will have 1GW of capacity (1000k€/GW). Also, on average, a wind power plant gives 47% of its capacity, while a solar power plant gives 28.127% of its capacity, as at night there's no sun and the power delivered can't be greater than 0%.

The demand is plotted in Figure 6. It simulates an approximate or generic profile of what would be expected for a weekly demand given the dimensions of the generation. The initial wind and solar generation with the current power plants installed per period is plotted as well.

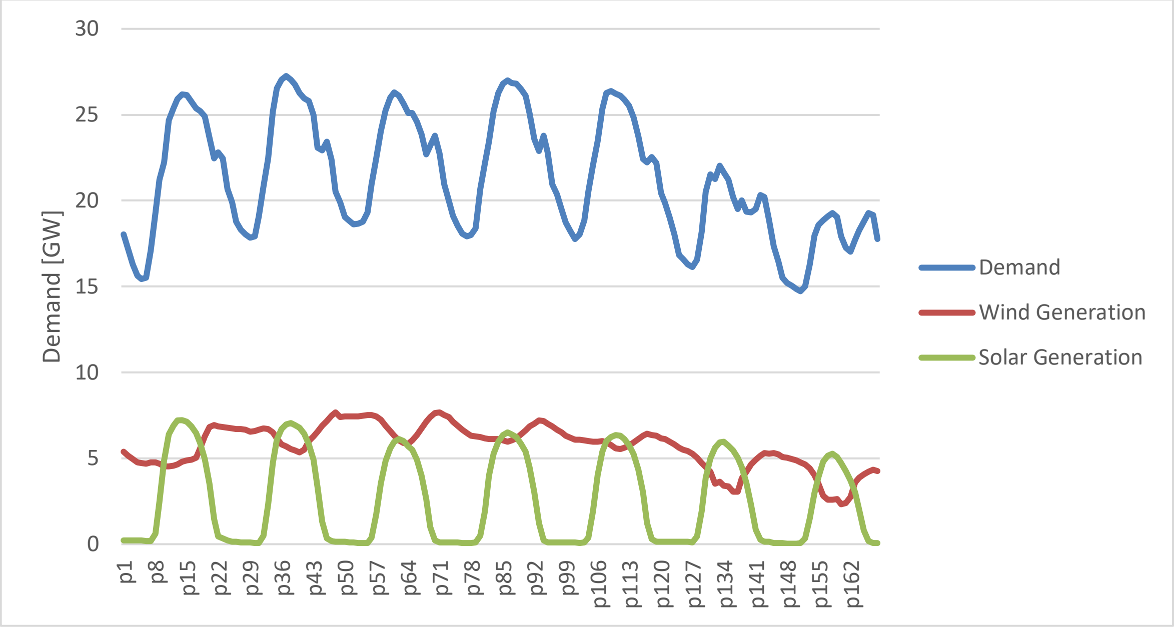

Figure 6. Solar and wind generation at the beginning and demand per period. [Source: own]

4.1.2 ANALYSIS OF THE RESULTS

With this data, the results for Model I are the following:

- Total wind power plants installed: 27
- Total solar power plants installed: 9
- Total investment cost: 36.000k€
- Total demand: 3573 GW
- Renewable generation: 2680.698 (Just exactly 75%, the minimum possible to comply with the EU requirement)
- Value of the objective function: 44404.1k€

The final renewable generation vs. the renewable generation already set before executing the program is plotted in Figure 7. It can be seen that the generation of the new plants installed maintain the dynamic of the existing generation.

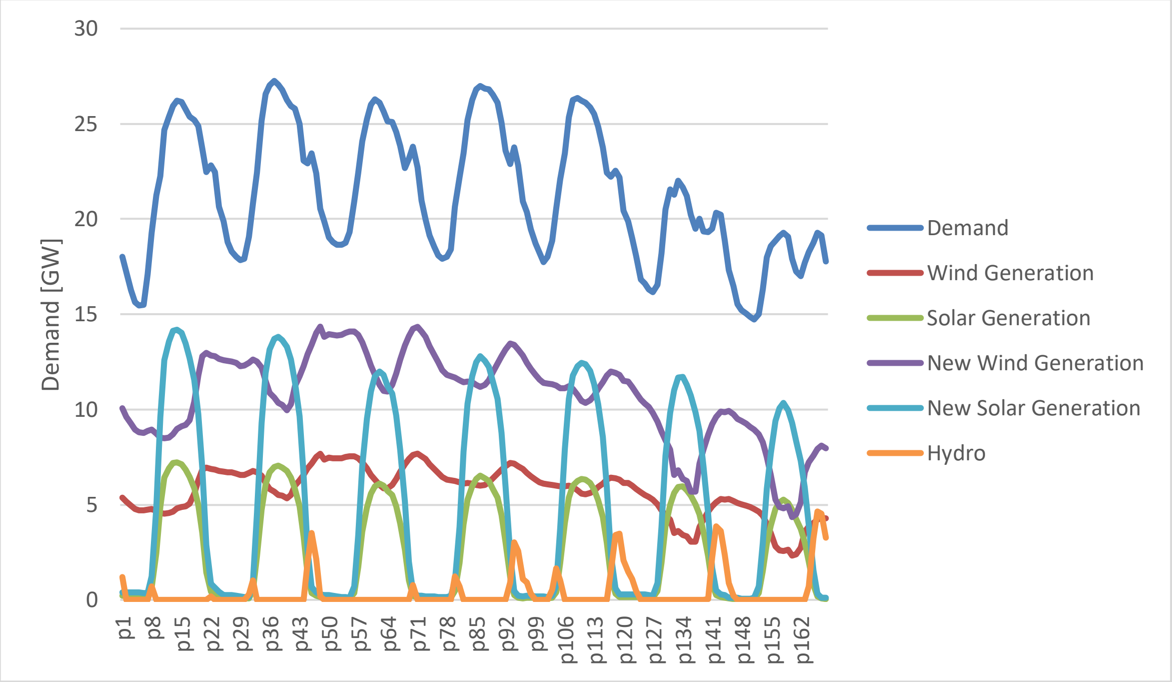

Figure 7. Old and new renewable generation [Source: own]

This solution makes sense. First, this is the price to generate one GW with each technology is gathered in Table 5:

Table 5. Generation Price of each thermal technology

	Price to generate (k€)	**Price to start-up (k€)**	**Price to shut-down (k€)**
Nuclear	4.7	10.5	10.5
Subbitumin	26.52	16	1.6
Bituminous	19.88	11.2	1.12
Anthracite	17.02	13.3	1.33
CCGT	29	22	2.2
Fueloil	51.34	1.61	0.161
Gas	43.8	2.2	0.22

Hydro sources and wind and solar are for free, as they are renewable energy sources.

In the first period, the demand is **18.03GW**. There is minimum production with the thermal productions and a margin to produce above the minimum in the first period as there is a ramp to increase production. Also, there is a maximum production and a margin to reduce that production. The composition of the generation in this first period is depicted in Table 6.

Table 6. Production of each technology in the first period

	PRODUCTION (GW)	**MINIMUM PRODUCTION (GW)**	**MAXIMUM PRODUCTION (GW)**
NUCLEAR	3.585	2	3.585
SUBBITUMIN	0.3098	0.0769	0.3845
BITUMINOUS	0.2455	0.0491	0.2455
ANTHRACITE	1.0229	0.4	2
CCGT	1.2899	2.5	13.125
FUELOIL		0.4	2
GAS		0.1149	0.5745
HYDRO_RES	0		8.547
HYDRO_PUM	1.2104		1.6655
WIND	5.38304		12.1112
SOLAR	0.20284		9.27

The nuclear power plant has to produce at least 2GW, and at most 3.585GW, so its production will just vary in 1.585GW at most. However, being the cheapest thermal technology to produce with, the production will always tend to be closer to the maximum. The wind and the solar will be used the maximum that it is possible at each period, as it is free, but there are not renewable energy sources always. This is due to the fact that the new capacities must still follow the dynamics of the existing resources and that the value is never 100% of what is installed. For instance, in the first period it just can be used 44% of the maximum capacity installed of wind and 2.1% of the maximum capacity installed of solar. The hydro plants will produce the maximum possible that they can, considering that there are reservoir limits and constraints that they have to fulfill.

Regarding the thermal power plants, Anthracite is the cheapest, but in the first period is turned-off, so to starting it up and generating, ends up being most costly than generating with other technologies. Bituminous is the cheapest then, so the maximum power installed is produced with bituminous. Subbituminous is the next cheapest one: the maximum power is not produced as there is a ramp limit that limits its increase: it just can produce 0.2328GW above the minimum, and that is exactly the output. That being said, with the wind, the solar, the nuclear, the anthracite, the subbituminous, the bituminous and the hydro plants the generation sums 11.9594GW. There are 6.07GW to satisfy yet.

It must be remembered that for every solar plant and wind plant that is installed, there is a compulsory power that they will deliver, depending on the amount of sun and wind that there is at that time, respectively. For example, each wind unit installed will generate exactly 0.177 GWh (44% of 0.4GW installed) in the first period, and each solar unit installed will generate 0.021 GWh (2.1% of 1GW installed): solar and wind generation are not manageable.

So, the options to satisfy the demand left are:

- Producing those 6.07GW with CCGT costs 22k€ to turn up and 176.03k€ to produce, totalizing 198.03k€.
- Producing those 6.07GW with gas costs 2.2k€ to turn up but it just can produce 0.5745 GW.
- To generate 6.07GW with wind you have to install 35 wind power plants = 35,000k€
- To generate 6.07GW with solar you have to install 289.5 solar power plants = 289,500k€

Of course, the cheapest to produce them with CCGT, but, on the one hand, the installation of the plant will save costs later and, on the other hand, there is a target to fulfil.

Considering those facts and taking into consideration that the goal is to minimize the total cost for the system, the wisest decision that the model has considered is to install 27 wind power plants and 9 solar power plants, generating 1.2899 GW with CCGTs.

For other periods, the analysis is similar, but particular for every hour as all the constraints need to be satisfied in every period of time. In the end, the goal is to reduce the total system cost but fulfilling all the restrictions. The marginal cost in each period is plotted in Figure 8.

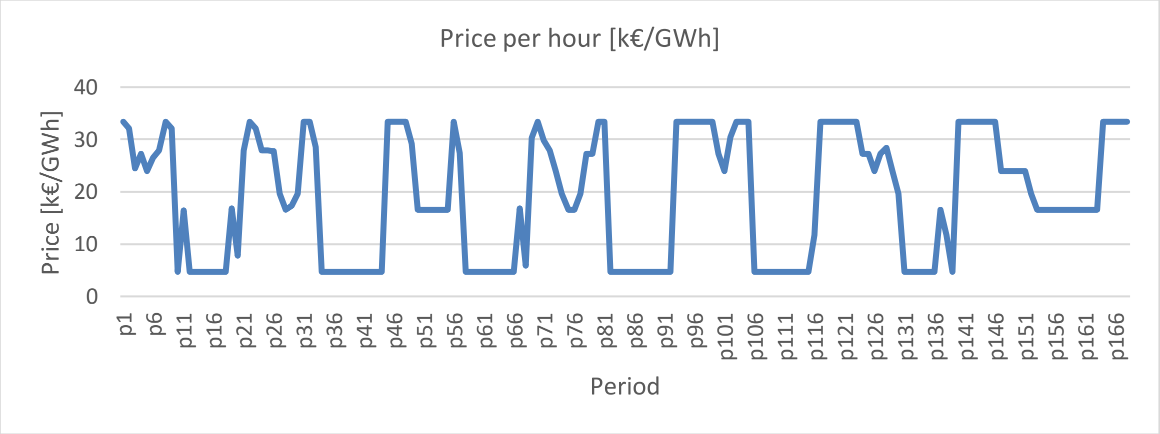

Figure 8. Price per hour [k€/GWh]

Multiplying the hourly price by the generation and assuming that producing it is free, a new wind producer will make 16141k€ along the week and a new solar energy producer will make 3772k€ along the week in this scenario. The investment made was 27000k€ for the new wind energy producer and 9000k€ for the new solar energy producer. Therefore:

- Profit for the new wind energy producer: -10,859k€
- Profit for the new solar energy producer: -5,228k€

Therefore, without considering time-value of money, they will need 2 weeks to breakeven. Also, last but not least, the profit that both the wind energy producer and the solar energy producer that already existed would be calculated.

- Profit for an already existent wind energy producer: 18,547k€
- Profit for an already existent solar energy producer: 3,910k€

4.2 THE REFM MARKET MODEL

The objective of this section is to observe the results of the REFM Market Model: they will exhibit the propitious scenarios for a Host Country to participate in the REFM regarding the percentage of renewable awarded to the Host Country and on the adaptation costs.

4.2.1 INPUT DATA

The input data is the same as in section 4.1.1 Input Data. There have been 21 cases conducted that will depend on the percentage of renewable awarded to the host country and on the adaptation cost.

For the percentage, three values have been studied: 20%, 50%, and 80%. The costs vary between 0 to 1000k€ (which is the investment cost of one wind or solar plant) in jumps of 50k€ each. The lower ones will represent low-cost adaptation scenario and the higher ones high-cost adaptation scenario.

This analysis is meant to discover, which integration cost should be the limit to stop accepting participating in the REFM.

4.2.2 ANALYSIS OF THE RESULTS

For the case studied without the REFM (See Section

4.1.2 Analysis of the Results) the results were the ones shown in Table 7: The host country would install 27 wind power plants and 9 solar power plants (totalizing 36 power plants), the objective function would result in 44404 k€ and the average marginal cost would be 18.954k€/GWh. Also, to the plants already installed, the profit for the solar power producer would be 3910k€ and for the wind power producer 18547k€.

Table 7. Results of the Electricity Market Model without REFM (in k€)

Wind plants HC	Solar plants HC	Wind plants CMS	Solar plants CMS	Tot Wind and Solar plants	Obj func	Average marginal cost	Profit for solar producer	Profit for wind producer
26.3516	8.9432	0	0	35.2948	44404	18.954	3910.114	18547.117

Now, let us see what happens when the REFM is established with the percentage of RES statistic of 20% (Remember this would mean that the Host Country would receive 20% of statistic share of what is being installed in its own country).

4.2.2.1 Results if the percentage of share of RES statistics is 20%

The results when the percentage of share statistic is 20% are shown in Table 8.

Table 8. Results if the percentage of share of statistics is 20%

PERCENTAGE 20%	Wind plants HC	Solar plants HC	Wind plants CMS	Total RES by HC	Total RES	Obj func	Marginal Cost	Profit for solar producer	Profit for wind producer
0	28.96	5.96	9.21	34.92	44.13	39374	12.91	398.90	606.09
50	28.96	5.96	9.21	34.92	44.13	39835	12.91	398.90	606.09
100	28.96	5.96	9.21	34.92	44.13	40296	12.91	398.90	606.09
150	28.60	6.24	8.94	34.84	43.78	40752	12.83	396.36	602.24
200	27.99	6.71	8.46	34.70	43.16	41188	13.01	402.17	611.07
250	27.62	6.99	8.18	34.62	42.80	41603	13.31	411.26	624.87
300	27.20	7.33	7.85	34.52	42.37	42001	13.56	418.92	636.52
350	26.96	7.51	7.67	34.47	42.14	42387	14.10	435.58	661.83
400	26.82	7.62	7.56	34.44	41.99	42768	14.62	451.90	686.62
450	26.13	8.15	7.03	34.28	41.31	43131	14.78	456.59	693.76
500	25.88	8.35	6.83	34.22	41.05	43477	15.50	479.00	727.80
550	25.69	8.54	6.35	34.23	40.57	43812	15.68	484.47	736.11
600	25.36	8.87	5.47	34.24	39.70	44104	16.47	508.97	773.35
650	25.00	9.41	3.29	34.41	37.70	44335	17.32	535.36	813.45
700	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
750	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
800	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
850	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
900	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
950	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
1000	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84

The first issue to notice is that, apart from the RES percentage of share of statistics, the cost that it takes to adapt the grid to account for the new installed plants is a determining variable. Figure 9 shows how the power plants installed vary depending on the adaptation costs of the grid. Remember that HC are the initials for Host-Country and CMS for Contributing Member State.

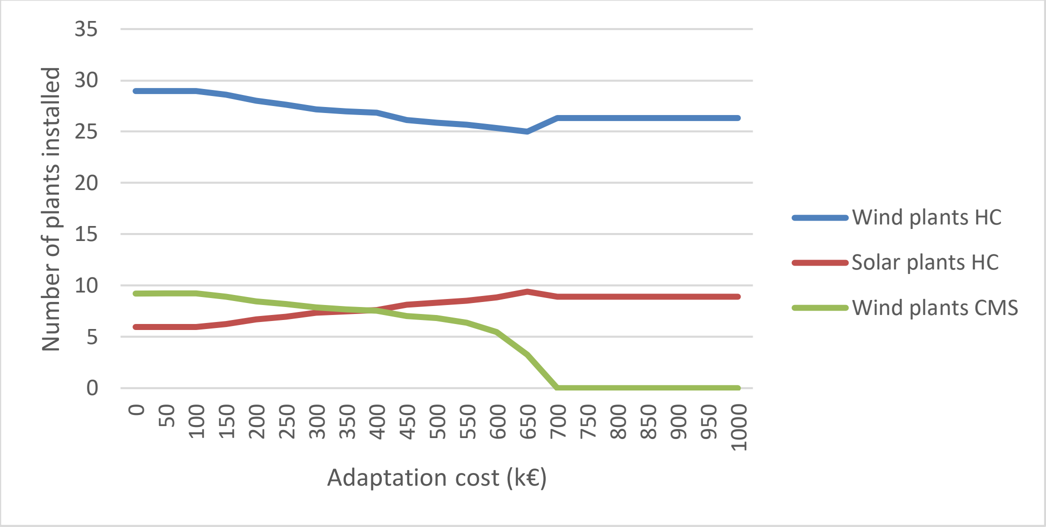

Figure 9. Number of plants installed (and typology) variation with the adaptation cost (k€)

If the mechanism is applied and there are no adaptation costs to bear, **the host country will start installing fewer power plants than before** (34.92 now vs. 35.29 in the no-REFM case), whereas **the total number of the RES will increase** (44.1406 now vs. 35.29 in the no-REFM case). This is because the RES investment is free for the host-country (it is paid by the contributing member state) and provides free energy, so it will be useful to lower the objective function result, that is, the total cost for the system. Therefore, if the contributing member state invests, the host country should invest in fewer plants. Additionally, since this investment is cost-free for the host and benefits the system by reducing the objective function, more renewables will be installed. However, of course, **as external investment is reduced, host investment must be increased to meet the target.** Moreover, there was no investment in solar power plants from the CMS. This is because of the generation curve that solar power plants contribute to: It has high peaks during the day compared with the lows at night. Then, as for the demand equation contributes with a 100% of generation and for the targets equation the contribution is just 20% of the total generation, if there is investment from the CMS, it is easy to get over the demand considering the rest of the restrictions (such as minimum generation, for example).

Also, it should be noted that **the more costs the system has to bear to adapt the new plants to the grid, the less RES will be installed as a whole.** This is also simple to understand: if a cost has to be assumed, then it is increasing the objective function, so it is better not to take it as it just contributes to the statistics a 20% of what it is installed. The higher the cost, the greater the potential objective function, so the decision that is taken is not to invest.

As well, **the objective function increases as the integration costs do, and so does the average marginal cost and the profit for the producers.** The higher the costs, the higher the objective function, the lower the renewables installed, the higher the average marginal costs (as the RES were used to lower these prices), and thus **the higher the profit for the producers,** that will obtain as profit the energy generated times the marginal cost.

Moreover, it is worth noticing that **the mechanism is not used when the grid costs are equal or higher than 700k€**. If this is the case, it is better to invest 1000k€ and obtain a 100% of RES statistics than to spend 650k€ to adapt the grid and obtain just a 20% of RES statistics. Of course, **the last results from 700k€ to 1000k€ are the same as the case without the REFM** (highlighted in green in Table 8) as it accounts for the minimum possible plants installed to comply with the UE requirements. This means that the tendency is to install just the required capacity. Rows from 700k€ to 1000k€ in Table 8 are the same results as in Table 7.

Finally, **the number of plants installed is unaffected between costs from 0 to 100k€** (although the average marginal cost and the objective function do change). Then the decision to participate would be based on whether the belief if the profit for the producers is sufficient. If the cost stands from 0 to 100k€, the maximum number of total renewables that the model, with the rest of its constraints, can sustain rise, which is 44.1316GW (highlighted in blue in Table 8).

4.2.2.2 Results if the percentage of share of RES statistics is 50%

The results, when the percentage of share statistics is 50%, are shown in Table 9.

Table 9. Results if the percentage of share of statistics is 50%

PERCENTAGE 50%	Wind plants HC	Solar plants HC	Wind plants CMS	Total RES by HC	Total RES	Obj func.	Marginal Cost	Profit for solar producer	Profit for wind producer
0	23.43	5.96	14.74	29.39	44.13	33848	12.91	398.90	606.09
50	23.43	5.96	14.74	29.39	44.13	34585	12.91	398.90	606.09
100	23.43	5.96	14.74	29.39	44.13	35322	12.91	398.90	606.09
150	23.43	5.96	14.74	29.39	44.13	36059	12.91	398.90	606.09
200	23.43	5.96	14.74	29.39	44.13	36796	12.91	398.90	606.09
250	23.43	5.96	14.74	29.39	44.13	37532	12.91	398.90	606.09
300	23.43	5.96	14.74	29.39	44.13	38269	12.91	398.90	606.09
350	23.43	5.96	14.74	29.39	44.13	39006	12.91	398.90	606.09
400	23.43	5.96	14.74	29.39	44.13	39743	12.91	398.90	606.09
450	23.43	5.96	14.74	29.39	44.13	40480	12.91	398.90	606.09
500	22.91	6.71	13.54	29.62	43.16	41188	13.01	402.17	611.07
550	22.53	7.27	12.64	29.80	42.44	41843	13.39	413.70	628.58
600	22.36	7.51	12.26	29.87	42.13	42463	14.10	435.58	661.83
650	21.96	8.09	11.34	30.05	41.38	43060	14.89	459.99	698.92
700	21.76	8.38	10.87	30.14	41.01	43613	15.12	467.25	709.96
750	22.08	8.87	8.75	30.95	39.70	44104	16.47	508.97	773.35
800	25.61	9.01	1.29	34.62	35.91	44400	18.63	575.66	874.67
850	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
900	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
950	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
1000	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84

The results and conclusions are almost the same as in the previous section (See 4.2.2.1 Results if the percentage of share of RES statistics is 20%). The tendency and the reasoning still apply, but the sensitivity and figures change:

- The more costs the system must bear to adapt the new plants to the grid, the less RES will be installed as a whole.
- There was no investment in solar plants from the CMS.
- The objective function increases as the integration costs do, and so does the average marginal cost and the profit for the producer. Thus, the higher the profit for the producers.
- The mechanism is not used when the grid costs are equal or higher than 850k€. The last results from 850k€ to 1000k€ are the same as the case without the REFM, that is, the same as in Table 7 (highlighted in green in Table 9)
- The number of plants installed is unaffected between costs from 0 to 450k€, and accounts for the maximum total renewable installation possible: 44.1316GW (highlighted in blue in Table 9)
- There are negative profits for producers when negative prices arise.

- To take the investment decision it should be considered that the producers of the country would not be making enough money and hence they would perhaps prefer to turn off their plants and not generate. Then, there could be other support mechanisms needed, such as those seen in Chapter 2 like feed-in tariffs, feed-in premiums, green certificates, or grants.
- It is also worth noticing that the minimum number of solar plants installed is 5.961 (as in the previous case). This is because the profile that solar generation contributes fits with the peaks of the demand profile. This means that 5.961 will certainly account for the peaks and it will be easy then to generate with other groups that have a low capacity to ramp up and down their generation. Then, of course, more solar is installed if the Contributing Member State investment is lower, but the necessary to account for the peaks is 5.961 solar plants.

Let us understand the differences, starting with Figure 10.

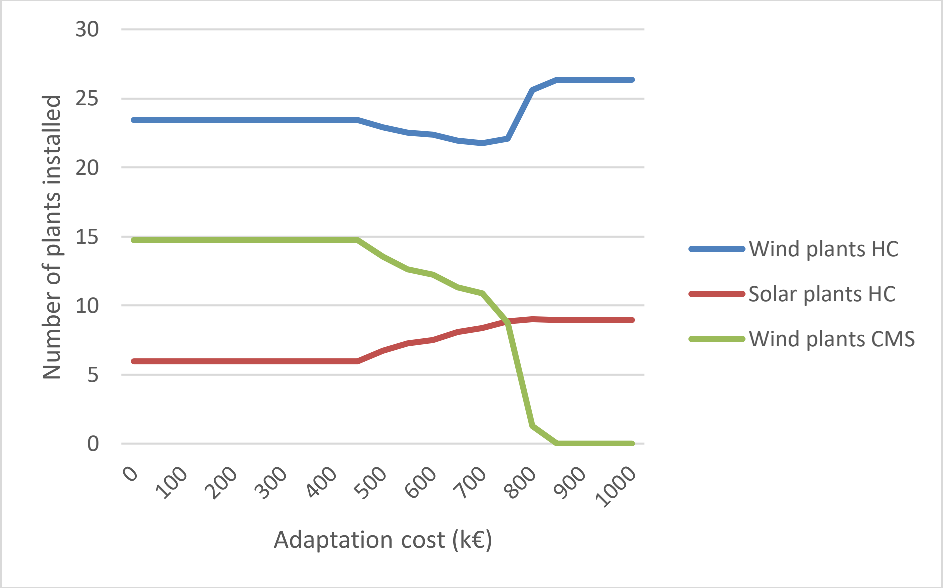

Figure 10. Number of plants installed (and typology) variation with the adaptation cost (k€)

There are three main differences:

The first one is that **the higher the percentage of RES statistics**, **the lower the sensitivity to prices in terms of plants installed when adaptation costs are low** that is, in number of plants installed (not in average marginal cost nor in objective function result) the number of these would remain constant for a longer period of cost variation. This is due to the fact that, as 50% of RES statistic is being received, it is worth to bear integration costs.

The second one is that **the greater the percentage of RES statistics, the more that it is worth for the host-country to participate in the mechanism**. This means that only when the integration cost is equal or greater than 850k€, it is not worth participating.

Finally, the third one is that **the higher the percentage, the great number of power plants installed by the Contributing Member State to the detriment of the ones installed by the Host Country.** The mechanism will award the Host country with half of the statistics, with just bearing a lower percentage of costs, so foreign investment is more than welcomed.

4.2.2.3 Results if the percentage of share of RES statistics is 80%

The results when the percentage of share statistic is 80% are shown in Table 10. Note that this case is extreme, as it is probable that the Contributing Member State would rather invest in his own country rather than just be awarded with 20% of the statics if the whole investment has been made by him. However, this evaluation is out of the scope of this thesis as just the host-country perspective is being studied.

Table 10. Results if the percentage of share of statistics is 80%

PERCENTAGE 80%	Wind plants HC	Solar plants HC	Wind plants CMS	Total RES by HC	Total RES	Obj func.	Marginal Cost	Profit for solar producer	Profit for wind producer
0	1.33	5.96	36.84	7.29	44.13	11743	12.91	398.90	606.09
50	1.33	5.96	36.84	7.29	44.13	13586	12.91	398.90	606.09
100	1.33	5.96	36.84	7.29	44.13	15428	12.91	398.90	606.09
150	1.33	5.96	36.84	7.29	44.13	17270	12.91	398.90	606.09
200	1.33	5.96	36.84	7.29	44.13	19111	12.91	398.90	606.09
250	1.33	5.96	36.84	7.29	44.13	20954	12.91	398.90	606.09
300	1.33	5.96	36.84	7.29	44.13	22796	12.91	398.90	606.09
350	1.33	5.96	36.84	7.29	44.13	24638	12.91	398.90	606.09
400	1.33	5.96	36.84	7.29	44.13	26480	12.91	398.90	606.09
450	1.33	5.96	36.84	7.29	44.13	28322	12.91	398.90	606.09
500	1.33	5.96	36.84	7.29	44.13	30164	12.91	398.90	606.09
550	1.33	5.96	36.84	7.29	44.13	32006	12.91	398.90	606.09
600	1.33	5.96	36.84	7.29	44.13	33848	12.91	398.90	606.09
650	1.33	5.96	36.84	7.29	44.13	35690	12.91	398.90	606.09
700	1.33	5.96	36.84	7.29	44.13	37532	12.91	398.90	606.09
750	1.33	5.96	36.84	7.29	44.13	39374	12.91	398.90	606.09
800	2.61	6.71	33.85	9.32	43.16	41118	13.01	402.17	611.07
850	4.15	7.62	30.23	11.77	41.99	42768	14.62	451.90	686.62
900	8.96	8.87	21.87	17.83	39.70	44104	16.47	508.97	773.35
950	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84
1000	26.35	8.94	0.00	35.29	35.29	44404	18.95	585.64	889.84

The results and conclusions are almost the same as in the previous section (See 4.2.2.2 Results if the percentage of share of RES statistics is 50%). The tendency and the reasoning still apply, but the sensitivity and figures change:

- The more costs the system has to bear to adapt the new plants to the grid, the less RES will be installed as a whole.
- There was no investment in solar plants from the CMS.
- The objective function increases as the integration costs do, and so does the average marginal cost and the profit for the producer. Thus, the higher the profit for the producers.
- The mechanism is not used when the grid costs are equal or higher than 950k€. The last results from 950k€ to 1000k€ are the same as the case without the REFM, that is, the same as in Table 7 (highlighted in green in Table 10).

- The number of plants installed is unaffected between costs from 0 to 750k€, and accounts for the maximum total renewable installation possible: 44.1316GW (highlighted in blue in Table 10).
- To take the investment decision you should consider that the producers of your country would be not making enough money and hence they would perhaps not generate. Then, there could be other support mechanisms needed.
- It is also worth noticing that the minimum number of solar plants installed is 5.961 (as in the other cases). This is because the profile that the solar generation contributes fits with the peaks of the demand profile. This means that 5.961 will for sure account for the peaks and it will be easy then to generate with other groups that have a low capacity to ramp-up and down their generation. Then, of course, more solar is installed if the Contributing Member State investment is lower, but the necessary to account for the peaks is 5.961 solar plants.

Figure 11 illustrates the same conclusions as in the previous section (See 4.2.2.2 Results if the percentage of share of RES statistics is 50%) but more exaggerated. It can be seen that with a percentage of 80% and a cost of 750k€, 37 plants would be installed by the CMS and 8 by the Host Country, whereas if the cost increases to 950k€, the mechanism will not be used and thus 0 plants would be installed by the CMS.

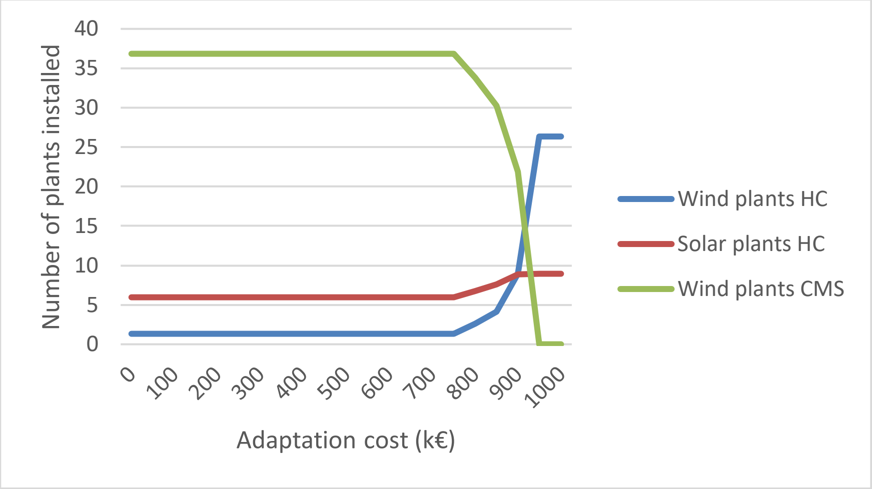

Figure 11. Number of plants installed (and typology) variation with the adaptation cost (k€)

4.2.2.4 General Differences between cases

Finally, Figure 12, that compares the objective function between the three cases studied and Figure 13, that compare the average marginal cost (and thus the profit for the producers), are analyzed, as there is a direct relationship between them.

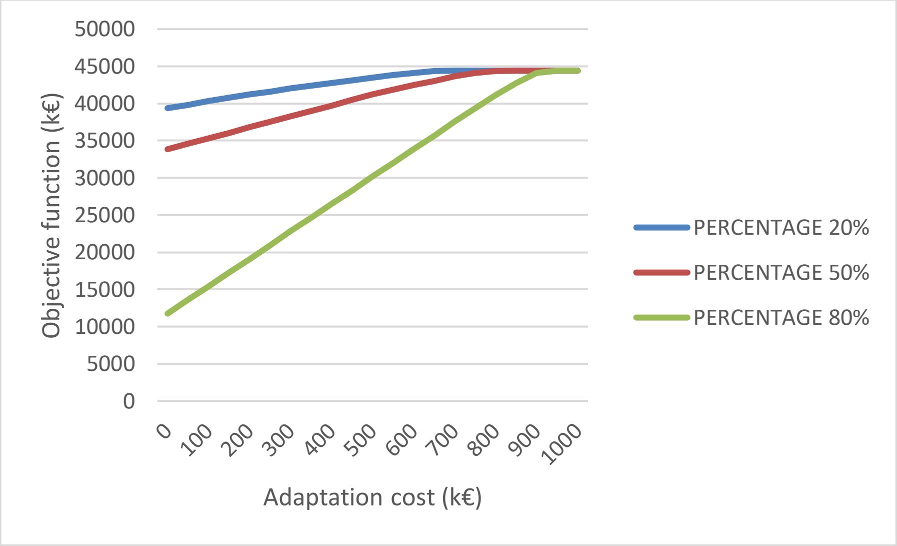

Figure 12. Comparison of the objective function result of the three case studies.

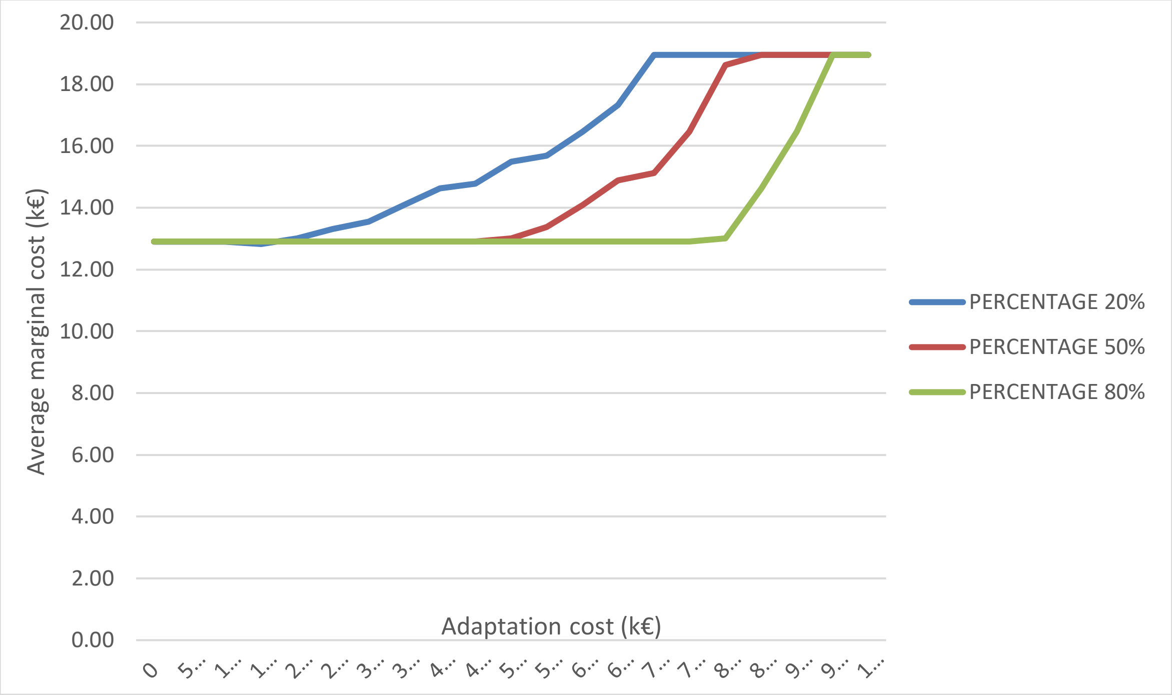

Figure 13. Comparison of the average marginal cost of the three case studies.

The higher the percentage, the lower the objective function result because there are more Contributing Member State power plants installed (and their investment cost is 0). Also, the higher the percentage, the lower the average marginal cost because there are more renewables installed. For instance, for an adaptation cost of 600k€, there are 39.70 plants installed in the 20% scenario, 42.13 plants in the 50% scenario and 44.13 plants installed in the 80% scenario. Therefore, in the one that there are more plants installed (80% in this case), the marginal cost is lower.

Chapter 5. CONCLUSIONS

This thesis has presented a methodology for identifying favorable scenarios for a Member State acting as a Host Country in the Renewable Energy Financial Mechanism (REFM).

The novelty of this study lies in its exploration of the host country's participation convenience, a topic that, to the author best knowledge, has not been previously addressed due to the recent introduction of the REFM Regulation in 2020.

The case study presented in this thesis serves as an example, focusing on a specific toy-case scenario with predefined demand and energy mix parameters. It is important to note that the conclusions drawn from this particular case study may not be directly applicable to other combinations of input parameters. However, the methodology itself can be generalized and utilized by interested parties to make informed decisions regarding their participation in the mechanism.

Above all, this thesis has revealed that the two necessary variables to be considered in the design of the mechanism are the percentage of statistics and the adaptation costs, as these affect the average marginal costs, so the profits obtained by the participants will be influenced mostly by this metrics. Mainly, this thesis highlights the importance of including the adaptation costs in the design of the REFM, as they can affect in a great extent the decision of a Host Country to participate or not in the mechanism.

Specifically, the case study revealed that for a percentage of 20%, the range of adaptation costs that the host country should be prepared to bear ranges from 0k€ to 650k€. If the costs exceed 700k€, it is not advisable for the host country to participate in the REFM. It is noteworthy that there is a general inclination to refrain from utilizing the mechanism if the adaptation costs are high. Nevertheless, the tolerance for higher adaptation costs increases as the percentage awarded to the Host Country in the statistics grows, indicating a willingness to bear the expenses due to the costless nature of the investment and the greater statistical impact.

For instance, if the adaptation costs are 650k€ and the percentage is 20%, a solar power producer would receive 535.36k€, while a wind power producer would receive 813.45k€. In the case of a 1000k€ investment, both producers would require a two-year period to recover their investments, or alternative mechanisms supporting renewable energy should be considered.

In conclusion, the methodology presented in this thesis offers valuable insights and guidelines for host countries considering participation in the REFM, enabling them to assess the convenience of their involvement based on specific parameters and considerations, like the percentage of the associated renewable production statistics to meet its own renewable energy targets, and the adaptation costs incurred in the mechanism. By employing this methodology, stakeholders can make informed decisions and navigate the complex landscape of renewable energy financing more effectively.

5.1 FUTURE WORKS

Finally, this thesis could be further developed, as there had been details that could be added to the model:

- The analysis that has been conducted considers fixed costs (one that is low and another that is high) varying the percentage of statistics that the host country will receive if a CMS installs a RES in their country. Future analysis could be performed the other way around: fixing the percentage and calculating which is the highest integration cost the host-country can bear for the statistic to be acceptable.

- The analysis that has been conducted does not consider the exhaustion of natural resources. Future works could do so.

- The analysis that has been conducted just considers a spring-week demand. Future analysis could vary the demand to see if this reasoning still applies.

- The analysis that has been conducted just considers a particular energy mix. Future analysis could vary this energy mix to see if this reasoning still applies.

- This mechanism could come to favor some technologies over others. Future works could propose the need to include in the design of REFM strategies that allow the different technologies to be involved in the mechanism appropriately, that is, taking into account whether you want to incentivize a particular technology or if you want to incentivize a balanced development of different technologies with the mechanism.

As well, it may be noted that this thesis considerates the Host-Country perspective, while the Contributing Member State might have the opposite perspective. For instance, the greater the percentage of statistics awarded to the Host-Country, the greater the willingness for the Host-Country to participate, but the lesser the desire for the Contributing Member State to do so. Another thesis could be initiated with these conclusions to study what is the probability of the Contributing Member State accepting the conditions that the Host-Country find acceptable.

Chapter 6. REFERENCES

[1] IEA (2022), Electricity Market Report - January 2022, IEA, Paris https://www.iea.org/reports/electricity-market-report-january-2022

[2] IEA (2021), World Energy Outlook 2021, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2021

[3] United Nations Climate Change (2022), The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[4] The world bank (2021), Total Population. https://datos.bancomundial.org/indicator/SP.POP.TOTL

[5] BP (2021) - Statistical Review of World Energy 2021 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

[6] OPEC Oil Reserves (2022) - https://www.opec.org/opec_web/en/data_graphs/330.htm

[7] Narasolar (2022) - ¿Qué es la dependencia energética? https://www.narasolar.com/dependencia-energetica-que-es-como-influyen-las-renovables/#:~:text=La%20dependencia%20energ%C3%A9tica%20puede%20definirse,la%20energ%C3%ADa%20que%20este%20consume.

[8] Samuel C. Hunington et al. (2016) - Revisiting Support Policies for RES-E Adulthood: Towards Market Compatible Schemes.

[9] European Commission. Agreement on Statistical Transfers of Renewable Energy Amounts between Lithuania and Luxembourg. 2017. Available online: https://europa.eu/!jF73gU (accessed on 05 February 2023).

[10] Renewable Energy Cooperation in Europe: What Next? Drivers and Barriers to the Use of Cooperation Mechanisms

[11] COMMISSION IMPLEMENTING REGULATION (EU) 2020/1294 of 15 September 2020 on the Union renewable energy financing mechanism

[12] European Commission. EU renewable energy financing mechanism. Available online: https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-renewable-energy-financing-mechanism_en (accesed on 05 February 2023)

[13] Von Blücher, F., Gephart, M., Wigand, F., & Resch, G. (2020). The new renewable energy financing mechanism of the EU in practice. A cooperation case study. Deliverable D6, 3.

[14] CEER (2021) - Status Review of Renewable Support Schemes in Europe for 2018 and 2019. Ref: C20-RES-69-04 https://www.ceer.eu/documents/104400/-/-/ffe624d4-8fbb-ff3b-7b4b-1f637f42070a

[15] Menanteau, P.; Finon, D.; Lamy, M. (2003). "Prices versus quantities: choosing policies for promoting the development of renewable energy." Energy Policy, (31, 8); pp. 799–812.

[16] Klein, A.; Pfluger, B.; Held, A.; Ragwitz, M.; Resch, G. (Fraunhofer ISI) (2008). Evaluation of Different Feed-in Tariff Design Options: Best Practice Paper for the International Feed-in Cooperation, 2nd Edition. Berlin, Germany: BMU. October 2008.

[17] NREL (2010) A Policymaker's Guide to Feed-in Tariff Policy Design https://www.nrel.gov/docs/fy10osti/44849.pdf

[18] Langniss, O.; Diekmann, J.; Lehr, U. (2009). "Advanced Mechanisms for the Promotion of Renewable Energy: Models for the Future Evolution of the German Renewable Energy Act," Energy Policy, (37, 4); pp.1289-1297.

[19] Kenton, W, Estevez, E. (2021) What is a Feed-in Tariff? https://www.investopedia.com/terms/f/feed-in-tariff.asp#:~:text=A%20feed%2Din%20tariff%20(FIT)%20is%20a%20policy%20designed,notably%20in%20Germany%20and%20Japan.

[20] IEA (2008). Deploying Renewables: Principles for Effective Policies, ISBN 978-92-64-04220-9.

[21] de Jager, D.; Rathmann, M. (2008). Policy Instrument Design to Reduce Financing Costs in Renewable Energy Technology Projects. Work performed by ECOFYS, Ultrecht, The Netherlands. Paris, France: International Energy Agency – Renewable Energy Technology Deployment. Accessed March 9, 2009, at http://www.iea-retd.org/files/RETD_PID0810_Main.pdf.

[22] Held, A.; Ragwitz, M.; Huber, C.; Resch, G.; Faber, T; Vertin, K. (2007). Feed-in Systems in Germany, Spain and Slovenia: A Comparison. Karlsruhe, Germany: Fraunhofer Institute Systems and Innovations Research. October 2007. Accessed October 9, 2008, at http://www/feed-in-cooperation.org/images/files/ific_comparison_of_fit-systems_de_es_sl.pdf.

[23] CEER (2016) Key support elements of RES in Europe: moving towards market integration. Ref: C15-SDE-49-03.

[24] KYOS - What is a green certificate? https://www.kyos.com/faq/green-certificate/ Last accessed 30 October 2022.

[25] European Comission - Before you apply: EU funding for beginners. https://ec.europa.eu/info/funding-tenders/how-apply/you-apply-eu-funding-beginners_en Last accessed 30 October 2022.

[26] European Comission - EU funding for offshore renewables https://energy.ec.europa.eu/topics/renewable-energy/financing/eu-funding-offshore-renewables_en Last accessed 30 October 2022.

[27] Oikonomopoulou, E et al. Clifford Chance. (2021) - The EU renewable energy financing mechanism – will it incentivise investment? https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2021/10/the-eu-renewable-energy-financing-mechanism.pdf

[28] Von Blücher, F. Gephart M., Wigand F., Resch G. (2020) - The new renewable energy financing mechanism of the EU in practice http://aures2project.eu/wp-content/uploads/2020/11/AURES_II_D6_3_EU.pdf

[29] Power World Analysis. https://www.powerworldanalysis.com/federal-network-agency-launches-germanys-first-cross-border-pv-auction-with-denmark/. Last accessed 22 June

[30] Directorate-General for Energy (2017). Second agreement on statistical transfers of renewable energy amounts between Estonia and Luxembourg. https://commission.europa.eu/news/second-agreement-statistical-transfers-renewable-energy-amounts-between-estonia-and-luxembourg-2017-11-13_en. Last accessed 22 June.

[31] Directorate-General for Energy (2023). Commission welcomes commitment by Finland and Luxembourg Renewable Energy Financing Mechanism. https://energy.ec.europa.eu/news/commission-welcomes-commitment-finland-and-luxembourg-renewable-energy-financing-mechanism-2023-02-27_en. Last accessed 22 June

[32] Directorate-General for Energy (2023). The Renewable Energy Financing Mechanism sees first tender established. https://energy.ec.europa.eu/news/renewable-energy-financing-mechanism-sees-first-tender-established-2023-04-14_en. Last accessed 22 June.

[33] García González, J. (2014) Decision support models in electric power systems https://sifo.comillas.edu/pluginfile.php/2887852/mod_resource/content/0/Documentation_Msem_Mmp_Mgr_v1.6.pdf

[34] EUROSTAT (2023). Final energy consumption in industry – detailed https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Energy_products_used_in_the_industry_sector

ANEX I. CODE FOR MODEL I

```
* Statement of sets and indices
SETS
p                Time Periods
g                Generators
dia              Days of the week

* Statement of dynamic sets: they are subsets of the previous sets.
t(g)             Thermal Generators
h(g)             Hydraulic Generators
pdia(p,dia)      Relationship between each period and each day
pa(p)            Time periods active in performance
;

* Statement of parameters
PARAMETERS
[Confidential]
cExpWIND Coste de expansion del viento /1000/
cExpSUN  Coste de expansion del sol /1000/
DATOS_WIND(g) Capacidad de cada unidad que puede instalarse de viento/EOL
0.4/
DATOS_SOLAR(g) Capacidad de cada unidad que puede instalarse solar /SUN 1/
CAP_EXP_WIND(g) Capacidad instalada en el instante inicial viento/EOL
12.1112/
CAP_EXP_SOLAR(g) Capacidad instalada en el instante inicial solar/SUN 9.27/
;

* Statement of free variables
VARIABLES
fobj             Value of objective function
;

* Statement of positive variables
POSITIVE VARIABLES
[Confidential]
PGEN_EX_WIND(g,p) Potencia generada debido a las expansiones de viento
PGEN_EX_SOLAR(g,p) Potencia generada debido a las expansiones solares
HOLGURA(p)   Variable de prueba
;
```

```
* Statement of binary variables
BINARY VARIABLES
[Confidential]

* Statement of integer variables
INTEGER VARIABLES
XX(g,p)     numero de unidades acumuladas de potencia eólica que se han
instalado hasta el periodo p
YY(g,p)     numero de unidades acumuladas de potencia solar que se han
instalado hasta el periodo p
;

* Statement of Equations
EQUATIONS
E_FOBJ           Objective Function
E_DMND(p)        Meet the demand
[Confidential]
EXPANS_WIND(g,p)  Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
EXPANS_SOLAR(g,p) Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
P_EXP_WIND(g,p)       Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del viento
P_EXP_SOLAR(g,p)       Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del sol
TARGETS Target of the EU to accomplish
;

* Read the data from the data file
$INCLUDE MSEM_DAT_EXPANSION_GREATRAMPS_LESSREN.INC
;
```

```
*Definition of active periods of execution
[Confidential]

*Relationship between days and periods
[Confidential]

*Modelling of inputs:
[Confidential]

* Formulation of equations:
E_FOBJ ..

                   fobj=E= SUM[p$pa(p),
                                cens* pns(p) +
                                       SUM[t,
                                               f(t) *[ beta(t) * u(p,t) +
                                                       gamma(t)* y(p,t)  +
                                                       theta(t)* z(p,t)  +
                                                       alfa(t) * q(p,t) /
k(t) ]+
                                               o(t) * q(p,t) / k(t)]]


*Costos de expansión
                        + SUM[(p,g),
                                XX(g,p)$(p.last)*cExpWIND]



                        + SUM[(p,g),
                                YY(g,p)$(p.last)*cExpSUN]



E_DMND(p)$pa(p) ..
                 SUM[t, q(p,t)]+ SUM[h, q(p,h)- b(p,h)]  + wind(p)+ solar(p)
+ pns(p) + SUM(g,PGEN_EX_WIND(g,p)$(ord(g) EQ 12)) +
SUM(g,PGEN_EX_SOLAR(g,p)$(ord(g) EQ 13)) =E= d(p);

[Confidential]
```

```
*El 12 corresponde a WIND y el 13 a SOLAR
EXPANS_WIND(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 12))..
      XX(g,p)
      =E=
      XX(g,p-1) ;

EXPANS_SOLAR(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 13))..
      YY(g,p)
      =E=
      YY(g,p-1) ;

P_EXP_WIND(g,p)$(ORD(g) EQ 12)..
      PGEN_EX_WIND(g,p)
      =E=
      (DATOS_WIND(g)/CAP_EXP_WIND(g))*wind(p)*XX(g,p) ;

P_EXP_SOLAR(g,p)$(ORD(g) EQ 13)..
      PGEN_EX_SOLAR(g,p)
      =E=
      (DATOS_SOLAR(g)/CAP_EXP_SOLAR(g))*solar(p)*YY(g,p) ;

TARGETS ..

        SUM[p$pa(p), solar(p) + wind(p) + SUM[h, q(p,h)- b(p,h)] +
SUM(g,PGEN_EX_WIND(g,p)$(ord(g) EQ 12)) + SUM(g,PGEN_EX_SOLAR(g,p)$(ord(g)
EQ 13))] =G= 0.75*SUM[p$pa(p),d(p)]

* Specification of equations to be used in the model
MODEL MSEM
/
E_FOBJ
E_DMND
[Confidential]
EXPANS_WIND
EXPANS_SOLAR
P_EXP_WIND
P_EXP_SOLAR
TARGETS
/;

[Confidential]
```

```
* Options for execution:
* Selection of the optimizer for solving binary variables
OPTION MIP = cplex;

* Selection of the optimizer for solving relaxed binary variables
OPTION RMIP = cplex;

* Tolerance for optimization convergence with binary variables
OPTION OPTCR = 0.0;
option iterlim=1e+6 ;

* Solve the problem using binary variables {0,1} (MIP), or relaxing them in
the continous interval [0,1], RMIP
SOLVE MSEM USING RMIP MINIMIZING FOBJ;
execute_unload "salidas.gdx"

* Write the results using text file
$INCLUDE MSEM_RES.INC
;
```

ANNEX II. CODE FOR MODEL II

```
* Statement of sets and indices
SETS
p                 Time Periods
g                 Generators
dia               Days of the week

* Statement of dynamic sets: they are subsets of the previous sets.
t(g)              Thermal Generators
h(g)              Hydraulic Generators
pdia(p,dia)       Relationship between each period and each day
pa(p)             Time periods active in performance
;

* Statement of parameters
PARAMETERS
[Confidential]
cExpWIND Coste de expansion del viento /1000/
cExpSUN  Coste de expansion del sol /1000/
DATOS_WIND(g) Capacidad de cada unidad que puede instalarse de viento/EOL
0.4/
DATOS_SOLAR(g) Capacidad de cada unidad que puede instalarse solar /SUN 1/
CAP_EXP_WIND(g) Capacidad instalada en el instante inicial viento/EOL
12.1112/
CAP_EXP_SOLAR(g) Capacidad instalada en el instante inicial solar/SUN 9.27/
PERCENTAGE /0.8/
ADAPTATION_COST /900/
;

* Statement of free variables
VARIABLES
fobj              Value of objective function
;
```

```
* Statement of positive variables
POSITIVE VARIABLES
[Confidential]
PGEN_EX_WIND(g,p) Potencia generada debido a las expansiones de viento [GW]
PGEN_EX_SOLAR(g,p) Potencia generada debido a las expansiones solares [GW]
PGEN_EX_WIND_CMS(g,p) Potencia generada debido a las expansiones de viento
del CMS [GW]
PGEN_EX_SOLAR_CMS(g,p) Potencia generada debido a las expansiones solares
del CMS [GW]
MARGINAL_PRICES(p) Precios marginales según las horas
TOTAL_RES_NEW(p) Total new RES


*Statement of scalars
SCALAR
AVERAGE media de precios marginales
PROFIT_WIND profit de eolica ya instalada
PROFIT_SOLAR profit de solar ya instalada
;

* Statement of binary variables
BINARY VARIABLES
[Confidential]

* Statement of integer variables
INTEGER VARIABLES
XX(g,p)     numero de unidades acumuladas de potencia eólica que se han
instalado hasta el periodo p
YY(g,p)     numero de unidades acumuladas de potencia solar que se han
instalado hasta el periodo p
XX_CMS(g,p) numero de unidades acumuladas de potencia eólica que se han
instalado hasta el periodo p por parte del Contributing Member State
YY_CMS(g,p) numero de unidades acumuladas de potencia solar que se han
instalado hasta el periodo p por parte del Contributing Member State
;

* Statement of Equations
EQUATIONS
E_FOBJ          Objective Function
E_DMND(p)       Meet the demand
[Confidential]
```

```
EXPANS_WIND(g,p)  Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
EXPANS_SOLAR(g,p) Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
EXPANS_WIND_CMS(g,p)  CMS:Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
EXPANS_SOLAR_CMS(g,p) CMS:Restriccion de expansion creciente a lo largo del
horizonte temporal. Si una unidad se instaló en el periodo p, debe
mantenerse en el resto del horizonte
P_EXP_WIND(g,p)       Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del viento
P_EXP_SOLAR(g,p)       Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del sol
P_EXP_WIND_CMS(g,p)       CMS:Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del viento
P_EXP_SOLAR_CMS(g,p)      CMS:Relacion entre la producción y las expansiones
acumuladas hasta un periodo. Corresponde a un porcentaje de la producci�n
total para conservar la din�mica del sol
E_TOTAL_RES(p)
TARGETS
;

* Read the data from the data file
$INCLUDE MSEM_DAT_EXPANSION_GREATRAMPS_LESSREN.INC
;

[Confidential]

* Formulation of equations:
E_FOBJ ..

                   fobj=E= SUM[p$pa(p),
                                cens* pns(p) +
                                        SUM[t,
                                                f(t) *[ beta(t) * u(p,t) +
                                                        gamma(t)* y(p,t)  +
                                                        theta(t)* z(p,t)  +
```

```
                                                        alfa(t) * q(p,t) /
k(t) ]+
                                                o(t) * q(p,t) / k(t)]]


*Costos de expansi�n
                        + SUM[(p,g),
                                XX(g,p)$(p.last)*cExpWIND]


                        + SUM[(p,g),
                                YY(g,p)$(p.last)*cExpSUN]

                        + SUM[(p,g),
                                XX_CMS(g,p)$(p.last)*ADAPTATION_COST]


                        + SUM[(p,g),
                                YY_CMS(g,p)$(p.last)*ADAPTATION_COST]



E_DMND(p)$pa(p) ..
                 SUM[t, q(p,t)]+ SUM[h, q(p,h)- b(p,h)]  + wind(p)+ solar(p)
+ pns(p) + SUM(g,PGEN_EX_WIND(g,p)$(ord(g) EQ 12)) +
SUM(g,PGEN_EX_SOLAR(g,p)$(ord(g) EQ 13)) +
SUM(g,PGEN_EX_WIND_CMS(g,p)$(ord(g) EQ 12)) +
SUM(g,PGEN_EX_SOLAR_CMS(g,p)$(ord(g) EQ 13))=E= d(p);

[Confidential]



*El 12 corresponde a WIND y el 13 a SOLAR
EXPANS_WIND(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 12))..
      XX(g,p)
      =E=
      XX(g,p-1) ;

EXPANS_SOLAR(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 13))..
      YY(g,p)
      =E=
      YY(g,p-1) ;
```

```
EXPANS_WIND_CMS(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 12))..
      XX_CMS(g,p)
      =E=
      XX_CMS(g,p-1) ;

EXPANS_SOLAR_CMS(g,p)$(ORD(p) GT 1 AND (ORD(g) EQ 13))..
      YY_CMS(g,p)
      =E=
      YY_CMS(g,p-1) ;

P_EXP_WIND(g,p)$(ORD(g) EQ 12)..
      PGEN_EX_WIND(g,p)
      =E=
      (DATOS_WIND(g)/CAP_EXP_WIND(g))*wind(p)*XX(g,p) ;

P_EXP_SOLAR(g,p)$(ORD(g) EQ 13)..
      PGEN_EX_SOLAR(g,p)
      =E=
      (DATOS_SOLAR(g)/CAP_EXP_SOLAR(g))*solar(p)*YY(g,p) ;

P_EXP_WIND_CMS(g,p)$(ORD(g) EQ 12)..
      PGEN_EX_WIND_CMS(g,p)
      =E=
      (DATOS_WIND(g)/CAP_EXP_WIND(g))*wind(p)*XX_CMS(g,p) ;

P_EXP_SOLAR_CMS(g,p)$(ORD(g) EQ 13)..
      PGEN_EX_SOLAR_CMS(g,p)
      =E=
      (DATOS_SOLAR(g)/CAP_EXP_SOLAR(g))*solar(p)*YY_CMS(g,p) ;

TARGETS..
        SUM[p$pa(p), solar(p) + wind(p) +SUM[h, q(p,h)- b(p,h)]+
SUM(g,PGEN_EX_WIND(g,p)$(ord(g) EQ 12)) + SUM(g,PGEN_EX_SOLAR(g,p)$(ord(g)
EQ 13)) + PERCENTAGE*SUM(g,PGEN_EX_WIND_CMS(g,p)$(ord(g) EQ 12)) +
PERCENTAGE*SUM(g,PGEN_EX_SOLAR_CMS(g,p)$(ord(g) EQ 13))]=G=
0.75*SUM[p$pa(p),d(p)];

E_TOTAL_RES(p)$pa(p) ..
    TOTAL_RES_NEW(p) =E= SUM(g,PGEN_EX_WIND(g,p)$(ord(g) EQ 12)) +
SUM(g,PGEN_EX_SOLAR(g,p)$(ord(g) EQ 13)) +
SUM(g,PGEN_EX_WIND_CMS(g,p)$(ord(g) EQ 12)) +
SUM(g,PGEN_EX_SOLAR_CMS(g,p)$(ord(g) EQ 13))
```

```
* Specification of equations to be used in the model
MODEL MSEM
/
E_FOBJ
E_DMND
[Confidential]
EXPANS_WIND
EXPANS_SOLAR
EXPANS_WIND_CMS
EXPANS_SOLAR_CMS
P_EXP_WIND
P_EXP_SOLAR
P_EXP_WIND_CMS
P_EXP_SOLAR_CMS
TARGETS
E_TOTAL_RES
/;

[Confidential]

* Options for execution:
* Selection of the optimizer for solving binary variables
OPTION MIP = cplex;

* Selection of the optimizer for solving relaxed binary variables
OPTION RMIP = cplex;

* Tolerance for optimization convergence with binary variables
OPTION OPTCR = 0.0;
option iterlim=1e+6 ;

* Solve the problem using binary variables {0,1} (MIP), or relaxing them in
the continous interval [0,1], RMIP
SOLVE MSEM USING RMIP MINIMIZING FOBJ;

Loop (p,MARGINAL_PRICES.l(p)=E_DMND.m(p));
```

```
AVERAGE = SUM(p,MARGINAL_PRICES.l(p))/168;
display AVERAGE;




PROFIT_WIND = SUM(p,MARGINAL_PRICES.l(p)*wind(p));
PROFIT_SOLAR = SUM(p,MARGINAL_PRICES.l(p)*solar(p));

display PROFIT_SOLAR;
display PROFIT_WIND;

*SOLVE MSEM USING RMIP MINIMIZING FOBJ;
execute_unload "salidas.gdx"
;
```