Towards a New Renewable Power System using Energy Storage: an Economic and Social Analysis

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Abstract

The energy transition is one of the main challenges in mitigating the CO_2 emissions from the power sector. Solar and wind resources are presented as the two most promising alternatives in the future energy mix. However, the inherent fluctuations of these two resources jeopardize the stability of the grid. To overcome this issue, the combination of intermittent and non-intermittent renewable energies along with different storage technologies is proposed. In this work, the integration of these technologies is evaluated using different future scenarios. Three renewable resources have been analyzed (solar, wind, and biomass) in combination with four different storage systems (battery, hydrogen, methane, and ammonia). This problem has been evaluated from two different perspectives, economic and social (for which a new indicator is developed).Particularly, this methodology is applied to Spain where different provinces have been assessed to implement these integrated facilities. The results show the paramount importance of using storage alternatives to satisfy the demand and to store energy seasonally. In economic terms, an average cost of electricity of about 100-200 €/MWh is expected with a high influence of the ratios of wind and solar in the different locations and the selected storage alternatives. Additionally, the proposed social index indicates the regions where these facilities could be installed to mitigate social inequalities. With this two-pronged approach, an orderly, fair, and efficient planning of the energy transition can be realized to achieve climate sustainability goals.

Keywords: Energy storage, Energy transition, Power-to-X, Renewable energy, Social index

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1. Introduction

The energy transition is an especially urgent issue today to meet global environmental agreements. The Sustainable Development Goals (SDGs) by the United Nations state, in SDG 7, that access to affordable, reliable, sustainable, and modern energy must be ensured for all (UN General Assembly, 2015). In line with this goal, the Paris Agreement emphasizes sustainable energy production as a major mean to reduce global temperature rise to below 2ºC above pre-industrial levels (Roelfsema et al., 2020). To meet the proposed targets, the entire energy system needs to be decarbonized. In this objective, the decarbonization of the power system is crucial since this sector accounts for around 25% of the total CO_2 emissions (EPA, 2021). Increasing the share of renewable energy sources (RES) will be the main strategy for sustainable electricity generation. Wind and solar will represent the two main RES with 56% of the total electricity generation by 2050 (BloombergNEF, 2020). However, these resources are inherently intermittent, and coping with this nature constitutes the main challenge for the new electricity system. To ensure the robustness and stability of the grid as well as the balance between electricity production and demand, a new integrated system based on intermittent and non-intermittent renewable sources and energy storage is needed (Bagherian and Mehranzamir, 2020).

Numerous energy storage technologies have been proposed for various time scales and power capacities (Gür, 2018), and with different environmental impacts (Sternberg and Bardow, 2015). Compressed-air energy storage (CAES) and pumped-hydro are the two options at commercial-scale currently (Alirahmi et al., 2021); however, there have been significant barriers to the widespread deployment of these technologies. For pumped-hydro, it is necessary to select a favorable geographical location with two water bodies separated by an appropriate vertical distance (Gür, 2018). In addition, water scarcity is also a major challenge for this storage system due to the limited availability of water and leading to conflicts over water use (Ali et al., 2021). In the case of CAES, a suitable geological cavern is required for commercial deployment at competitive costs (Tong et al., 2021). Therefore, limited expansion of these two technologies is expected in the coming years. At this time, batteries and H_2-based alternatives have risen as the two most promising choices for minimizing the cost of storage (Schmidt et al., 2019). On the one hand, batteries have been proposed for different applications in residential and grid-scale uses. Corengia and Torres (2018) optimized the operation of a consumer Li-ion battery considering tariff policy and battery degradation. The main trade-off lies between the energy saving due to the possibility of storing low-price electricity and the cost of battery replacement. Different types of batteries have also been analyzed for this storage purpose such as lead-acid, NaS, or Li-ion (Jiang et al., 2020). On the other hand,

H_2 and different H_2-derived fuels (such as methanol (Chen and Yang, 2021) or ammonia (Zhang et al., 2020)) have been considered for seasonal and long-term storage (Stančin et al., 2020). Wulf et al. (2020) summarized the main Power-to-X projects in Europe showing the rapid rate of increase in the current years with more than 220 projects by June 2020. At this point, different works have addressed the problem of integrating renewable power generation with energy storage. Leonard et al. (2018) integrated power generation using wind turbines or solar PV panels with H_2 production as a pathway for energy storage. They proposed this alternative as an option to replace traditional base load power production using coal. No restrictions have been imposed on H_2 storage, resulting in large storage capacities that are a challenge today. Palys and Daoutidis (2020) proposed a system with H_2 and NH_3 as energy storage alternatives. The cost of electricity for different locations in the U.S. has been assessed using the proposed system. The integrated ammonia energy storage framework is especially suitable for areas with high wind potential and strong demand variability. Demirhan et al. (2020) proposed the synthesis of dense energy carriers (DEC) to reduce the cost of renewable energy in areas with lower potential, in particular, they studied the connection between Texas and New York in the U.S. Other authors have evaluated the impact of integrating intermittent and non-intermittent renewables. Bagheri et al. (2019) proposed a 100% renewable system based on a combination of wind, solar, and biomass together with batteries. According to their results, biomass can mitigate the high cost of electricity in an integrated renewable system. The integration of concentrated solar power (CSP) and different biomass (Vidal and Martín, 2015) or waste (de la Fuente and Martín, 2020) has also been evaluated. The location plays a key role due to the different solar irradiance profiles and the contrasting biomass/waste availability of rural and urban areas.

But, the energy transition is not only a technical or economic challenge. The social impact of the energy transition must also be taken into account (Carley and Konisky, 2020). One of the main consequences of the energy transition is the decline in the use of coal as an energy resource. Therefore, employment opportunities decrease in this sector including mining and power facilities. In particular, job losses are concentrated in rural areas with low population density, aging problems, etc. This is the case of Spain, which this work focuses on, with the main traditional power plants located in rural areas. The Spanish government has introduced a new strategy to try to mitigate the effects of the energy transition in areas where coal and nuclear sources are in decline. The public policies are focused on creating new job opportunities, increasing the population in rural areas, or promoting new economic activities. All these measures are included under the umbrella of the so-called ”fair transition strategy” (Ministerio para la Transicion Ecologica y el Reto Demografico, 2021). The introduction of renewable energies and also the storage technologies at grid-scale can mitigate the social effects of the transition if these facilities are installed in these particularly affected areas (Fragkos and Paroussos, 2018). Different job opportunities can be generated depending on the stage of the facilities: construction, manufacturing, etc. (Cartelle Barros et al., 2017). Additionally, the investment associated with the new energy system can be a useful way to mitigate social disturbances in societies, for instance, migration of youth from rural areas (Faggian et al., 2017), different unemployment rates between regions (Boeri and Jimeno, 2016) or low population density in certain areas (Syssner, 2020). But, clearly, this social factor should be considered in the implementation of a new renewable energy system.

Therefore, a holistic approach is necessary to tackle this energy production/storage problem in the context of the energy transition considering economic and social aspects. First, an integrated facility for power production and storage is evaluated considering a combination of intermittent (wind/solar) and non-intermittent (biomass) resources together with energy storage. Four different storage alternatives have been evaluated: batteries, hydrogen, and ammonia/methane to capture the different storage timescales. In previous literature, only a partial approach is considered either using only batteries or Power-to-X storage in combination with wind or solar production or considering intermittent and non-intermittent sources but without energy storage. However, an integrated approach is necessary to develop a new power system considering all the available technologies to guarantee demand satisfaction. And this approach has been developed in this work. But, it is not only the economic and technical aspects that have been previously and traditionally mentioned. The social impact of the energy transition to locate these integrated facilities have also been assessed. To evaluate this impact, this work has proposed a new social index based on two main factors: the impact of the energy transition and the general social environment of the region. Only very few previous works have addressed this issue by quantifying the social impact (Heras and Martín, 2020). Consequently, the integration of all sources and technologies to ensure power production is required in addressing this challenge from a social and economic perspective, and, to the best of our knowledge, no research in this area is performed. Particularly, this work focuses on Spain where European goals are driving a major challenge in order to achieve climate neutrality by 2050. The implementation of the proposed integrated power production and storage facilities in different provinces of Spain has been evaluated from an economic and social perspective. Special attention is given to the regions most affected by the energy transition according to the Spanish government's criteria and to those with high potential for wind and solar energies.

The remainder of this work is organized as follows. In Section 2, an overview of the proposed superstructure for an integrated facility including power production and storage is included. The modeling approach followed in this work is also briefly presented in this section. In Section 3, a new social index is proposed to evaluate the social impact of these facilities. The case study in which the proposed formulation is applied is presented in Section 4. Section 5 presents the main results of the work grouped in three blocks: operating, economic and social results. Finally, some conclusions are drawn in Section 6.

2. Process Description and Model Formulation

The first goal of this work is to determine the optimal design and scheduling of power facilities integrating different intermittent and non-intermittent renewable resources and various energy storage alternatives. This integrated system must minimize the operating cost of satisfying a given power demand regardless of the availability of renewable resources. For this purpose, the superstructure presented in Figure 1 is considered with all the processes listed in Table 1. Two different intermittent RES have been introduced in the framework: solar (photovoltaic panels) and wind (wind turbines). In addition, biomass is also incorporated as a non-intermittent RES. For energy storage, four different pathways have been evaluated: Li-ion batteries, hydrogen, and methane/ammonia. Methane has been selected due to the possibility of using the existing natural gas infrastructure for energy storage. Furthermore, ammonia has also been evaluated because it is a chemical without an associated carbon dioxide that can be used for energy storage in the future scenario aiming for complete decarbonization. Using this general framework, three different scenarios have been studied:

- **Scenario 1**: Wind and solar have been considered as input resources. Biomass is not introduced in this case. Three different storage alternatives have been evaluated: Li-ion battery, hydrogen, and methane. This scenario is considered as the base case.

- **Scenario 2**: Wind and solar are introduced as intermittent renewable sources and, additionally, biomass is also included. The same three storage alternatives have been considered as in scenario 1. With this option, the integration of intermittent and non-intermittent resources together with energy storage is assessed.

- **Scenario 3**: Only wind and solar have been considered as input resources. In order to envision a future electricity system without associated CO_2, biomass has not been introduced and, as forms of storage, battery, hydrogen, and ammonia (a carbon-free energy carrier) are used.

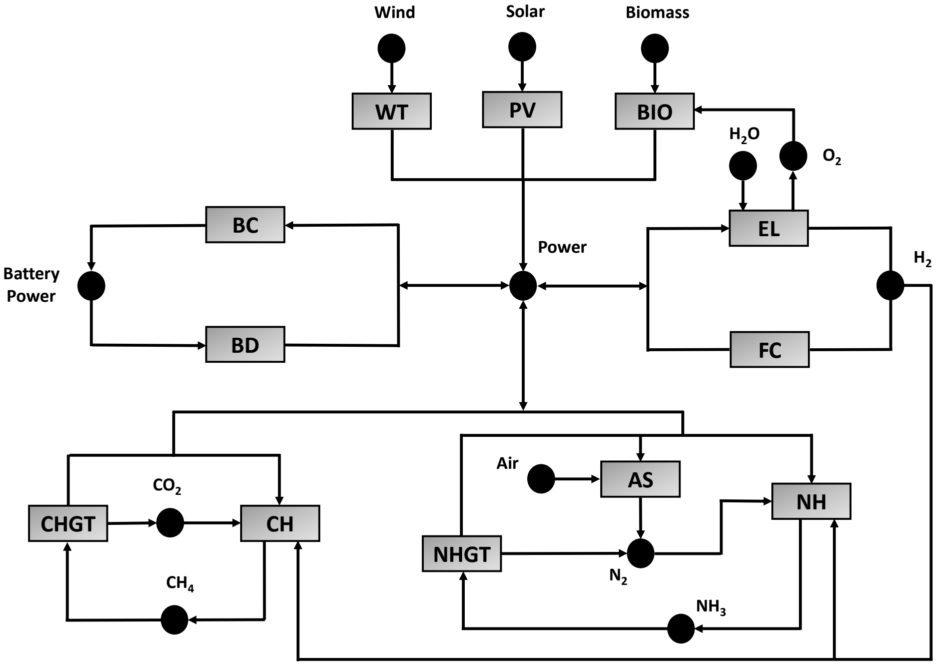

Figure 1: Process-resource network superstructure for power production. WT: Wind turbines; PV: Photovoltaic panels; BIO: Biomass; BC: Battery charge; BD: Battery discharge; EL: Water electrolysis; FC: Fuel cell; CH: Methane production; CHGT: Methane gas turbine; AS: Air separation unit; NH: Ammonia synthesis; NHGT: Ammonia-to-power.

The detailed models, technical and economic parameters, etc. for the different processes have been obtained from previous works (as shown in Table 1). For solar PV panels, the efficiency is fixed to 25% and the performance ratio is calculated as a function of the ambient temperature and incident radiation (Hlal et al., 2019). Each module has a nominal power of 0.3 kWp with an area of 1.96 m^2. As a wind turbine, a Nordex N100 (de la Cruz and Martín, 2016) with a nominal power of 2,500 kW is employed with direct land requirement of 7,500 m^2 per turbine (Denholm et al., 2009). A Li-ion battery is selected due to its paramount properties for energy storage (Schmidt et al., 2019). A maximum capacity of 30,000 kWh is set with a limiting charge or discharge ratio in a given hour of 10% of the total capacity (Allman et al., 2019). Hydrogen is produced by electrolysis of water assuming a specific energy consumption of 53.14 kWh/kg H_2 (Yates et al., 2020). This hydrogen can be stored as such and, subsequently, converted into power using a fuel cell yielding 50 kWh/kg H_2. Alternatively, hydrogen can be used for the synthesis of methane, with simple conditions for a long-term storage horizon (Davis and Martín, 2014). This methane can be transformed into power via a gas turbine. From a carbon-free perspective, ammonia can be synthesized from H_2 and N_2, which can be produced by different air separation technologies (Sánchez and Martín, 2018b). Finally, power can be obtained from ammonia by two different routes: electrochemical (fuel cell) or thermochemical (combustion). For large production capacities, the most suitable is thermo-chemical using a combined cycle with an ammonia/hydrogen blend as the feed stream (Sánchez et al., 2021a). The use of biomass for power production is based on the scheme of gasification plus gas turbine (Lan et al., 2018). Direct gasification as proposed by Sánchez et al. (2019) has been used to treat the inlet biomass. The use of anaerobic digestion for biomass processing is discarded in this work due to the low yields to biogas production of this technology (and, consequently, for electricity) and the high requirements in terms of moisture content. For large-scale power production, the use of thermochemical alternatives is more appropriate including the proposed gasification system (Banja et al., 2019). The data required in the model for the different processes have been included in the Supporting Information. Each of the processes has been previously analyzed by optimizing the operating conditions and selecting the best technology. For each of them, a systematic economic evaluation is performed, using the same methodology, which allows a fair comparison between the different processes.

To model the operation of these integrated storage facilities, a scheduling model is proposed based on the previous models of Zhang et al. (2016) and Sánchez et al. (2021b). Only a brief description of the model is included here and the full formulation is presented in the Supporting Information. The model is based on a multiscale time representation where the time horizon of one year is divided into a set of arbitrary seasons. Each season can have diverse lengths to capture the different patterns of input resources. Cyclic scheduling is applied to each season, although inventory can be carried over from one season to the next to allow for seasonal storage, which is key for the long-term horizon. From a process perspective, each unit can operate in four different operating modes (off, startup, on, and shutdown) with a minimum time period at each stage. A given power demand must be satisfied by using the available power production technologies. As the objective function of the optimization problem, the operating cost (OC) of the framework is used:

$$\begin{aligned} OC = {} & \sum_{i} \sum_{m \in M_i} \sum_{h} \sum_{t} J_{imht} + \sum_{i} \sigma_i \left(\delta_i x_i + \gamma_i C_i \right) + \\ & \sum_{j \in \hat{S}} \left(\alpha_j \bar{x}_j + \beta_j \overline{C}_j \right) + \sum_{i} \sum_{j} \sum_{h} \sum_{t} \xi_j \rho_{ij} P_{iht} \\ & + \sum_{h} \sum_{t} \varphi_{CO_2} B_{CO_2,ht} \end{aligned} \tag{1}$$

Table 1: Process description with the input/output resources

Name	Description	Input Resources	Output Resources	Reference
WT	Wind turbines	Wind	Power	de la Cruz and Martín (2016)
PV	Photovoltaic panels	Solar	Power	Sánchez and Martín (2018a) ; Hlal et al. (2019)
BIO	Biomass integrated gasifier/gas turbine	Biomass, O_2	Power	Sánchez et al. (2019) ; León and Martín (2016)
BC	Battery charge	Power	Battery power	Gonzalez-Castellanos et al. (2020)
BD	Battery discharge	Battery power	Power	Gonzalez-Castellanos et al. (2020)
EL	Water electrolysis	Power,Water	O_2, H_2	Sánchez and Martín (2018a)
FC	Hydrogen fuel cell	Hydrogen	Power	Kashefi Kaviani et al. (2009); Palys and Daoutidis (2020)
CH	Methane production	CO_2, Hydrogen, Power	Methane	Davis and Martín (2014)
CHGT	Methane gas turbine	Methane	Power	León and Martín (2016)
AS	Air Separation Unit (PSA)	Air, Power	N_2	Sánchez and Martín (2018b)
NH	Ammonia synthesis	N_2, H_2, Power	NH_3	Sánchez and Martín (2018a)
NHGT	Power production from ammonia	NH_3	Power	Sánchez et al. (2021a)

which includes the operating cost of the production processes and storage. The cost of the processes is divided into two terms. The first one, J_{imht}, includes all the terms non-related to the capital cost of the facility as raw materials or utilities. The second one, last term in the first line of the equation, includes all the operating costs associated with the initial investment as capital charges or maintenance (Sinnott, 2014). A linear approximation of the capital cost of the processes is considered. For the storage cost, as in the previous case, two terms are included. One is related to the amortization of the capital cost (also assuming a linear behavior, first term of the second line of the equation) and the other to the operating and maintenance cost of storage (last term of the second line). Finally, the cost of captured carbon dioxide (φ_{CO_2}), the raw material of methane production and captured in different industrial plants, is added with a price of 50 $/t (third line of the equation 1) (Rubin et al., 2015).

The optimization problem proposed is a mixed-integer linear program (MILP) that has been implemented in Julia using the JuMP package and solved with Gurobi with an optimality gap of 1%.

3. Social Index

To be able to quantify the social impact of the energy transition and to provide tools to determine the best location of the energy facilities involving the social impact, a new social index has been developed. In this particular case, the social index has been used to determine the social effects of the installation of one integrated power production/storage facility in the different study regions. The social index proposed in this work is organized into ten different items. The first three involve the social impact of the energy transition in the studied area, and the rest quantify the global social situation of the region. All the items are normalized (as shown in equation 2) using a minimum score of 0 and a maximum of 10, with this value corresponding to the worst social situation of the indicator. Therefore, the maximum score of the index is equal to 100, corresponding to regions very affected by social issues and where the installation of different facilities is highly beneficial from a social perspective. This index is calculated in parallel to the economic optimization of the system. This proposed indicator assesses the social situation of the region prior to the implementation of the integrated power facilities. The objective is to determine the best location in social terms, based on the assumption that if one of these plants is installed in a region, new investments, employment opportunities, local taxes, etc. could be generated. Throughout this section, each of the items of the social index has been explained and further details can be found in the Supporting Information.

$$SocialScore = 10\left(\frac{Value - Value_{Min}}{Value_{Max} - Value_{Min}}\right) \tag{2}$$

1. **Loss of installed capacity in the region vs. total capacity lost**: in the energy transition, some facilities will be decommissioned, mainly coal and nuclear power plants. The regions where these units are installed are particularly affected by the loss of job opportunities, economic activities, local taxes, etc. Therefore, regions with a higher rate of decommissioning will have a higher social impact. The lost installed capacity is calculated by multiplying the total capacity by a factor that is the inverse of the remaining useful life years. This factor takes into account facilities with an established closing date in the near future.
2. **Loss of jobs related to energy transition vs. total employment in the region**: The decommissioning of the traditional power facilities involves a loss of direct

and indirect jobs in the region. And, this loss is especially significant in those regions where the total active population is reduced. Therefore, regions with a high percentage of loss of jobs versus the total active population will have a higher social impact on the energy transition. To compute the loss of jobs, as in the previous item, the factor to take into account the active life years is applied. The number of employments in the sectors concerned has been obtained from different reports from trade unions, employers' organizations, or public authorities.

3. **Loss of installed capacity vs. total GDP of the region**: The aim of this item is to reflect the relative importance of the power industry in the productive sector of the region. If the power sector represents an important share of the total GDP of the province, the social importance of the energy transition increases. Due to the difficulty in obtaining the contribution to GDP of the power sector in specific regions, the ratio of the total loss of installed capacity to the GDP of the region is employed as an indicator.
4. **GDP of the region vs. total GDP of the country**: This component is the first item related to the total social environment of the region. In regions with a lower share of the total GDP of the country, the social impact of introducing new facilities such as the one proposed in this work is higher.
5. **Unemployment rate**: Some regions are especially affected by higher unemployment rates, therefore, the power production/storage facilities could be an attractive measure to alleviate this to some extent. Thus, regions with higher unemployment rates required more social actions and higher scores on the social index.
6. **Population decline over the last 20 years**: The population decline, expressed as percentage of decrease, is particularly significant in some rural areas where the migration from small/medium villages to towns has reduced the population at alarming levels. The introduction of the facilities studied in this work could help to fix the population and to fight against this demographic problem. Therefore, a higher social impact is expected in those regions where a deep population decline has taken place.
7. **Aging index**: the aging of the population is one of the emerging problems in some areas due to the migration of young people to other areas with larger economic perspectives and the low birth rate. This is a challenge for the authorities in terms of public services, the sustainability of the pension system, etc. To take into account this aspect in the proposed metric, the aging index is used. This index is determined as the ratio between the number of elderly people (over 64) and the number of children and young people (under 16) and is reported by national statistical offices. The higher the rate of aging, the greater the social impact.

8. **Population density**: Some areas are severely affected by the problem of the low population over a very large territory. This problem is a major challenge for the different governments because of the cost of public services, maintenance of infrastructures, etc. In the proposed metric, population density is introduced considering the high social impact of new facilities in those areas with lower levels of this parameter.
9. **Youth migration in the last 10 years**: A migratory movement of the youth from, mainly, rural to urban areas is taking place. This leads to a loss of productive labor in villages, a lack of generational replacement in certain economic activities, or a major demographic problem. Therefore, the installation of new infrastructures associated with the energy transition could help to mitigate this problem. Data on youth migration, measured as number of migrations, has been collected from the national statistical office and the time period is set between 2010 and 2020.
10. **GDP per capita**: GDP per capita is often linked to a better economic situation, better public services, etc. Thus, the new energy infrastructure in areas with low GDP per capita can contribute to mitigating inequalities in income distribution, reducing the social gap between territories.

4. Case Study

Figure 2: Selected regions in Spain for the analysis including the current nuclear or coal power plants

The case study evaluates the implementation of the proposed integrated power production/storage facilities in different regions (provinces) of Spain. A technical and economic perspective is followed using the design and scheduling methodology of section 2 and, from a social angle, using the new social index proposed in section 3. The energy transition is a major challenge in Spain due to the new European aims to be climate-neutral by 2050 and, therefore, the necessary high penetration of renewables in the energy system. Fourteen locations have been evaluated (as shown in Figure 2). Six are areas particularly affected by the energy transition due to the decommissioning of coal and nuclear power plants and with special measures by the Spanish government (Ministerio para la Transicion Ecologica y el Reto Demografico, 2021): Asturias, Teruel, Leon, Coruña, Almeria, and Cordoba. There are other locations in Spain where nuclear power facilities are installed such as Tarragona or Cáceres. However, the expected decommissioning date of these plants is 2030, therefore, the Spanish government has not included these regions in the selected areas most affected by the energy transition. Hence, these provinces have not been included in this case study. Three others are included for their high solar potential: Badajoz, Ciudad Real, and Sevilla. Zaragoza, Burgos, and Navarra are areas with high availability of wind resources. Finally, two areas with significant social problems (such as depopulation or aging) have been included: Salamanca and Soria. Solar irradiation and wind speed data have been obtained from public databases (JRC European Commission, 2019; Energy Data, 2021). Additionally, the power demand of Spain has been collected from the grid operator's website (Red Electrica de España, 2021). For the different installations analyzed in this work, the demand for electricity to be satisfied is set at 0.5% of the total demand in Spain in each time period, which corresponds with an energy demand of 1275 GWh per year with a maximum hourly peak demand of about 205 MW. For the scenario in which biomass is introduced (scenario 2), the total availability of biomass in the specific region is calculated (Cabrera et al., 2011). For each region, it is determined which is the largest contributor to the total biomass production: forest, herbaceous agricultural, or woody agricultural biomass. For this value, the maximum biomass availability is taken, and only 10% of this biomass can be processed in the proposed power plant to make a conservative estimation.

5. Results and discussion

5.1. Operating results

In this section, the operation of integrated energy production and storage facilities is analyzed in depth. Only two different locations, for the sake of brevity, are shown in this section, Asturias and Almeria, in order to capture two different regions with contrasting weather conditions (additional operating results can be found in Figures

S1-S3 and Tables S1-S3 of the Supporting Information). First, for scenario 1, Figure 3 shows the profile for two different weeks in July (summer) and December (winter) in Asturias. The columns, in different colors, indicate the power generation for each of the production technologies (including indirect production from storage). The black line shows the power demand to be satisfied, and the maroon line, the total power dispatched at the facility.

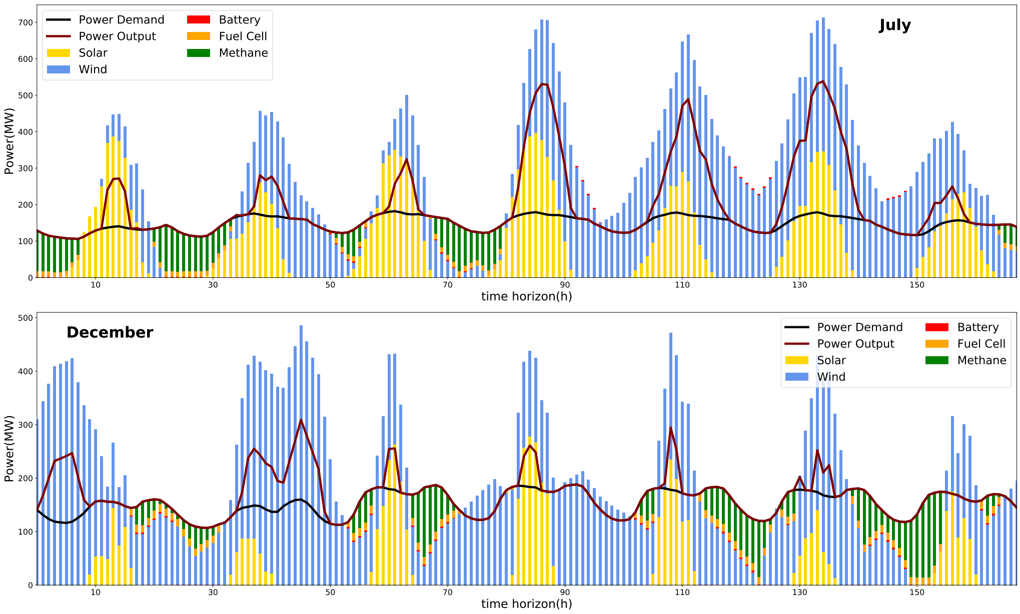

Figure 3: Scheduling results for the Scenario 1 in Asturias

In Asturias, wind is the preferred resource with about 71% of the total power generation. This is reflected in the weekly profiles of Figure 3. In December, wind production is the major contributor to meet the demand. In the summertime, solar production is higher than in winter due to higher solar radiation and longer sunshine hours. However, the wind resource is also significant in this season. Solar production follows a more recurrent pattern with a range of sunshine hours (higher in summer) and with different intensities (higher in summer). In contrast, wind availability is more volatile and does not follow an expected pattern which is a major challenge in terms of the operability of these facilities. Storage technologies are used when solar/wind production is not enough to meet the demand. If only wind/solar technologies are introduced, it is not possible to guarantee demand satisfaction in this context of variable renewable energy sources. Therefore, these technologies emerge as essential in the future energy system to ensure the robustness and stability of the grid. Storage technologies are mainly operated at night due to the lack of solar resource and the fluctuating availability of wind. Within the different storage technologies, batteries and fuel cells are first ones used to bridge the gap between production and demand. If these alternatives are not sufficient due to the limited capacity, methane is introduced, which allows for higher storage and production capacities. Due to the use of energy storage, power demand is satisfied in each time period regardless of the weather conditions. However, power production is higher than the power demand at different times throughout the year, in which wind/solar production exceeds energy demand (as can be seen in the black and maroon lines in Figure 3). This excess of power could be used to store energy using the different technologies proposed but energy storage is expensive and minimum required levels are used to meet the demand. Therefore, even using these storage alternatives, some of the excess energy must be discharged. This is particularly important in the summer hours when high solar and wind generation converge. At this time, where, for example, in the Spanish national grid about 40% of power is produced from renewables, this excess could be also introduced in the grid by avoiding the introduction of natural gas combined cycle or other non-renewable technologies in the power mix. However, in a context where 97% of national electricity is expected to be produced from renewable energies by 2050 (Ministerio para la Transicion Ecologica y el Reto Demografico, 2020), this excess can hardly be integrated into the electricity grid. This raises the possibility of integrating this excess energy with other electricity-consuming industries that do not have such a restrictive hourly demand or where the storage of the products is possible. A promising alternative is the integration of power and chemical industry due to the future expected electrification of the latter sector. An interesting example is ammonia synthesis where an increasing number of projects to electrify the current production devoted to fertilizer require new renewable electricity. Therefore, excess of energy could be used in ammonia production and the chemical could be stored for use on demand (Sánchez and Martín, 2018a). This perspective can also be extended to other chemicals although further research in the operation of these new non steady-state chemical plants is required. Possible synergies between the use of these chemicals as a storage pathway and the production as such for the chemical industry should be also explored.

In Figure 4, the results for scenario 2 for the province of Almeria are presented. In this scenario, biomass is introduced into the power generation pool to evaluate the optimal scenario in which a non-intermittent renewable source is available. The optimization results show that the biomass is used as a base-load generation source. The biomass-based power production is almost constant over time with only small fluctuations in time periods when solar and wind generation is particularly high (mainly during the central hours of the day). The fluctuations in the biomass units are limited

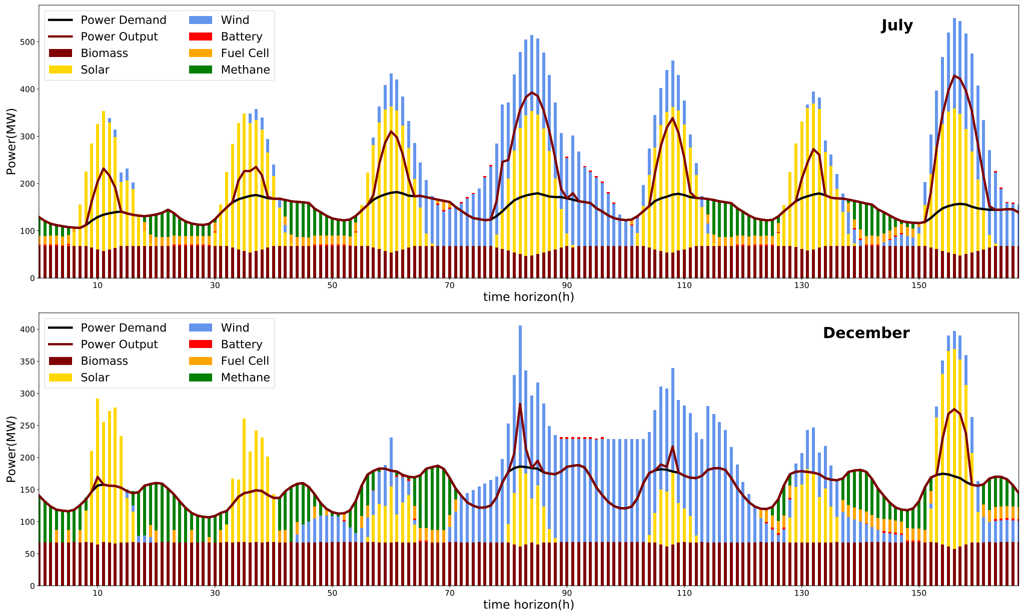

Figure 4: Scheduling results for the Scenario 2 in Almeria

in the model (using the minimum time period in each mode) due to this technology normally operating at or near steady-state. The introduction of biomass power production reduces the installed capacity of wind and solar, thus, reducing the difference between the total electricity discharged and the power demand. In terms of process capacities, in Almeria, a reduction of more than 40% in solar PV panels and 50% in wind turbines is expected compared to scenario 1 (as shown in Table 2). This reduction also affects electrolysis/fuel cell and methane production/gas turbine due to lower storage requirements. For example, the methane storage capacity decreases from about 5,700 t of methane to around 3,100 t. As it is explained in the next section, the use of biomass is economically beneficial compared to the use of storage technologies in order to ensure demand satisfaction, which justifies the use of biomass in electricity production. Figure 4 shows the results for a province dominated by solar generation contrasting with the case of Asturias. In scenario 2, almost 40% of the power is produced from solar PV panels in Almeria, and, this percentage increases to 55% in scenario 1. Due to this fact, the excess of energy during the central hours of summertime is particularly significant in locations such as Almeria.

Finally, Figure 5 shows the scheduling results in scenario 3 where ammonia is introduced and there are no direct CO_2 emissions associated with power production. In particular, the results are presented for the province of Asturias. A significant increase

Table 2: Process capacities for the different scenarios in Asturias and Almeria

	Scenario 1		Scenario 2		Scenario 3	
	Asturias	Almeria	Asturias	Almeria	Asturias	Almeria
Solar (ha)	193.18	282.87	103.59	158.03	317.52	438.76
Wind (ha)	107.55	98.22	59.09	48.17	127.51	134.02
Battery (MW)	3.00	3.00	3.00	3.00	3.00	3.00
Electrolysis (MW)	173.76	223.08	85.16	118.81	195.07	321.43
Fuel Cell (MW)	14.16	40.65	3.14	18.81	78.29	85.17
CH_4 production (kW)	6.64	7.90	3.10	3.69	0	0
CH_4 Turbine (MW)	174.55	148.06	117.52	101.85	0	0
Biomass (MW)	0	0	68.05	68.05	0	0
ASU (MW)	0	0	0	0	9.18	13.18
NH_3 (MW)	0	0	0	0	10.94	17.13
NH_3 power production (MW)	0	0	0	0	111.27	104.39

in the installed capacity takes place, mainly in the solar PV panels (as shown in Table 2), which is associated with an increase in the excess of produced power. For example, in scenario 1 in Asturias, there is a 30% energy excess but, when scenario 3 is evaluated, this value rises to about 60%. The use of H_2 also grows compared to the previous scenarios. The reason for this worst economic performance is the high cost of ammonia production and its respective conversion into power. Hence, the use of ammonia is reduced to the minimum necessary to meet the given demand prioritizing other forms of storage. Therefore, the results in scenario 3 show an increase in the installed capacity of the renewable sources, which implies a larger excess of energy when solar and wind availabilities are higher.

It is also interesting to highlight that in all the locations, a combination of wind and solar energies is selected. In none of the locations studied has a single renewable source been chosen. The advantages in terms of operation of the facility justify the introduction of both technologies. Therefore, the use of scheduling models for this kind of problem is essential in order to determine the proper combination of renewable resources and the appropriate production capacities in each case.

The seasonal storage of chemicals as methane or ammonia in the different scenarios is one of the main advantages of the Power-to-X alternatives. In Figure 6, the storage results for methane in scenario 1 are presented for two different locations: Asturias and Almeria. Similar results are obtained for the other two scenarios. In both cases, there is a seasonal storage with different profiles depending on the weather conditions in the

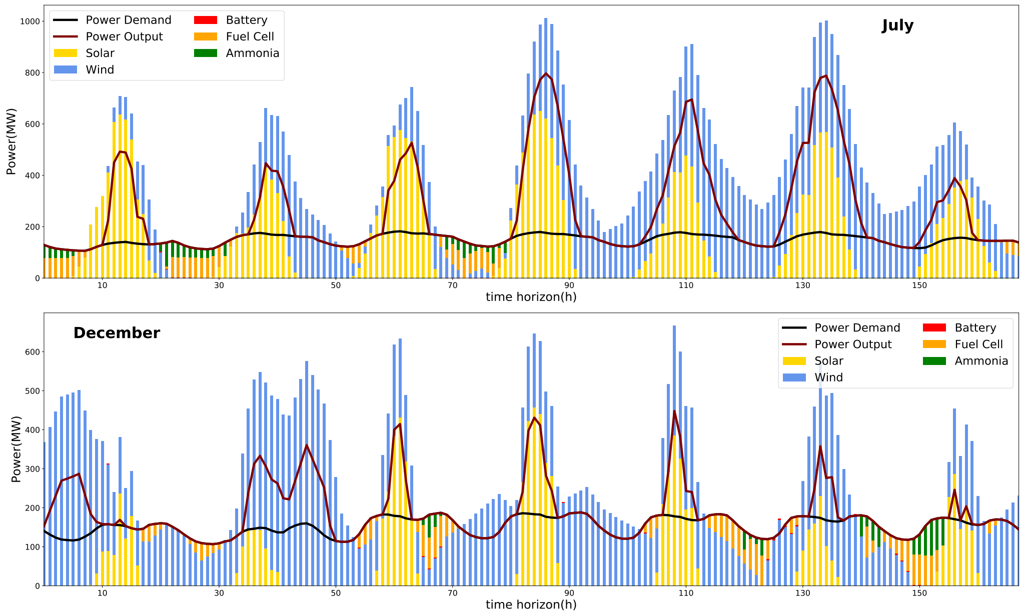

Figure 5: Scheduling results for the Scenario 3 in Asturias

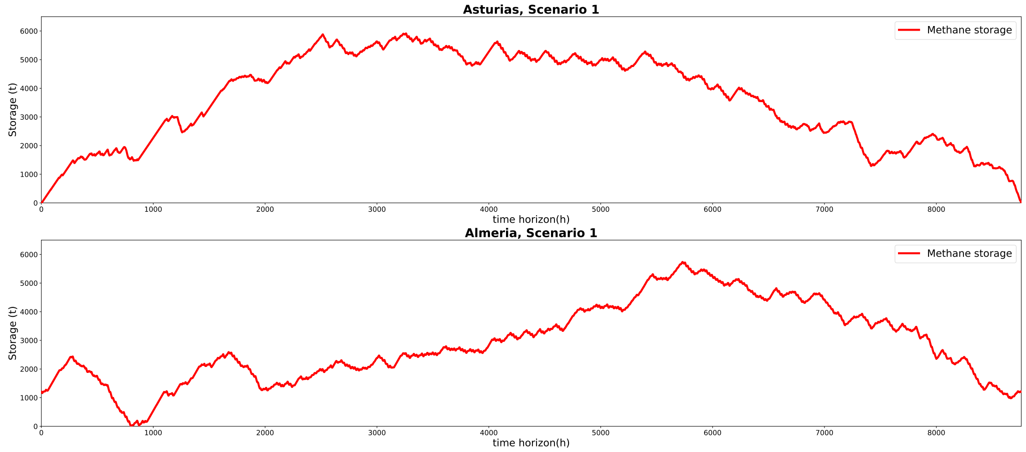

Figure 6: Storage results for methane in scenario 1

region. As a general trend, during spring/summer higher solar power production is expected, which leads to an increase in the production of chemicals as storage systems. Within the two locations shown, this is especially visible in Almeria, where solar radiation is predominant. Seasonal storage is a technology to ensure demand satisfaction but also to reduce the installed capacity of the different power generation technologies, because it is not necessary to increase it to meet the demand in all the time periods of

Table 3: Economic results for scenario 1

	Excess (%)	% Solar	% Wind	Demand cost (€/MWh)	Total cost (€/MWh)
Asturias	31.0	28.5	71.5	108.7	83.1
Almeria	42.7	54.7	45.3	127.8	89.8
Badajoz	113.9	67.7	32.3	168.7	79.0
Teruel	39.7	51.2	48.8	128.1	91.8
Leon	53.7	55.4	44.6	146.2	95.3
Coruña	29.0	29.8	70.2	100.8	78.3
Cordoba	165.1	70.8	29.2	196.2	74.2
Ciudad Real	107.6	66.1	33.9	167.8	81.0
Sevilla	59.8	58.2	41.8	142.9	89.6
Zaragoza	37.0	40.2	59.8	118.8	86.9
Burgos	38.2	48.6	51.4	131.5	95.4
Navarra	37.8	33.8	66.2	112.9	82.1
Soria	39.2	50.5	49.5	132.3	95.2
Salamanca	68.0	57.1	42.9	149.1	88.9

the year.

5.2. *Economic Results*

Based on the optimization results, the cost of electricity in the integrated facilities analyzed is calculated for each of the locations in the different scenarios proposed. Table 3 shows the results for scenario 1. Two different prices (annual average) are presented in the table. The ”Demand cost” assumes that only the power that satisfies the demand can be sold. Therefore, the excess of energy in periods with a high generation rate cannot be computed in the cost of electricity. On the contrary, the ”Total cost” assumes that all the power can be discharged at the same price including the excess of energy.

The demand costs for scenario 1 are in the range of 100-200 €/MWh which is higher than the direct generation using solar/wind energy as expected. IRENA (2020) determines an average electricity price of 53 €/MWh for wind energy and 68 €/MWh for solar energy, therefore, the cost of electricity in an integrated facility is significantly higher than the cost when only power caption units are included. The results are expected because the investment and maintenance cost required when storage technologies are included. If the total power that can be produced is computed, the range of prices decreases to 70-90 €/MWh, closer to the renewable technologies themselves. The main advantage of using these integrated facilities is that power demand can be guaranteed regardless of the weather condition (security of the energy supply). If storage technologies are not included, in different periods of time, power production does not meet power demand, which cannot be assumed in a modern electricity system. This is particularly important in the context of a power generation mix where a 97-98% share of renewable resources is expected by 2050.

Looking at the cost behavior, when the excess of energy is higher, the demand cost increases, and the total cost decreases. A larger excess of energy is due to the large number of collection units, therefore higher investment is required and, if the excess of energy cannot be sold, the demand cost significantly increases. As a general trend, locations where solar energy is predominant, have larger excess of power production compared to those where the wind is the principal source where the excess is considerably less. To illustrate this point, the largest excess takes place in Cordoba where solar generation rises to about 71%. On the contrary, Coruña is the location with the lowest excess and, in this area, 70% of the power is produced from wind turbines. In general, when the solar share increases, the total demand cost is higher. The reason for this lies in the strong seasonal nature of solar energy. Solar availability follows a recurring pattern during the day and night hours but the differences between seasons are very significant. In summer, solar production is clearly higher than in winter. Therefore, satisfying the power demand in the most restrictive time periods, implies a certain installed capacity leading to an excess of energy during the time when the resource is more available. In contrast, wind production is more volatile but does not show such strong seasonal differences.

Table 4 includes all the economic information about scenario 2 where biomass is introduced in order to assess the combination of intermittent and non-intermittent sources, and storage alternatives. As a general comment, the introduction of biomass is beneficial in economic terms with a significant reduction in the demand cost of more than 20% in most cases. One of the main reasons for the decrease in the cost of electricity when biomass is introduced is the level of utilization of the different production technologies. One of the most extended indexes to measure this utilization ratio is the capacity factor (George, 2015). For scenario 2, the average capacity factors are around 29% for solar PV panels, 37% for wind turbines, and 94% for biomass (as mentioned in the previous section, biomass operates almost as a base load generation). This large difference makes investment in biomass much more profitable (due to longer hours of operation) comparatively than in the case of solar or wind energy and can reduce the overall price of electricity. In the results of scenario 2, the excess of energy is significantly lower than in the case of scenario 1. The average value for the excess in scenario 1 is approximately 62% which decreases to about 23% when biomass is introduced. The

Table 4: Economic results for scenario 2

	Excess (%)	% Solar	% Wind	% Biomass	Demand Cost (€/MWh)	Total Cost (€/MWh)
Asturias	14.2	19.2	49.3	31.5	87.8	76.8
Almeria	19.7	39.3	28.6	32.1	96.2	80.3
Badajoz	28.3	56.7	15.7	27.6	113.2	88.3
Teruel	19.0	36.6	30.8	32.6	96.1	80.9
Leon	23.4	46.8	29.3	23.9	112.3	91.2
Coruña	12.8	20.5	48.1	31.4	83.6	74.2
Cordoba	27.5	58.1	10.7	31.2	110.4	86.7
Ciudad Real	31.5	58.3	19.1	22.6	117.9	89.4
Sevilla	21.5	46.7	20.4	32.9	101.2	83.5
Zaragoza	18.6	28.3	40.2	31.5	91.6	77.3
Burgos	22.3	39.2	36.8	24.0	105.1	86.1
Navarra	19.3	24.6	48.0	27.4	92.9	78.1
Soria	20.5	40.9	34.8	24.3	105.1	87.3
Salamanca	39.5	53.6	27.5	18.9	116.4	83.6

addition of biomass in the generation pool reduces the variability in power production because it is a non-intermittent renewable source. The reduction in the excess of energy also implies a reduction in the gap between the demand and the total cost. These results show the large potential of the combination of intermittent and non-intermittent production technologies together with storage alternatives to meet a given demand independently of the weather conditions at competitive costs. The use of biomass could be an interesting option due to the reduction of the production cost using only a small fraction of the total biomass in the region.

Finally, Table 5 contains the main results of scenario 3, where the use of ammonia is introduced as a storage alternative to develop a power facility without direct CO_2 emissions. This scenario could be feasible in a horizon in which a complete decarbonization is achieved. Ammonia as a long-term storage pathway significantly increases the cost of electricity. For the demand cost, the average value is around 280 €/MWh, and for the total cost around 145 €/MWh. Ammonia technology is a more complex process that requires higher power consumption to synthesize this chemical. All these factors translate into higher capital and operating costs which determine the final cost of electricity. Further improvements in the Haber-Bosch ammonia process could lead to a substantial reduction of the operating cost, for example, by reducing the pressure of the synthesis loop (Smith et al., 2020). On a long-term horizon, the use of electrochemical methods to produce ammonia could turn this option into a technically and economically feasible solution (MacFarlane et al., 2020). The high cost of storage leads to high excess of elec-

Table 5: Economic results for scenario 3

	Excess (%)	% Solar	% Wind	Demand Cost (€/MWh)	Total Cost (€/MWh)
Asturias	60.6	35.7	64.3	223.0	139.3
Almeria	78.0	57.6	42.4	259.8	146.6
Badajoz	135.9	64.9	35.1	344.9	146.5
Teruel	76.5	55.4	44.6	263.9	149.8
Leon	71.4	54.7	45.3	291.4	170.4
Coruña	64.7	37.8	62.2	213.5	129.9
Cordoba	188.9	64.5	35.5	389.3	135.0
Ciudad Real	122.3	62.7	37.3	340.5	153.5
Sevilla	80.7	57.1	42.9	277.6	153.9
Zaragoza	87.3	48.1	51.9	246.1	131.7
Burgos	80.4	55.4	44.6	266.6	148.1
Navarra	73.4	40.1	59.9	222.9	128.9
Soria	70.0	48.1	51.9	266.8	157.2
Salamanca	122.0	63.3	36.7	310.3	140.0

tricity. While the average excess in scenario 1 was about 60%, in this case, the average rises to about 90%. The results minimize the storage increasing the installed capacity of wind/solar resources, which on high production days leads to large energy excesses.

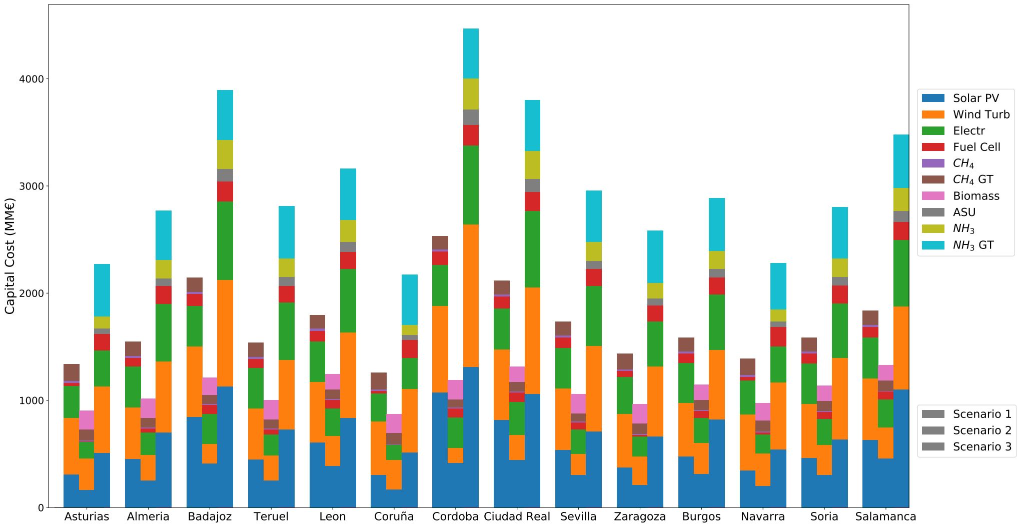

Figure 7: Capital cost for the different locations and scenarios

Regarding the total investment required, Figure 7 shows the capital costs for the different scenarios and for the different regions with an associated satisfied demand of about 1275 GWh per year. For scenario 1, capital costs range between 1,000-2,000 MM€. The main source of this investment is the power production technologies. In all cases, wind and solar accounts for about 60-70% of the total capital cost. Investment in wind/solar falls sharply in scenario 2 to levels close to 50%. The share of storage technologies also decreases due to the non-intermittent nature of the biomass source. The introduction of this renewable resource also reduces the total capital cost in all regions, as expected based on the capacity factor calculated above. To satisfy a given level of demand, the lower the capacity factor of a technology, the higher the installed capacity required and, hence, the higher the investment. Finally, when scenario 3 is analyzed, there is a very substantial increase in the total capital cost. Investment in solar/wind technology and in electrolysis rises to avoid the use of ammonia that presents a higher cost. Large differences can be found between investments in the different regions. In general, in locations with a high proportion of solar-based power production, the total capital cost of the integrated facility increases. For example, Cordoba is one of the provinces with the highest share of solar energy, and the investment in this region, for example in scenario 3, exceeds 4,000 MM€ while in Coruña, with high wind penetration, the total capital cost is around 2,000 MM€.

As expected, the introduction of storage technologies into power generation in order to ensure demand satisfaction in the context of a new energy system based on variable renewable energies is a challenge in economic terms. The use of storage technologies increases the cost of electricity, but is necessary for a robust power system. To incentivize the introduction of storage technologies in the power grid, an interesting option could be to use the existing capacity payments. These, in the current system, guarantee a sufficient generation capacity to meet the demand for electricity at all times (including the peak demand). In the case study assessed in this work, the capacity payment budget amounts to around 658 MM€ per year distributed, mainly, between natural gas power plants and, during the last years, also coal-based facilities (now decommissioned) (Fundacion Naturgy, 2020). Therefore, if this budget is used in terms of energy storage technologies, the cost of electricity in these integrated facilities could be reduced targeting a competitive cost. All these measurements to introduce energy storage at grid scale will be included in the future regulations of the capacity market, the tool to face the new power system with high penetration of renewable generation (Huhta, 2019).

5.3. Social results

In addition to the economic results, the social impact of the energy transition must also be assessed. The results for the proposed social index are presented in Table 6.

Table 6: Results of the social index for the studied locations

	1 - MW	2- Loss of jobs	3- MW/GDP	4 - % GDP	5 - Unemployment	6 - Loss of pop.	7- Ageing	8 - Pop. density	9 - Youth mig.	10 - GDP per cap.	Total
Asturias	7,47	6,53	2,84	4,38	3,10	9,25	8,95	3,40	4,38	8,95	59,24
Teruel	3,80	10,00	10,00	9,73	0,62	8,50	5,84	9,97	7,94	5,84	72,24
Leon	6,99	6,06	6,19	7,95	3,12	10,00	10,00	8,44	7,36	10,00	76,11
Coruña	10,00	1,05	3,32	3,46	2,11	7,92	6,97	0,00	1,99	6,97	43,78
Almeria	4,00	0,92	2,54	6,88	5,26	0,00	0,00	4,39	3,41	0,00	27,40
Cordoba	1,12	0,42	0,68	6,73	7,34	7,84	2,58	6,37	7,68	2,58	43,35
Badajoz	0,00	0,00	0,00	7,30	8,34	7,85	2,86	8,32	7,01	2,86	44,54
Ciudad Real	0,00	0,00	0,00	7,76	7,29	7,38	3,19	8,77	10,00	3,19	47,57
Sevilla	0,00	0,00	0,00	0,00	10,00	5,66	0,69	0,16	3,38	0,69	20,59
Zaragoza	0,00	0,00	0,00	3,28	2,30	5,20	3,51	6,40	1,67	3,51	25,86
Burgos	1,61	3,14	1,36	7,81	0,11	7,56	5,82	8,73	6,28	5,82	48,22
Navarra	0,00	0,00	0,00	5,25	1,22	3,81	2,37	5,56	0,00	2,37	20,56
Soria	0,00	0,00	0,00	10,00	0,00	8,61	7,05	10,00	6,95	7,05	49,66
Salamanca	0,00	0,00	0,00	8,74	4,62	9,35	8,39	8,64	9,88	8,39	58,01

As indicated, the higher the social index, the worse the social situation of the region under study. The original data to calculate this index for each location is presented in the Supplementary Information.

As mentioned above, the first three items of the index are related to the energy transition and its social impact, and the last seven are to the general social situation of the region. In terms of the social impact of the energy transition, Teruel emerges as one of the regions with the highest impact. The small size in economic and employment terms of this province means that the relative importance of the traditional electricity sector is high. In general, the regions located in the northwest of Spain (Leon, Asturias, Coruña) are the most affected group by the energy transition due to the high importance of the coal sector (including mining and power generation). If the entire social environment is analyzed, the results are different. Various regions of the center of Spain are the most affected by social issues, for example, Leon, Soria, Salamanca, or Ciudad Real. Therefore, the investment in the new energy system can help to mitigate the social distance to other parts of the country. Job opportunities could be created in the different phases of the plant. During operating and maintenance of the solar PV panels and wind turbines, around 0.4 jobs/MW and 0.3 jobs/MW respectively could be generated (Cartelle Barros et al., 2017). For the Power-to-X storage processes, the correlation for job creation in chemical plants developed by Heras and Martín (2020) could quantify the new jobs opportunities. Additionally, in the areas where these facilities are installed, different local and regional taxes on these facilities could improve public services in the selected areas. Furthermore, the region's economic activity is boosted by new capital investments, land rental fees, etc. (Springer and Daue, 2020).

If all factors of the index are included, Leon is selected as the region with the most social disturbances (the highest social index) and, therefore, where the new investment and the public policies should be targeted to ensure equal opportunities for citizens regardless of territory. This region is affected by the energy transition, with important mines and about 2,000 MW of the coal-based power capacity decommissioned, and, also, by social problems such as aging or low population density. On the other end, regions such as Sevilla or Navarra have the lowest social impact. Although these regions have been selected to be included in this work due to the high potential in wind or solar energy, the social impact of the investment in these locations is significantly lower. Therefore, a trade-off between economic and social impact arises. For scenario 1, Figure 8 shows the comparison between the social index and the cost of electricity (demand cost) for all the studied regions. Similar results are obtained for the other two proposed scenarios (as shown in the Supporting Information).

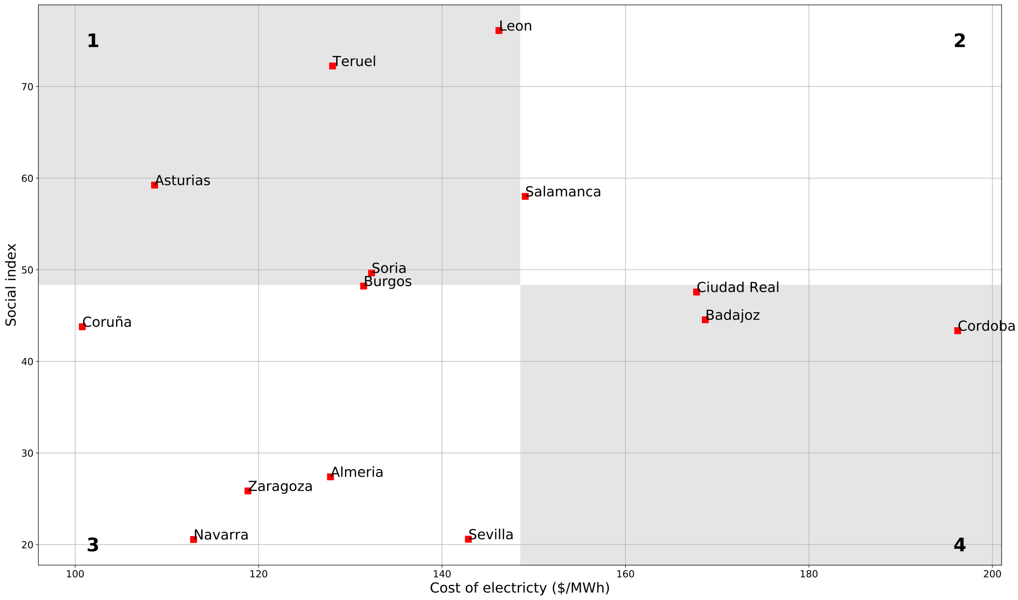

Figure 8: Social and economic results for scenario 1

In this Figure, it is possible to divide the space into four different sections: high social impact and low cost of electricity (1), high social impact and high cost of electricity (2), low social impact and low cost of electricity (3) and low social impact and high cost of electricity (4). The most promising regions are those in the first sector (1) where the social impact of the new facilities is high and it is possible to produce renewable electricity at a low cost. Particularly, Asturias and Teruel could be the two best performing locations in both indexes. In these two locations, the energy transition is significant and the weather conditions make it possible to reduce the electricity cost. In other places, the cost of electricity may be reduced or be similar, however, the social impact is lower. For example, Navarra and Asturias have similar costs of electricity, but, if the facility is located in Asturias, the social impact increases drastically, helping to mitigate the effects of energy transition and social problems in these areas.

Therefore, these results show the paramount importance of using these two indicators, economic and social, to plan the energy transition in a scenario targeting a 100% renewable power system. Using this dual perspective, stakeholders could make the fair decisions in the uncertain horizon of a new energy system.

6. Conclusions

This work presents an optimization analysis of integrated facilities combining intermittent and non-intermittent renewable sources together with different storage technologies. The objective is to ensure demand satisfaction regardless of the weather conditions. Three different scenarios are evaluated for various power sources and energy storage alternatives. For all regions and scenarios, it is demonstrated that the use of storage alternatives is required to meet the demand at all times of the year. These storage technologies also allow for seasonal storage of energy since solar energy is more intense during summertime. In all cases, there is an excess of power production, mainly, when high availability of solar and wind is expected. From an economic perspective, the demand cost of electricity for the base case scenario is about 138 €/MWh, depending on the selected location.

If biomass is introduced in the power generation pool, the optimization results show that a base-load behavior is expected with only small fluctuations when the solar/wind based power production is high. The use of this non-intermittent renewable source is beneficial from an operational and economic point of view, with a reduction of about 20% in the cost of electricity. In this work, the use of biomass has been assessed due to the more mature state of the art. Other non-intermittent sources such as geothermal, with a more limited expansion at present, could be analyzed in future works. Finally, in a forthcoming economic system free of CO_2 emissions, the use of ammonia as an energy storage alternative could be an interesting and feasible solution. According to the results presented, ammonia-based storage is expensive compared to the methane alternatives evaluated in scenarios 1 and 2, reaching values for the cost of electricity of around 280 €/MWh.

In the planning of the new energy system based on sustainable criteria, the economic factor should not be the only one evaluated, directing the actions of all actors involved. The social aspect is very significant, in order to mitigate the negative social effects of the energy transition and the social inequalities of the society. In this work, a new social indicator has been developed to determine the regions that require special social support to mitigate the social impact and, therefore, where investment in the new energy system could have the strongest impact. The results show that in certain regions (as Teruel or Asturias), it is possible to ensure a good economic performance of the integrated facilities in locations with a high positive social impact of the new projects. The complete planning of the new energy system using this methodology (social and economic perspectives) at country/continent level is a challenging future work in this area. To conclude, the importance of introducing non-intermittent renewable sources and energy storage at the grid level is demonstrated in order to guarantee demand satisfaction in a new energy paradigm based on, mainly, solar and wind renewable sources. To deploy these new technical requirements, this work provides an economic and social evaluation for different regions with the objective of providing the tools to make the best decisions to achieve a fairer and more sustainable society.

Nomenclature

Indices / sets/ subsets

$h \in H$	Seasons in the multiscale time representation
$i \in I$	Processes evaluated in network
$j \in J$	Resources involved in the network
$m \in M$	Operating modes for each of the process
M_i	Operating modes for a process
$\hat{S}$	Resources that could be stored
$t \in T$	Time periods in the multiscale time representation

Variables/ parameters

$B_{CO_2,ht}$	Amount of CO_2 introduced
C_i	Production capacity for different processes
$\bar{C}_j$	Storage capacity for different resources
J_{imht}	Process operating cost not related to capital cost
OC	Operating cost
P_{iht}	Amount of reference resource produced
x_i	Binary variable to select process units
$\bar{x}_j$	Binary variable to select storage units
α_j	Annualized fixed capital cost for storing
β_j	Annualized unit capital cost for storing

γ_i	Unit capital cost coefficient
δ_i	Fixed capital cost coefficient
ρ_{ij}	Conversion factor of the different products with respect to the reference resource
σ_i	Conversion factor between capital and operating cost for a process
ξ_j	O&M cost for storing
φ_{CO_2}	Cost of carbon dioxide

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