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Modelling a Decarbonization Agenda for Bembibre's Industrial Park

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Abstract. The design of the Sustainable Strategy Agenda for the Bembibre industrial zone in the Bierzo region employing the Open-Source Energy Modeling System (OSeMOSYS) is presented. This municipality, which has been affected by the collapse of the coal mining industry, is at the epicentre of the reindustrialization and Just Transition (none left behind) initiatives of the Spanish government. Among the challenges to be tackled are the zone's entire decarbonization by 2030, the incorporation of circular economy initiatives, and the development of quality jobs that attract and retain new residents. To facilitate decision-making, different roadmaps have been evaluated, including the repurposing of an old coal mine galley as a reverse hydro storage system, the deployment of enterprises dedicated to the recycling of solar panels, and the incorporation of second-life batteries from electric vehicles as energy storage. Among the scenarios evaluated, the most complex turns out to be the most interesting. With an initial outlay of 190 M€, it incorporates a 210 MW photovoltaic park linked to a mixed storage system comprised of 0.25 GWh of reverse hydraulic systems and 68MWh of second life reconditioned batteries. About 850 jobs in the implementation stage and 70 more permanent in the exploitation phase are envisaged.

Key words. Sustainable Energy Transition, Circular Economy, Leaving No-one behind, OSeMOSYS.

1. Introduction

The Bierzo region located in León (Spain) has been catalogued by the Ministry of the Ecological Transition and Demographic Challenge (MITECO) as priority region for social sustainable transition actions in the frame of leaving no one behind. Formerly, by the middle part of the 20th century, the region's economy was mainly based on mining and electricity generation, including hydroelectric and coal fueled power plants. Most mines were shuttered beginning in the late 1980s, and the region experienced a period of hardship following the collapse of the mining industry. Undoubtedly among the most glaring effects of the crisis is the massive loss of the youthful population due to emigration, together with a shortage of decent employment. In fact, these vulnerable areas became regarded as the "emptied Spain". In the last years, the region underwent a major transformation with the establishment of several industrial and service firms, the resumption of commercial wine production, and in general a radical improvement of the region's infrastructure.

Furthermore, the municipality of Bembibre is developing a self-managed industrial park, among other actions. The objective is to facilitate the establishment of innovative technology-based companies that will put Bembibre on the map. The purpose is to attract enterprises that are concerned in renewable energy, either directly or indirectly. As an added value, the responsible managers propose designing strategies that allow a decarbonized and energetically self-sufficient park.

The NEXT generation EU fund will give these vulnerable regions a special opportunity for the establishment of an ambitious 2030 strategic agenda. The main targets are the rehabilitation and recovery of natural areas harmed by coal mining activities, as well as the generation of employment in the short term, with a focus on hiring former mining workers, especially those from auxiliary firms.

However, as a condition, such sort of funding has a knock-on effect for electric enterprises attracted by favorable economic conditions. The broad offer of initiatives, alongside a lack of awareness of the medium-long term social, economic, energy, and environmental implications, makes it even more challenging for local leaders to take concrete and well-informed decisions.

In the current nexus frameworks for sustainable development, various tools are being developed and validated. Among them, OSeMOSYS (Open-source Energy Modeling System) [1], a tool that allows predictive modeling and can evaluate the medium-long-term effects of different development strategies or scenarios, favoring the making of appropriate decisions. The model can be freely applied according to the user's needs and constrains.

The several plans being considered for the development of the Bembibre industrial park ranges from solar panel recycling enterprises to hydrogen or biogas generating plants. The installation of a solar panel recycling facility with an anticipated yearly processing capacity of 7000 tons of solar panels are also included. Another intriguing proposal is to repurpose an old mine gallery as an energy storage system. Further, as a storage solution, applying reconditioned second-life batteries is contemplated in the optimal pathway. In essence, each of the initiatives favors the objectives of circular economy, decarbonization, or mining space rehabilitation and this work focuses on the feasibility study and economic optimization of these initiatives by applying the OSeMOSYS tool.

2. Case Study

Bembibre [2] is a municipality of 8,279 inhabitants located in the Bierzo region of Spain**.** After serving as one of the main country's coal mining regions, the area is undergoing transformation in accordance with Spain's fair transition strategy, which includes the implementation of an industrial zone controlled by the local government. The industrial zone, known as Bierzo Alto [3], has 660,490 m² with a potential development of 110.000 m² and more than 80 established companies. It has strong road and rail connectivity. The related plant is illustrated in Figure 1. The Municipality's Department of Industrial Promotion is intended to focus on the growth of renewable energies and the promotion of the circular economy, becoming a focus of quality employment creation for the area.

Fig.1. Bembibre industrial park plant [4]

A solar panel production company has already been established. ESCELCO [5] is a R&D&I factory being the only producer in Europe with a line of cells and panels integration and offering customized products. Among the future development plans is the commissioning of a dedicated plant for solar panels recycling once they reach their operational lifetime. According to an extensive market study [6], recycling solar panels initial factory processing annual capacity can be estimated at 7.000 tonnes of solar panels. A rough estimate of the annual energetic demand will be 195 GWh. As working hypothesis, a processing capacity linear increment of 0.25% is assumed and the project implementation is foreseen to kickstart in 2023.

Regarding actions aimed at the recovery and enhancement of the territory, another interesting initiative is the possible reconversion of the retired underground coal mine into a reverse pumped storage for active energy storage [3]. The project could deliver a blueprint for providing continuous power from intermittent and zero-emission sources. Even if the total useful water failing is estimated in 1450 m a first phase exploiting the more accessible 740 m is considered. The forecasted storage capacity is 0.25 GWh.

Other medium-term proposals for inclusion in Bembibre's transformation strategy, such as the construction of a green hydrogen plant or the generation of biogas, are too relatively early in the development process to be included in the current study.

3. Methodology

This section explains the fundamental components of the OSeMOSYS core of economic energetic modeling as well as the Reference energy system (RES) of the technologies under consideration in this study. The purpose of achieving the specified objectives, along with the precise cost values of each technology, are emphasized in OSeMOSYS through scenario comparison, that is to be addressed in this subsection.

A. OSeMOSYS Modelling tool.

Following the 1970s oil crisis, demand-side energy system assessments arose and continued to evolve, culminating in forecasting methodologies that were eventually turned into top-down models [7]. Meanwhile, the supply-driven method has advanced, yielding integrated bottom-up models that are technologically focused on predicting needed investments or operating short-term solutions [8], [9]. Ultimately, merging bottom-up and top-down models provided better insights for decision-makers [10], [11], [12]. As an outcome, multiple models, notably OSeMOSYS, have been developed to improve the design of energy supply networks by increasing knowledge of current and future interactions between demand and supply, the environment, and the economy.

OSeMOSYS is a dynamic bottom-up linear optimization model used for integrated assessment and energy planning with a medium-to-long time horizon. It is precisely evolved to model and calculate the energy supply mix in terms of generation capacity and delivery as well as meeting the demand for energy services every year and at every stage of the case under investigation by minimizing the total costs across the board [13]-[7]. The system total cost, which includes the Capital cost, Fixed cost, and the Variable cost are the merit variable to be optimized.

OSeMOSYS employs deterministic linear optimization in conjunction with various input variables relating to technological constraints, economic realities, or environmental targets, and thereby provides insight to decision makers [14].

Since its inception in 2011, various versions of OSeMOSYS have been developed to enhance the simulation condition such as timing and relaxing optimization; as well as energy-related coding blocks like storage, short-term flexibility, interconnections, and improved reality modeling to name a few. Currently, several analysis interfaces are in use, with MoManI being chosen for this work.

B. Reference Energy System (RES)

The economic viability of different scenarios has been evaluated using OSeMOSYS. Renewable energy resources (solar and wind) are considered as energy production technologies. The storage can be covered for either reversible hydro (RH) or Lithium based batteries. Always in the philosophy of promoting initiatives based on circular economy, the possibility of incorporating used batteries from electric cars (second life batteries) is opened. The option of import energy from the electrical grid coming from REE ("green power grid") was allowed. The RES (Reference Energy System) of the technologies employed in the investigation is displays in figure 2.

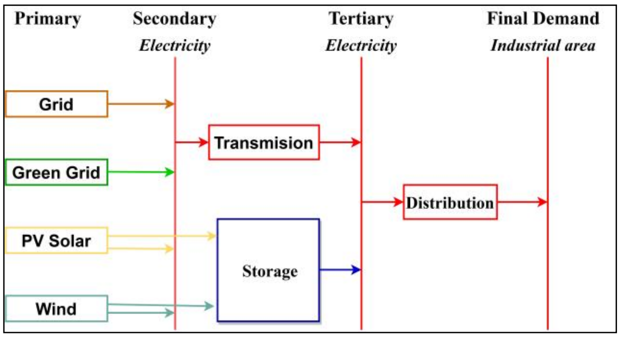

Fig.2. RES of the analysis-related technologies

Concerning technological and economic data sets, both annual reports of REE [4,6] and those of specialized production and distribution companies in the sector have been used.

The associated costs, specifically the investment, production, and maintenance costs presented in table I, were acquired from [15]-[18]. The analysis does not account for any additional costs related with emissions penalties.

Concerning emissions, only grid-related technology is associated with an activity ratio of 0.80 (tons/MWh), corresponding to the average rate of CO_2 emission from the Spanish grid [19].

C. Definition of scenarios

The aims of Bembibre's decision-makers for the development of the industrial zone was incorporated as constraints for the energy transition modelling more specifically to:

- Select initiatives that will ensure complete decarbonization by 2030,
- Promote initiatives based on circular economy processes,
- Create a R&D industrial pole.

From a technological point of view, the reference energy system is portrayed in Figure 2. As sources of self-produced energy, both solar and wind energy resources are included. The centralised electricity grid constitutes the imported source. Both the standard grid and the so-called *green electricity* [3] are also included. Green electricity is an energy product that emerged from the liberalization of the sector based on the distribution of electricity generated with renewable energies.

For storage technology, hydraulic reverse pump (RH) is taken into consideration. Other possibilities that involve battery storage are also being examined, including first-life batteries (FLB), second life battery (SLB), and second-life reconditioned battery (RSLB). The economic data sets for batteries were gathered from report [20] of and those of specialist production and distribution businesses within the industry [21], as detailed in Table I.

Table I: Associated cost data set for each technology included in the RES. In brackets the reference used to extract data.

Technology	Variable cost (M€/GWh)	Capital cost (M€/GW)	Fixed cost (M€/GW)
Grid	0.14 [15]	0	0
Green Grid	0.18 [16]	0	0
Solar PV	0	875.90 [17]-[18]	28 [17]-[18]
Wind	0	1538 [17]	2.70 [17]
RH	0	632 [18]	5.64 [18]
FLB	151 [20]-[21]	8.99 [20]-[21]	10 [20]-[21]
RSLB	77 [20]-[21]	8.99 [20]-[21]	10 [20]-[21]
SLB	53 [20]-[21]	8.99 [20]-[21]	8 [20]-[21]

Under this study, six scenarios are elaborated using the energy mix of technologies mentioned in RES and afterwards analysed employing strictly economic optimization. The defined scenarios are as follows:

- **BAU scenario.** (Business as Usual). In this scenario, only carbon emissions were limited, and it was assumed that no new initiatives were implemented. It corresponds to the least ambitious scenario and serves as a base to evaluate the rest of the proposals.

- **Productive initiatives scenario (PIS).** Under this scenario, renewable energies, and circular economy was considered through the implementation of a plant for solar panel recycling. Both solar PV and wind technologies are incorporated to the RES.

- **Reverse Hydraulic Storage scenario (RH).** In this case, the first phase project of rehabilitating the ancient mine's galleries to reverse hydro is included with the assumption that the power need for the pumping will be covered by renewable resources. The usable storage capacity has been evaluated from the characteristics available after the recovery of the old galleries of the nearby abandoned mine (740m fall).

- **Battery storage scenario**. The three types of batteries previously described as accumulation sources are analysed throughout this scenario. As in the RH scenario, the supposition is that renewable energies will be the primary source of the energy to be accumulated. As working hypothesis, a pilot project of 68 MWh is foreseen.

- **RSLB storage scenario.** Facilitating the process towards the circular economy, in this case, only reconditioned second-life batteries are regarded, which are powered by renewable technologies. The same storage capacity limitation that in the previous scenario is applied.

- **RH & RSLB scenario.** Because storage capacity for each technology is limited, this scenario incorporates reconditioned second life batteries as well as reverse hydraulic in the RES. As main hypothesis renewable energy will be harnessed to power the two storage technologies.

As common working hypothesis, the polluting emissions will linearly drop till 2030 to ensure the full decarbonization of the industrial park. Following the actual Spanish legislation, no emissions penalties are applied.

4. Results

For each scenario, the power capacity installed, the initial capital investment as well as the total costs were evaluated. In all cases, the variables are integrated along the time interval under study. In our case, from 2022 till 2035. Tables II summaries the new capacities installed for each technology.

From the point of view of implementation of productive technologies, it should be noted that solar energy appears dominant probably because of the reduced local wind resource. As for storage technologies, in both cases the installed capacity completes the limits imposed.

Table II: Main technical results for the scenarios

Scenario	PV Capacity (MW)	Hydro Storage Capacity (GWh)	Battery Storage Capacity (GWh)
BAU	0	0	0
PIS	100	0	0
RH	120	0.25	0
Battery Storage	237.5	0	0.11
RSLB	190	0	0.068
RH & RSLB	210	0.25	0.068

Regarding the contribution of each of the technology to the energy production, Fig.3. shows the details of the temporal evolution of each scenario in the period under evaluation.

In the most conservative scenario (BAU) the decarbonization process forces the progressive incorporation of green electricity. Obviously, this scenario maintains a total external energetic dependence.

The incorporation of new productive initiatives marks the incorporation of photovoltaic production that contributes almost 50% to total energy needs.

The scenario incorporating reverse hydro storage favours, as expected, the local production. In fact, in this case the external dependence decreases by 70% compared to the BAU scenario.

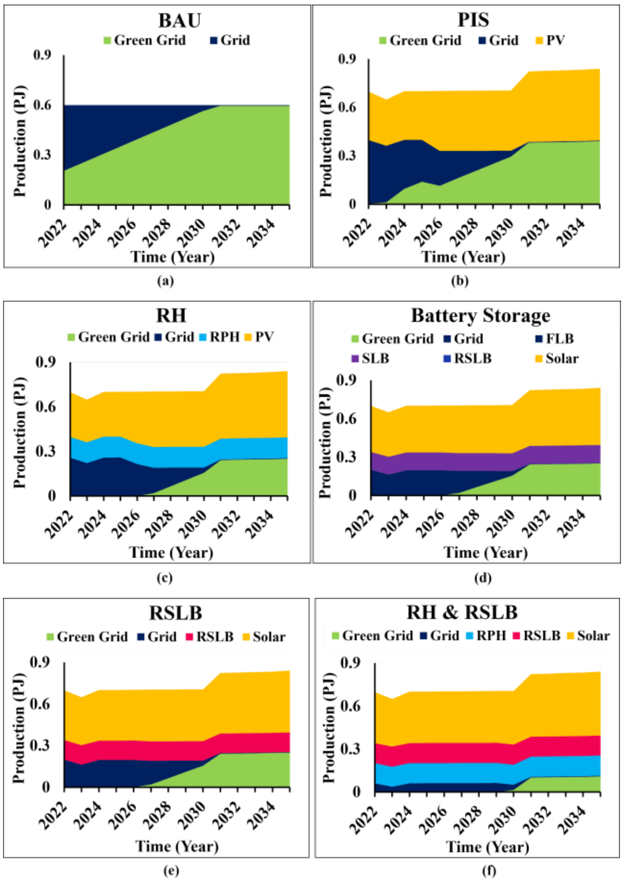

Fig.3. Yearly distribution of the energetic production differentiated by technologies. (a) the BAU scenario; (b) the New Initiatives scenario; (c) the Reverse Hydro storage scenario; (d) the Battery storage scenario; (e) the Reconditioned second life battery storage scenario; (f) the Storage mix scenario: reverse hydro & reconditioned second life battery storage.

A deeper evaluation shows that the energetic production capacity of the RH storage system reaches its limit. This extension can be completed by expanding the reverse pumping or by including other technologies such as a second-life battery system. In this regard, scenarios combining reverse hydro and reconditioned second life batteries greatly benefit local independency. In contrast to the BAU scenario, the external dependence in this instance declines by 90%.

Lastly, table III highlights the economic analysis focused on both the initial capital investment and the overall costs.

In the case of first life battery storage scenario, both investment and global costs have more than doubled as contrasted to the RH scenario. Indeed, within the battery storage scenario, the pure economic optimization provides a decision alternative toward the second life battery. However, when deployed in a high-energy system, this sort of battery presents several technical hurdles. These challenges include a decline in energy density and power potential while fast charging. The battery will eventually reach a point where it can no longer serve its purpose in the new application because internal resistance develops during the battery's first life [22]-[23]. This has resulted in a significant oversizing of both PV and battery to reduce the DOD and achieve a competitive service life.

Hence, unless battery storage installation is desired, the better option may be to use reconditioned second life batteries, which are more advantageous in both technical and economic terms (see Table II and Table III for detail).

Table III: Main economic results for the scenarios under study

Scenario	Global Cost (M€)	PV Invest Cost (M€)	Hydro Invest Cost (M€)	Battery Storage Invest Cost (M€)
BAU	395.53	0	0	0
PIS	359.18	84.51	0	0
RH	358.35	101.41	8.19	0
Battery Storage	499.57	238.83	0	5.53
RSLB	376.13	158.46	0	5.24
RH & RSLB	396.17	177.47	8.19	5.24

When considering the overall integrated cost, the outcome to highlight is that, in regard to the long-term performance, the most complex scenario (RH & RSLB) that permits 90% energy independence is equivalent to the Basic (BAU) that is 100% dependent on the central electrical grid. It is however vital to note in that 48% of this overall cost corresponds to initial investment. This necessitates initiatives to secure external funding.

Furthermore, the socioeconomic impact of the renewable energy sector has contributed to the development of a wide range of employment opportunities in the manufacturing, distribution, construction and installation, operation, and maintenance of local installer utilities.

This job creation will be crucial for sustainable social development given its economic impact as well as population fixation. Employing job statistics from various leading countries [24] in the solar [25], hydroelectric [26]-[27], and battery storage [24] sectors, an approximate assessment of the expectations of quality job creation associated with each of the scenarios under consideration is conducted (see Table IV). Jobs associated with companies committed to the recovery of solar panels and the reconditioning of used batteries are not being considered.

Table IV : Main socio-economic results

Scenario	Installation Process (Number of Jobs)	Operation process (Number of jobs)
PIS	500	20
RH	750	50
Battery Storage	600	35
RSLB	540	30
RH& RSLB	850	70

5. Conclusions

The current paper assesses, the feasibility of different prospective proposals for the Bembibre industrial park within the framework of a sustainable social transition. OSeMOSYS has been applied as optimization tool. A circular economy initiative based on the implementation of a panel recycling plant with a capacity of 7000 tonnes of solar panels per year is being contemplated and included in the overall energetic demand. The deployment of a solar photovoltaic park and the possibility to harness the galleries of an old Coal mine as an accumulation system that relies on a reverse hydraulic system with a capacity of 0.25 GWh/year as well as the implementation of a pilot project for a storage based on second-life batteries from electric cars of 68MWh/year are evaluated. Furthermore, to ensure complete decarbonization of the industrial park, the so-called "green electricity network" upgrade is incorporated.

Considering the aim of offering convenient energy plans favoring comprehensive decarbonization by 2030, newer initiatives in addition to the conservative scenarios are investigated, one of which requires the deployment of PV and the other with PV and reversible hydraulic. Investigations into additional scenarios that call for the use of batteries and solar power are also conducted (first life, second life and reconditioned second life). And last, a scenario that combines PV with reverse hydro and reconditioned second-life batteries.

In term of economical and local reliance, the tendency tends to the storage option more particularly the mix of the reverse hydro and reconditioned second-life battery scenario is the most promising. Indeed, combining the two storage systems reduces the amount of supply from green network technology, guaranteeing local production capable of meeting 90% of polygonal demand. With total overall costs during the study period similar to those of the current model (BAU), a substantial initial investment of close to 200M€ is required.

Finally, through previous experiences, a significant social impact is expected associated with the creation of some 850 jobs in the implementation phase and 70 more permanent in the exploitation phase.

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