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Techno-economic benefits of grid-scale energy storage in future energy systems

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Abstract

The increasing penetration of renewable energy sources in the power sector represents an important challenge for energy systems due to their elevated intermittency. Energy storage constitutes a key component for its ability to add flexibility to the system allowing further integration of these renewable sources. Therefore, the aim of this study is to analyse the impact of grid-scale energy storage in a hydro dominated power system with increasing renewable generation shares. The Colombian energy system is used as a case study. The model used in this work is built using the EnergyPLAN tool and validated against actual data. Successively, the techno-economic effects of large-scale energy storage technologies are assessed on three different future scenarios for the year 2030. The results evidence that increasing levels of storage could allow significant reductions in both the curtailed energy and the total fuel consumption of the country. The best-case scenario shows an estimated 67% reduction in the emission intensity of the power sector by 2030 compared to the baseline scenario.

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Keywords: Energy storage, modelling, EnergyPLAN, Colombia, renewable energy.

1. Introduction

Increasing the flexibility of power systems is a key component in the global efforts oriented to meet the climate change mitigation goals defined at the 21st Conference of Parties (COP21) in Paris in 2015. Flexibility is needed in order to

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reach renewable integration targets without affecting the reliability and efficiency of the grid. Utility-scale electricity storage is considered one of the technologies suited to assist in the effective integration of these sources, especially in countries with weak infrastructure [1].

Each country has a specific potential for energy storage according to its characteristics, such as energy resources available, grid infrastructure, regulatory framework, and electricity demand patterns and trends. Latin America is considered as one of the most attractive emerging markets for energy storage development due to its recent growth in renewable generation, rapidly growing populations, and relatively unstable grid conditions [2]. In order to understand the effects of this technology in the power system, the development of models that allow the assessment of its performance is required. A considerable amount of literature has been published on this issue [1,3–6]. However, the majority of the studies are usually focused on small-scale applications [1] and power systems with electricity mix dominated by fossil fuels [4,5]. In the case of countries with high share of hydropower in the electricity mix, very few studies have investigated the impact of utility-scale energy storage [7]. Therefore, the aim of this study is to analyse the techno-economic effects of large-scale energy storage in the integration of variable renewable energy by using the Colombian power system as a case study. The EnergyPLAN tool has been used to build the model and simulate the scenarios.

This paper has been divided in five sections. Section 2 provides a description of the Colombian electricity system. Section 3 introduces the methodology, including a description of the modelling tool used, the main assumptions and the defined scenarios. Section 4 summarises the main findings of the study, and the last section presents the conclusions and recommendations for future works.

2. Power sector in Colombia

The power sector in Colombia has been traditionally dominated by hydro and thermal generation, with average contributions of 71% and 28%, respectively during the last years. The remaining 1% of the total is produced by other renewables (i.e. wind, solar and bioenergy) [8]. In 2017, the installed capacity was 14.4 GW and it consisted of 69.9% hydropower, 24.8% natural gas power plants, 4.9% coal power plants, 0.4% cogeneration and 0.1% wind [9]. Currently, there is not any grid-scale electricity storage system in the country, and even though the large amounts of energy stored in the dam reservoirs can be used for long-term purposes, its short-term operation is restricted due to the system configuration. The elevated reliance on hydro resources makes the system vulnerable to strong droughts caused by El Niño and La Niña southern oscillation (ENSO). The hydropower generation can vary between 45% and 95% during these periods because of the changes in natural water inflows to the hydropower plant reservoirs [10]. Thermal generation is used to keep the stability and reliability of the national grid due to limitations in the power transmission system. Furthermore, they are used to match the demand during dry seasons when large hydropower plants operation is limited. According to the Mining and Energy Planning Unit (UPME) [11], an average annual increase of 3.1% in the national electricity demand is expected for the next 11 years.

3. Methodology

This section introduces the methodology applied in order to develop the Colombian power system model. The modelling tool, input data and defined scenarios are outlined.

In order to analyse the effects of large-scale energy storage on the power system, a model that represents the Colombian power system was first developed. After revising the different modelling tools available for these analyses [12], the EnergyPLAN tool was selected. The objective of this tool is to provide assistance in the design of regional or national long-term energy planning alternatives on the basis of the techno-economic assessment of different strategies [13]. EnergyPLAN produces a deterministic model using analytical programming, and therefore the tool is able to calculate the results in less time compared to iterative solvers. The tool runs a high temporal resolution simulation for a complete year and generates hourly outputs. The overall sketch of the EnergyPLAN inputs/outputs can be seen in figure 1. General inputs include system demands, renewable energy sources (RES), power plant capacities and efficiencies, costs, and a number of optional regulation strategies. The main outputs are annual energy productions, imports and exports of electricity, CO_2 emissions and excess of electricity production [14]. Even though EnergyPLAN can represent the primary sectors of any energy system, in this study only the power sector is considered. A more detailed description of the modelling tool and an extensive selection of case studies can be found in [15].

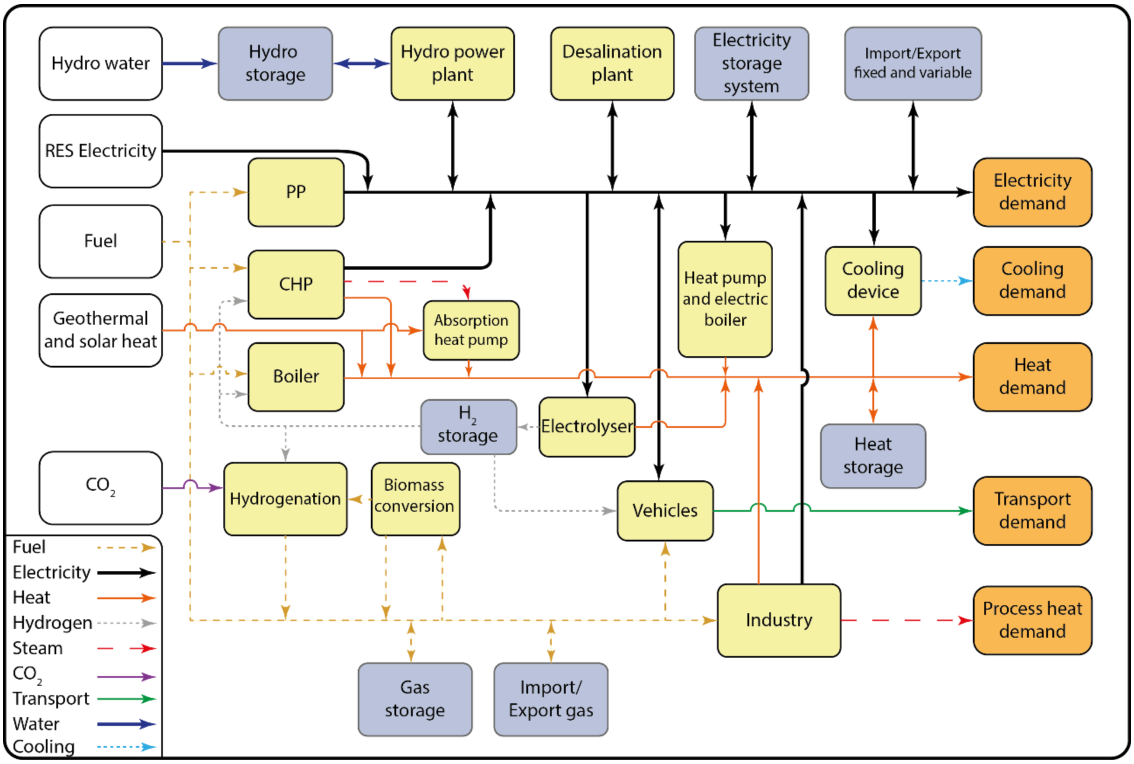

Figure 1. Overall sketch of the EnergyPLAN modelling tool [15].

Building a model in EnergyPLAN that represents a national energy system requires a series of inputs and assumptions, and thus, it is necessary to ensure that the model is validated against actual data (this is described in detail in section 4.1) [4]. The reference energy system model was developed based on 2014 inputs from Colombian statistics. Hourly electricity supply and demand data were supplied by XM (National grid) through its PORTAL BI [16] and the electricity demand for the reference year was 64.3 TWh. The capacity and efficiency of the power plants were obtained from the Colombian Electrical Information System (SIEL) [9]. Wind power was the only variable renewable source (VRS) that supplied electricity to the national grid in the reference year with an installed capacity of 19.5 MW. In order to include further integration of RES in the future scenarios, wind and solar datasets were built following the approach suggested by George et al. [17].

The simulation of energy storage in EnergyPLAN is performed by defining power and energy capacity, charging and discharging efficiency and the operation strategy. The storage system can simulate different technologies (PHES, CAES, battery or hydrogen storage) and is charged during periods when critical excess of electricity production (CEEP) occurs in the power system. Additional information about the equations used and the simulation process can be found in [3].

3.1 Future scenarios

Once the system reference model (2014) was validated, three future scenarios were generated as follows:

1. Scenario 1 (baseline): This scenario is based on the business as usual (BaU) outlook defined by the Colombian government [18], and it assumes that the current perspectives in energy supply and demand are expected to remain unchanged.

2. Scenario 2 (COL 2030): This scenario was built based on inputs from the Colombian power flexibility assessment report developed by the International Renewable Energy Agency (IRENA) [19], and it suggests further penetration of solar photovoltaic and wind power plants in the electricity mix without energy storage.

3. Scenario 3 (COL 2030 + storage): Built from scenario 2, this alternative includes energy storage levels that could be technically achievable by 2030 [19].

The main inputs for the defined reference and future alternative scenarios can be seen in detail in table 1.

Table 1. Input data for the defined reference and future scenarios.

	Ref. 2014	Scenario 1	Scenario 2	Scenario 3
Electricity Demand				
Total electricity demand (TWh/year)	64.37	100.53	100.53	100.53
Electricity Supply				
Hydropower (MW)	10920	14895	14895	14895
Thermal power (MW)	4735	6149.8	6149.8	6149.8
Biomass (MW)	72	108	108	108
Wind power (MW)	19.5	594	4000	4000
Solar PV power (MW)	0	0	7000	7000
Electricity storage				
Charge/discharge power (MW)	0	0	0	2000
Storage capacity (GWh)	0	0	0	10

As mentioned in the introduction, increasing shares of RES into the electricity mix creates new challenges for the system and it is necessary to analyse the effects of adding electricity storage capacity to it. Therefore, the scenario 3 was used to simulate different capacities of wind and solar penetration and four storage power levels (500 MW, 1 GW, 1.5 GW and 2 GW) in order to evaluate its effect on the power system. An energy storage capacity of 10 GWh was used based on the results reported in [19] and this value remained constant for all the simulations.

4. Results and discussion

In this section, the results of the validation process and the simulated scenarios are described.

4.1 Model validation

The reference scenario was validated following the process described by Connolly et al. in [13] (see table 2). The electricity demand and supply, primary energy supply (PES) and greenhouse gas (GHG) emissions were compared against the actual figures reported by the International Energy Agency (IEA) [20]. The modelled outputs and the actual values are within expected margins (less than 4% difference), and therefore the reference model represents accurately the Colombian electricity system and can be used to develop future energy scenarios for the country.

Table 2. Model validation results.

	Modelled in EnergyPLAN	Actual data	Percentage Difference
Electricity production [GWh/year]			
Wind	70	70.23	-0.32%
Hydro	44760	44742	0.04%
Conventional Power Plant	19110	19074	0.18%
Biomass	450	442	1.81%
GHG emissions [$MtCO_{2e}$]	12.46	12.97	-3.93%

4.2 Scenario results

Increasing levels of RES penetration create new challenges for the electricity system operation. However, energy storage could increase the flexibility of the system and assist in addressing some of these challenges. In this study, the effects of increasing storage capacity in the Colombian power system are assessed by recording the changes in RES shares, CEEP or electricity curtailed, fuel consumption (PES) and GHG emissions. One of the main objectives of adding electricity storage to the grid is to minimise the CEEP and use it to replace thermal plants production, and thus reduce fuel consumption.

Figure 2 shows the change in both the CEEP and PES as the wind, solar and storage power levels increase. As expected, the results illustrate that increasing levels of energy storage can reduce the amount of CEEP and PES, and thus assist in the integration of higher shares of wind and solar energy. It can be observed that including energy storage (2 GW charge/discharge power and 10 GWh storage capacity) in the system could result in an increase in the combined technical feasible RES penetration (wind and solar) from approximately 19% to 25% of the total electricity production. It should be noted that as the storage power level increases (from 500 MW to 2 GW), the difference in CEEP and PES is reduced, thus establishing a technical limit to the storage capacity. For the scenario presented, charge/discharge power levels above 2 GW do not produce significant changes to the system.

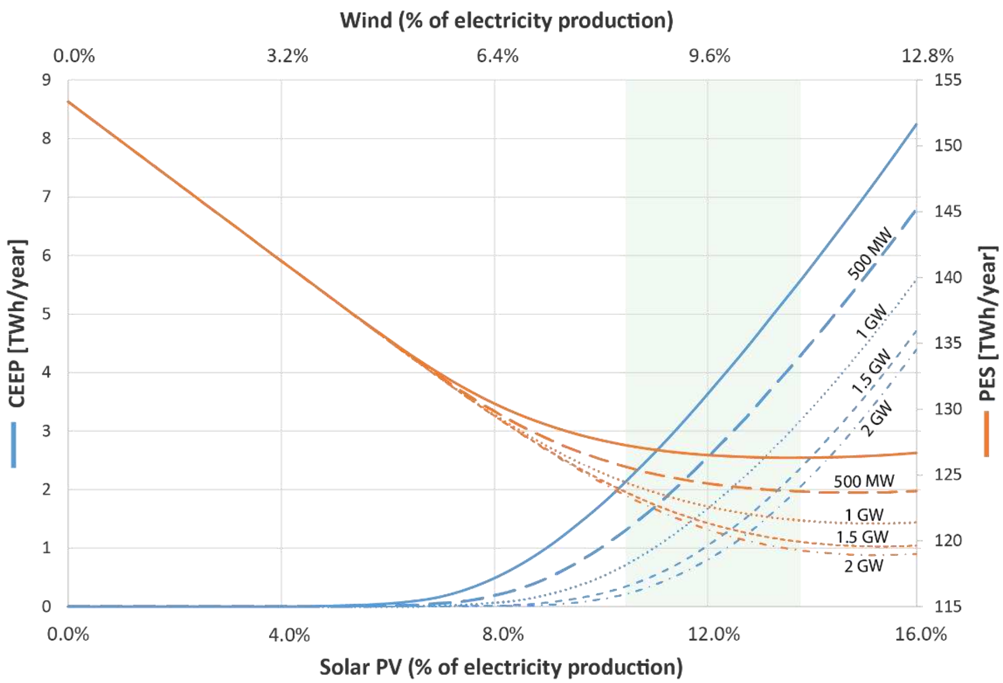

Figure 2. CEEP and PES change with increasing storage power (10 GWh capacity).

The total amount of electricity produced and the estimated GHG emissions in 2030 for all the three scenarios are shown in figure 3. Hydropower is expected to continue being the main source of electricity production, and this represents an advantage in terms of RES integration. The results of the scenario 2 evidence the benefits of adding RES to the power system represented in a reduction of about 60% in the GHG emissions of the sector. However, the energy curtailed in this scenario is approximately 4.98 TWh. The results of the scenario 3 show that adding energy storage could assist the system to reduce approximately 67.3% of this CEEP. This is the best-case scenario, and compared to the scenario 2, further reductions are achieved in both the GHG emissions (21%) and the fuel consumption (20%). The emission intensity of the sector could also be further reduced to approximately 62.1 gCO_{2e}/kWh, which is about a third of the value estimated in the BaU scenario (195.3 gCO_{2e}/kWh).

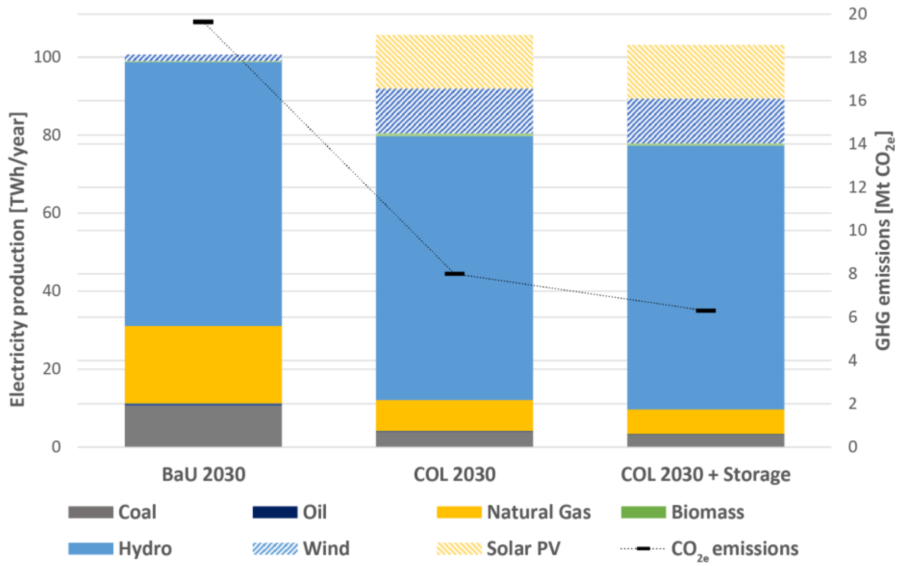

Figure 3. Electricity production and GHG emissions for the scenarios.

4.3 Cost analysis

After discussing the technical impacts of adding energy storage to the Colombian system, pumped hydro energy storage (PHES), compressed air energy storage (CAES) and lead-acid battery storage were selected to be introduced in the power system in order to estimate its cost and feasibility. These technologies were considered due to their current level of development [21], suitability for assisting in the integration of large-scale RES [7,19] and the great potential reported [19,21] for use in countries such as Colombia. In this analysis, the total costs of the power systems were annualised, and these include investment repayments, fixed and variable operation and maintenance (O&M), integration and CO_2 costs. Only the investment costs associated with new capacity added to the system were considered. A complete description of the equations and assumptions used to estimate these costs can be found in [15]. The scenario 3 is used to simulate the selected storage technologies and their cost and efficiencies are modified accordingly. All the future technology efficiencies and technology and fuel costs are based on 2030 projections by IRENA [22] and the EnergyPLAN cost database [15]. An interest rate of 8%, which has been used when assessing other infrastructure projects in Colombia, and a CO_2 price of 40 €/tCO_{2e} were defined into the model.

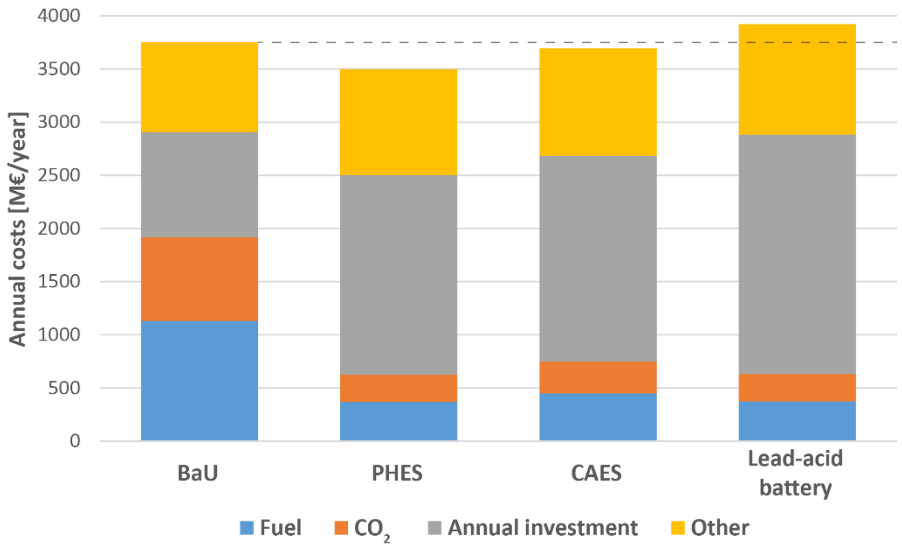

Figure 4. Estimated costs of the evaluated energy storage technologies.

The total annual cost of the power system and each of its components are illustrated in figure 4. PHES is found to be the most cost-effective storage alternative, and this is mainly because of its low annual investment cost and the fuel savings (approximately 68% compared to the baseline scenario). Due to the topography of the country and the characteristics of the power system infrastructure, the capital cost of PHES could be further reduced if the current reservoirs are used as part of the storage system. CAES technology is the least-attractive option in terms of fuel savings and its capital cost is higher compared with PHES. Lead-acid battery technology is the least-cost effective of all the alternatives, but it could represent an attractive option if its capital cost falls in the future due to technology improvements.

5. Conclusions

In this paper, a techno-economic assessment of the impacts of grid-scale energy storage in a hydro dominated power system with increasing RES shares was developed. The results evidenced that energy storage has an important role in enabling greater levels of wind and solar penetration into the electricity system, and thus adding more flexibility and reducing its carbon intensity. In the case of Colombia, the best-case scenario could allow an increase in the combined technical feasible RES penetration (wind and solar) from approximately 19% to 25% and assist in the reduction of the CEEP to 1.63 TWh. In addition, the GHG emissions could drop approximately 67% compared to the baseline scenario. PHES was found to be the most cost-effective storage technology and it appears to be the best option for the Colombian power system.

This study concentrated on the techno-economics aspects of energy storage and renewables integration only in the power sector. However, additional scenarios that include different sectors and technical solutions to add flexibility to the complete energy system should be analysed and compared to the results presented in this research. Expansion of the transmission grid capacity, active demand response, energy efficiency and electrification of transport are part of a set of prospective solutions that could assist in achieving a smooth transition towards more sustainable energy systems.

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