Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 136 (2017) 251–257

Energy Procedia

www.elsevier.com/locate/procedia

4th International Conference on Energy and Environment Research, ICEER 2017, 17-20 July 2017, Porto, Portugal

Energy storage for renewable energy integration: the case of Madeira Island, Portugal

Miguel Miguel[a], Teresa Nogueira[a,b]*, Florinda Martins[a,c]

[a]*ISEP- School of Engineering, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal*
[b]*CIETI-Center for Innovation in Engineering and Industrial Technology, R. Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal*
[c]*REQUIMTE/ LAQV/ ISEP- School of Engineering, P. Porto, Rua Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal*

Abstract

Energy storage has become a crucial issue regarding renewable energy management, even more important in an island system with the inherent fluctuating operation and inaccurate energy forecast. The growth of decentralized generation in an isolated electrical grid means load stability problems and requires energy storage as a potential solution to guarantee safety and reliability standards. The study described in this paper highlights the need to store energy in Madeira island system and evaluate the operational power dispatch with the introduction of batteries. A simulation tool was developed to quantify the impact of batteries in wind and thermal power plants technologies.

Peer-review under responsibility of the scientific committee of the 4th International Conference on Energy and Environment Research.

Keywords: Batteries power balance; current scenario; electrical energy storage; isolated grid; re-dispatch; simulation tool

1. Introduction

The development of efficient and environmentally safe energy storage systems is an important and urgent issue to save our society from potentially serious damage due to various pollutants in the atmosphere [1]. Electrical Energy Storage (EES) is a way of converting electrical energy from a power plant into a form that can be stored for

* Corresponding author. Tel.: +351 228 340 500; fax: +351 228 321 159.
E-mail address: tan@isep.ipp.pt

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 4th International Conference on Energy and Environment Research.
10.1016/j.egypro.2017.10.277

converting back to electrical energy when needed [2]. This allows the use of intermittent energy sources in peak hours or at any time when no other generation means is available [3]. Distributed electricity generation and the introduction of fluctuating sources like renewable energy, increase the difficulty of stabilizing the power network, mainly due to a supply demand imbalance [4]. More than ever, EES has become a necessity, in particular at isolated electrical systems [5]. When an utility company supplies electricity within a small and isolated power network, the power output from small-capacity generators such as diesel and renewable energy must match the power demand. By installing EES the utility can supply stable power to consumers [6].

This paper aims an analysis on the potential benefits of introducing electrical energy storage in a small isolated system, the case of Madeira, a Portuguese island. We will present a real case study focusing on large-scale batteries and the achieved improvements on grid's management criteria in order to maximize renewable energy injection [7]. In the different scenarios were considered batteries of *NaS* with power between 5 MW and 100MW and capacity between 2.5 MWh and 600 MWh.

2. Madeira energy system characterization

Madeira electrical energy system is based on conventional thermal power plants and hydro plants, complemented by a solid amount of wind energy and steady growing solar energy production. Table 1 shows the power plants existing in Madeira Island's system, detailing the rated power and annual produced energy by each energy technology [8] at the year of 2012. Although renewable energies have been achieving considerable integration in island's energy mix, it is still predominantly dominated by conventional thermal power plants.

Table 1. Energy power plants in Madeira

Source	Thermal	Hydro	Wind	Urban waste	Photovoltaic	Total	Renewables *(%)*
Power *(MW)*	233.94	51.09	43.91	8.00	17.56	354.51	-
Energy *(GWh)*	649.38	74.58	82.62	27.72	27.68	861.9	21

There are two thermal power plants in Madeira, most of the groups supplied by fuel oil and some of them are natural gas generating groups. There is a mix of single and combined cycle, where older and recent energy generation technology coexists. We can find ten hydropower plants in Madeira and the island's hydrography is of small flow water streams type, making it difficult to have big reservoirs. Due to this geographical limitation, nine of the existing hydroplants are run-of-the-river type power plants. Those facilities have a huge strategic importance because they reduce the need for the thermal plants at rainy periods. All the wind power plants are onshore facilities, with a variety of windmill technologies across the island, from full speed control technologies to no control at all. There are still some places with wind potential for building new plants to increase the actual nominal power, wind´s share of the electricity mix increases each year [9]. When it comes to photovoltaics plants, there are two large-scale plants, with 6 MW and 9 MW of rated power. The rest of the installed solar power is about mini and micro producers, with a highly promising future, costs are currently on a fast reducing track, compared to costs of other renewable energy systems [10].

Isolated grid systems face unique conditions that introduce challenges that are different from large mainland power grids. A specific study of technology and applications is needed for that type of energy system.

3. Power dispatch operation: calculation and results

In this work the simulator was developed aiming to replicate the real island system. For a yearly load diagram, we simulate the usual Madeira grid operation and study the impact on the batteries introduction. All data was provided by EEM company [8], concerning the gross annual from all generation technologies, energy grid management and order criteria, with the minute as a time horizon. The method aimed the optimization of battery usage in energy system and renewable energy integration. The power calculation process is based on the difference between power generation and consumption at every moment.

All of the simulated scenarios relate to production values of the year 2012, one-year production diagram from

Madeira power grid with the described network dispatching criteria. The results are the technologies annual energy balance and graphical representation of daily energy diagrams, as well as energy, and power balance in batteries.

3.1. Current Scenario with batteries

This scenario aims to reproduce the annual energy values from Madeira electrical grid with the aggregate production, colored areas correspond to energy production by power plant type. Comparing results in Table 2 with values on Table 1, can be assessed that the simulation values, come close to real values. InFig. 1 we can see a specific present scenario, organized by three graphs: the first is the load diagram by generation technology (MW versus daily hours), the second is the batteries energy (kWh) and the third is the power battery (MW).

Table 2. Current Scenario results

Battery		Energy (GWh)										
Energy Capacity	Power	Thermal		Hydro	Solar	Wind			% Renewables	Battery		
MWh	MW	Produced	Reduction			Net Production	Absorbed by grid	% of Surplus		Charge	Discharge	Total Losses
Real Data		677.10	-	74.58	27.68	-	82.62	-	21	-	-	-
No Batteries (simulation)		681.03	-	74.15	24.41	94.38	82.55	12.54	21.02	-	-	-
10	5	680.52	0.50	74.15	24.41	94.38	83.09	11.96	21.08	0.62	0.62	0.15
	10	681.52	0.51	74.15	24.41	94.38	83.14	11.91	21.08	0.64	0.64	0.22
20	5	681.32	0.70	74.15	24.41	94.38	83.29	11.75	21.10	0.86	0.86	0.20
	10	681.27	0.75	74.15	24.41	94.38	83.41	11.62	21.12	0.95	0.95	0.29
30	5	680.11	0.92	74.15	24.41	94.38	83.58	11.44	21.14	1.15	1.15	0.33
	10	680.16	0.87	74.15	24.41	94.38	83.63	11.38	21.14	1.15	1.15	0.46

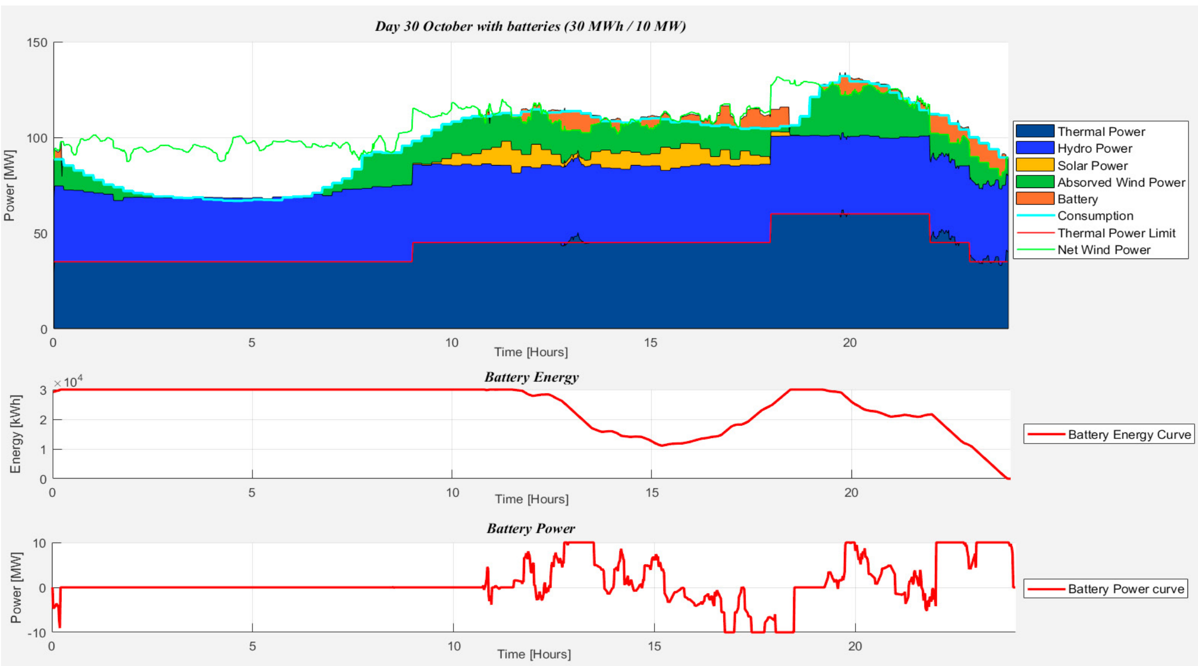

Fig. 1. Day 30th of October 30 MWh / 10 MW

3.2. Current Scenario with Re-dispatch

The re-dispatch scenario assumes that a battery with a rated power of 10MW, can replace a thermal group of equivalent power, allowing the base of the energy diagram to lower, without harming safety and grid stability.

As expected, we can see in Table 3, lowering minimum thermal energy limits, allows for more absorption capacity of the grid of renewable energy, achieving a surplus of 2.02%, as well as a better reduction in thermal energy production. Although renewable energy surplus and thermal energy production decreases, the battery usage is lower and thermal production is more variable, which could result in worst efficiency.

Table 3. Re-dispatch Scenario results

Battery		Energy (GWh)										
Energy Capacity	Power	Thermal		Hydro	Solar	Wind			% Renewables	Battery		
MWh	MW	Produced	Reduction			Net Production	Absorbed by grid	% of Surplus		Charge	Discharge	Total Losses
Real Data		677.10	-	74.58	27.68	-	82.62	-	21	-	-	-
No Batteries (simulation)		681.03	-	74.15	24.41	94.38	82.55	12.54	21.02	-	-	-
10	10	674.68	6.34	74.15	24.41	94.38	88.60	6.12	21.72	0.42	0.42	0.14
20	10	674.50	6.52	74.15	24.41	94.38	88.81	5.90	21.74	0.65	0.65	0.21
30	10	674.36	6.67	74.15	24.41	94.38	88.97	5.72	21.76	0.83	0.83	0.24
	20	670.89	10.14	74.15	24.41	94.38	92.47	2.02	22.17	0.66	0.66	0.28

3.3. Comparison between Scenario A and B

Comparing the two scenarios A and B, we can see in Table 4 the results from current scenario versus re-dispatch scenario, for a 10 MWh battery capacity and 10 MW power. This re-dispatching solution combined with the introduction of batteries can be an acceptable and technical feasible one, indicating that the inclusion of batteries may indeed play a critical role in increasing the capacity of engagement of wind, and in future the solar technology. By improving grid management criteria and maximizing battery potential, we can get better results than without any grid management criteria alteration. In this situation renewable energy surplus goes down from 11.91% to 6.12%, almost doubled, whether as thermal energy production reduction goes up from 0.51 GWh to 6.34 GWh.

Table 4. Comparison between re-dispatch and current dispatch

Year of 2012	Battery		Energy (GWh)				
	Energy Capacity	Power	Thermal		Wind		
	MWh	MW	Production	Reduction	Absorbed by grid	Increase	% of surplus
Current Scenario	10	10	680.52	0.51	83.14	0.59	11.91 %
Year of 2012	Battery		Energy (GWh)				
	Energy Capacity	Power	Thermal		Wind		
	MWh	MW	Production	Reduction	Absorbed by grid	Increase	% of surplus
Current Scenario with re-dispatch	10	10	674.68	6.34	88.60	6.05	6.12 %

3.4. Current Scenario with high energy batteries

This scenario has the main objective of assessing impacts of the introduction of high capacity batteries in thermal and renewable energy production, bearing in mind that the percentage of surplus renewable energy would require huge batteries in order to store it all.

As expected, results in Table 5, confirm that even with large capacity batteries (600 MWh), percentage of surplus renewable energy would continue to be high (7.82%).

On the other hand, there are advantages in large capacity batteries, allowing high levels of energy to be stored and provided to the grid when necessary, minimizing thermal production variation, which can lead to better efficiency, and consequently less greenhouse gas emissions.

Table 5. Current Scenario with high-energy batteries results

Battery		Energy (GWh)										
Energy Capacity	Power	Thermal		Hydro	Solar	Wind			% Renewables	Battery		
MWh	MW	Produced	Reduction			Net Production	Absorbed by grid	% of Surplus		Charge	Discharge	Total Losses
No Batteries		681.03	-	74.15	24.41	94.38	82.55	12.54	21.02	-	-	-
120	20	679.36	1.67	74.15	24.41	94.38	84.61	10.35	21.26	2.21	2.21	0.79
240	40	678.81	2.22	74.15	24.41	94.38	85.53	9.37	21.36	3.08	3.08	1.37
480	80	678.10	2.93	74.15	24.41	94.38	86.51	8.33	21.48	4.08	4.08	1.84
600	100	577.76	3.27	74.15	24.41	94.38	86.99	7.82	21.53	4.56	4.55	2.05

3.5. Current Scenario with Re-dispatch, low energy and high rated power batteries

Opposed to scenario D, this one is based on lower energy capacity batteries with discharge times of 15 minutes, and high rated power, allowing the best of battery usage as backup power reserve, and lower minimum thermal power, in order to maximize renewable energy integration.

Results in Table 6confirm that this would be the best scenario when it comes to renewable energy integration, achieving a residual surplus of 0.55% with a 7.5 MWh and 30 MW of rated power battery. This battery allows minimum thermal power to reduction in 30 MW.

Table 6. Current Scenario with Re-dispatch, low energy and high rated power batteries results

Battery		Energy (GWh)										
Energy Capacity	Power	Thermal		Hydro	Solar	Wind			% Renewables	Battery		
MWh	MW	Produced	Reduction			Net Production	Absorbed by grid	% of Surplus		Charge	Discharge	Total Losses
No Batteries		681.03	-	74.15	24.41	94.38	82.55	12.54	21.02	-	-	-
2.5	10	674.87	6.15	74.15	24.41	94.38	88.37	6.37	21.69	0.17	0.17	0.07
5	20	671.20	9.82	74.15	24.41	94.38	92.05	2.47	22.12	0.23	0.23	0.10
7.5	30	669.38	11.65	74.15	24.41	94.38	93.86	0.55	22.33	0.18	0.18	0.08

As expected, a day with high renewable energy production, integration is near 100%, with low battery interference. There is a possible downside to this scenario, regarding thermal production variability increase. This can lead to less efficiency levels, and potentially some influence in grid frequency and voltage variations.

3.6. Scenarios analysis

For the different simulated scenarios, the best results were found for re-dispatch versus current scenario, where we can get reduction in thermal energy and an increase in wind energy injection. On the other hand, in case of re-dispatch, energy in battery is lower, indicating that battery influences will be lower on production smoothing, so greatest contribution to grid management order.

In wind increase scenarios, we can have higher wind energy injection and a consequent reduction in thermal, but that causes an increased wind power waste. For the increased consumed energy scenario, we get a higher wind energy injection as well as for thermal power plants.

In each case study, the best balance between power and capacity will be the best solution for achieving the renewable integration and the thermal generation stability. This balance is doubly profitable because increases flexibility and range battery usage, thereafter, battery monetization is faster.

3.7. Carbon Dioxide Emissions

In addition to the previous technical analysis carried out, we can estimate the avoided CO_2 emissions by using *SimaPro.* Emissions from thermal power plants are an issue of great concern nowadays, especially the ones related to greenhouse gas (GHG), that are responsible for climate change [11]. Low carbon energy systems are a goal to be achieved by European Union and solutions that avoid GHG emissions [12] are very important and valuable [13]. In this work in addition to the technical analysis carried out, the avoided carbon dioxide emissions were estimated. To evaluate these emissions, it was considered that the generating groups of the thermal power plants use natural gas, which will give the minimum avoided CO_{2eq} emissions since that are groups that use oil. Results in Table 7 show that the amount of CO_2 emissions avoided are higher for Re-Dispatch Scenarios, especially the scenario with a 7.5 MWh and 30 MW of rated power battery, which avoid roughly 3000 tons of CO_{2eq}. This is an expected result since this last scenario presents the highest reduction in energy.

The analysis of the environmental impacts, including GHG emissions, due to the manufacture of batteries, consumption of auxiliary systems (e.g., battery management systems, ventilation and air conditioning of the buildings), etc., is out of the scope of this work.

Table 7. Avoided CO_{2eq} emissions

Simulation Scenario	MWh	MW	GWh	Avoided CO_{2eq} Emissions (tons)
Present Scenario	No batteries		-	-
	10	5	0.50	132
	10	10	0.51	134
	20	5	0.70	184
	20	10	0.75	197
	30	10	0.92	242
	30	20	0.87	229
Re-Dispatch Scenario	No batteries		-	-
	10	10	6.34	1670
	20	10	6.52	1720
	30	10	6.67	1760
	30	20	10.14	2670
Present Scenario with high-energy batteries	No batteries		-	-
	120	20	1.67	440
	240	40	2.22	584
	480	80	2.93	771
	600	100	3.27	861
Re-Dispatch, low energy and high rated power batteries	No batteries		-	-
	2.5	10	6.15	1620
	5	20	9.82	2580
	7.5	30	11.65	3070

4. Conclusions

The developed simulation tool shows real and reliable results with minimal error, so we can have confidence on the scenarios analysis. The tool looks to be reliable and accurate on the technical analysis of the batteries integration on network, in a way to increase wind energy injection and to decrease thermal output, a great combination to reduce greenhouse gases emission.

After all the simulation scenarios aiming to explore many combinations, we could accept that a solution with a short time battery and large rated power would be the most effective in reducing energy waste, allowing re-dispatch of thermal units and more clearance for renewable energy integration. However, this solution would require higher complexity battery control algorithm.

On the other hand, a solution with high capacity batteries and long-term discharge (some hours) would be better for production stability, resulting an increased system efficiency.

Finally, installing large-scale batteries in Madeira electrical grid can lead to great benefits, in addition to some already mentioned, the better service quality in grid stability in frequency and voltage.

References

[1] Rahman F, Rehman S, Abdul-Majeed M. (2011) "Overview of energy storage systems for storing electricity from renewable energy sources in Saudi Arabia" *Renewable and Sustainable Energy Reviews* 16 (2011): 274-283.

[2] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. (2009) " Progress in electrical energy storage system: A critical review" *Progress in Natural Science* (2009): 291-312.

[3] Sebastián R, Alzola P. (2011) "Simulation of an isolated Wind Diesel System with battery energy storage." *Electric Power Systems Research*, February (2011): 677-686.

[4] DTI. Status of electrical energy storage systems. (2004), DG/DTI/00050/00/00, URN Number 04/1878. UK

[5] Ibrahim H, Ilinca A, Perron J. (2008) "Energy storage systems - Characteristics and comparisons." *Renewable and Sustainable Energy Reviews* 12(5) (2008): 1221-1250.

[6] Amiryar M, Pullen K. (2017) " Review of Flywheel Energy Storage System." *Applied Sciences* (2017)

[7] IRENA. (2015) "Battery Storage for Renewables Market Status and Technology Outlook." *International Renewable Energy Agency* (2015)

[8] EEM. Parques Eólicos. [Online].; N/Date [cited 2017. Available from: http://www.eem.pt/pt/conteudo/sistema-el%C3%A9trico/produ%C3%A7%C3%A3o/parques-e%C3%B3licos.

[9] Martins F, Nogueira T, Smitková M. (2016) "Sustainable Energy in Europe: the Wind Contribution." In 6th International Scientific Conference, *Renewable Energy Sources*, Tatranské Matliare, Slovak Republic: Energetika Power Engineering (2016): paper 685.

[10] Rodrigues M, Brito M, Nogueira T, Martins F. (2016) "Modeling and Simulation of a Three-Phase Inverter to Inject Energy in Grid from Photovoltaic System." In 6th International Scientific Conference, *Renewable Energy Sources*; Tatranské Matliare, Slovak Republic: Energetika Power Engineering (2016): paper 650.

[11] Odeh N, Cockerill T. (2008) "Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage." *Energy Policy*. (2008): 367–380.

[12] Li S, Gao L, Jin H. (2016) "Life cycle energy use and GHG emission assessment of coal-based SNG and power cogeneration technology in China." *Energy Conversion and Management* (2016): 91–100.

[13] Alic J, Sarewitzb D. (2016) "Rethinking innovation for decarbonizing energy systems." *Energy Research & Social Science* (2016): 212–221.