Miguel Miguel; Teresa Nogueira; Florinda Martins

ENERGY STORAGE IN ISOLATED ELECTRICAL SYSTEM

Abstract

Energy storage has become a key issue in management of any renewable energy system. That is even more important in an isolated electrical system, as is the case with island system, due to the inherent fluctuating operation and inaccurate energy forecast.

The growth of the 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 electrical system and evaluate the technical and environment benefits with the introduction of batteries to strengthen power network.

A simulation tool was developed, suitable to quantify the impact of batteries in wind energy and thermal power plants existing technologies. This tool also allows the graphical analysis of the daily production, as well as the evolution of the power and energy in battery.

Palavras-chave: *Electrical energy storage. Isolated grid. Daily energy diagram. Batteries power balance. Re-dispatch. Simulation tool.*

1. Introdução

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 is a way of converting electrical energy from a power plant into a form that can be stored for 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].

The history of the stationary Electrical Energy Storage (EES) dates back to the turn of the 20th century, when power stations were often shutdown overnight, with lead-acid accumulators supplying the residual loads on the direct current networks [4].

Distributed electricity generation and the introduction of fluctuating sources like renewable energy, increase the difficulty of stabilizing power network [5], mainly due to a supply demand imbalance. It is therefore convenient to generate the energy, transmit it, convert it, and then store it if need be. More than ever, EES has become a necessity [6].

When a utility company supplies electricity within a small, isolated power network, for example on Portuguese Madeira island, 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 [7].

Nowadays, utility companies recognize the importance of the flexibility that energy storage provides in networks, in particular in isolated electrical systems.

This study 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 batteries introduction and the achieved improvements on grid's management criteria in order to maximize renewable energy injection.

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]. Although renewable energies have been achieving considerable integration in island's energy mix, it is still predominantly dominated by conventional thermal power plants.

2.1 Thermal power plant

There are two thermal power plants in Madeira, Vitória and Caniçal, with several generating groups, supplied mainly by fuel oil. The bigger plant – Vitória has a rated power of 212.94 MW provided by 20 groups, 5 of them are natural gas generating groups. There is a mix of single and combined cycle, where older and recent energy generation technology coexists.

The potential growth of such power plants is almost unlimited, however, the efficiency and environmental impact of them can be improved with the increase of more natural gas groups, less polluting than fuel oil.

2.2 Hydro power plants

There are 10 hydroelectric 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.

The most relevant hydroplant in the island is the Socorridos, with 2 generator-turbine groups of rated power of 24 MW and 11.25 MW, this last one of pumping power. The plant has a complex tunnels system, with the upper reservoir - Túnel do Covão, of 40 000 m3 of total water storage capacity, sited at 547 meters above sea level. The lower reservoir has a similar storage capacity, located at 85 meters above sea level.

That facility has a huge strategic importance because it allows a water charging during peak hours for energy generation, reducing the need for the thermal plants. At the off-peak hours, with higher wind generation, surplus generation is used for the plant to pump the water.

2.3 Wind and photovoltaic plants

All the wind power plants are onshore facilities, most of them located in Paúl da Serra, and Caniçal, with a variety of windmill technologies across the island, from full speed control technologies to no control at all. However, the harder demands of the local grid, EEM - Electricity Company from Madeira, requires a path towards wind mills equipped with power converters that can contribute with better quality of service to the grid. There are still some places with wind potential for building new plants to increase the actual nominal power and wind´s share of the electricity mix increases each year [9].

When it comes to photovoltaics (PV) 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].

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

2.4 Main challenges on isolated grids

Small isolated grids have specific conditions that lead to several challenges:

- No interconnection to larger grids
- Low short-circuit power (limits renewable power connection, due to voltage variation that lead to flicker problems)
- Need for power plants that can provide for grid stability services (typically thermal and hydro)
- Hydro systems with small storage capacity
- Excess of renewable resources in off-peak, humid periods
- Need for high levels of rotating reserve, due to the high risk of sudden power loss
- Great frequency variations due to variable energy resources (wind and solar)
- High-risk system management criteria and lower quality of service standards
- 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. Energy Storage Technologies and Applications

Electrical energy storage has been massively used worldwide for decades, via hydro pump plants with large reservoirs that could store weeks, months or even years of water for later production.

However, nowadays, the need for energy storage is much more oriented towards short-term electrical system stability, due to the high levels of variable renewable sources.

In line with this new paradigm, energy storage technologies, have suffered a huge development in the last few decades, with special emphasis in chemical storage technologies like batteries.

In Fig. 1 we can see a great diversity of technologies, graphically sorted by Rated Power and Energy Capacity, which gives us a hint about possible applications of each technology.

The battery choice is an interesting issue and the electric energy storage study area is huge and comprehensive, with large technologies variety in capacity and timelines, suitable for each operation mode. This variety also results from the wide range of functions and applications for each case study, to get a higher service quality like: generation stability, increased transmission network efficiency and electricity supply security and reserve in contingency situation. One of the determining factors in successful rollout of storage solutions will be the players' level of understanding of the cost and functionality of the different technologies [11].

The most effective solution can reduce the energy waste and increase the energy sustainability, by improving the renewable energies power guarantee and making them more predictable, so, with greater integration in electric system dispatch.

Batteries can have different operation modes. In this work we will analyze the NaS (sodium sulfur) because they are suitable for applications with daily cycling. As the response time is in the range of milliseconds, NaS batteries meet the requirements for grid stabilization [11]. This technology could be very interesting for utilities and large consumers, according to their operation graphic information.

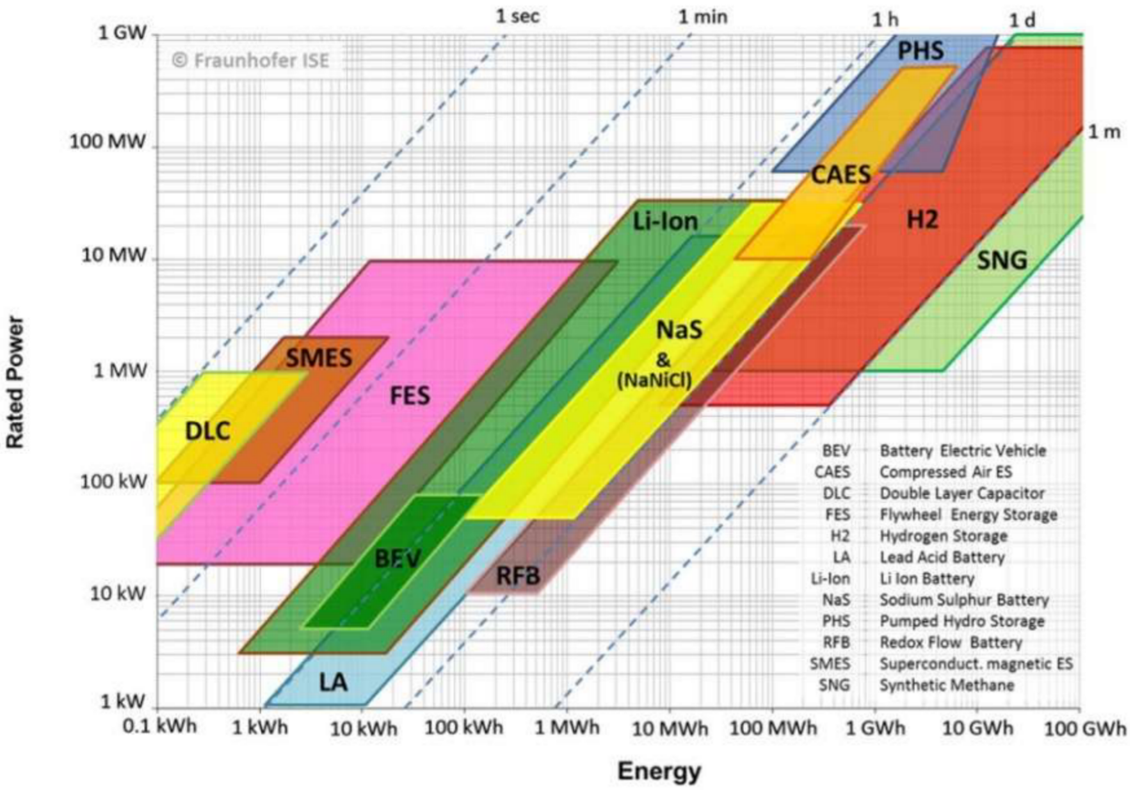

Fig. 1. Energy Storage Technologies – Comparision

3.1 Production curve leveling

Production curve leveling has the focus on making the production curve as stable as possible, so the output from the plant to the grid is predictable and delivers a better quality of service.

In Fig. 2 we can see the graphic description of that technology mode operation from NaS battery, with benefits to renewable energy integration and time shifting effect [12].

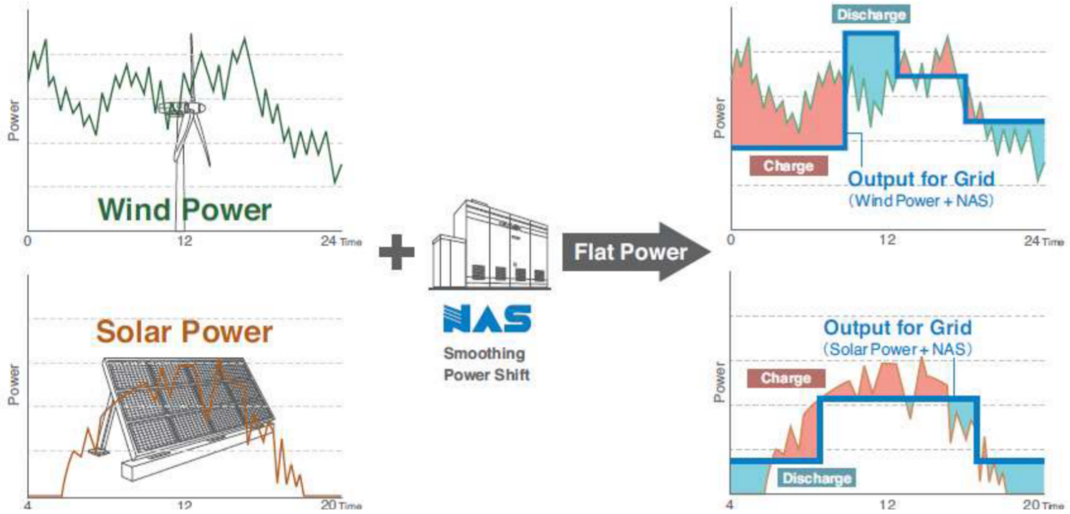

Fig. 2. Production curve leveling

3.2 Charge curve leveling

This technology aims to make the load value as flat as possible, so the power plants work on a stable maximum efficiency regime, decreasing energy consumptions with consequent CO2 emissions reductions. In Fig. 3 we can see how this system works.

3.3 Grid frequency leveling

In grid frequency leveling mode, ramp rate is the most important parameter, so batteries must have response times in millisecond time horizon, making up for inequalities between produced power and consumption, as seen in Fig. 4.

4. Energy Diagram Calculation Method

In this work the simulator was developed aiming the optimization of battery usage in energy system and renewable energy integration.

Batteries are characterized by their energy capacity (in watt-hour), the rated power (in watt) and charge/discharge efficiency (%). The power absorbed or provided by the battery is symmetrical whether it is absorbing (negative), or providing (positive).

In the operation scenarios were considered batteries of NaS with power between 5 MW and 100 MW and capacity between 2.5 MWh and 600 MWh.

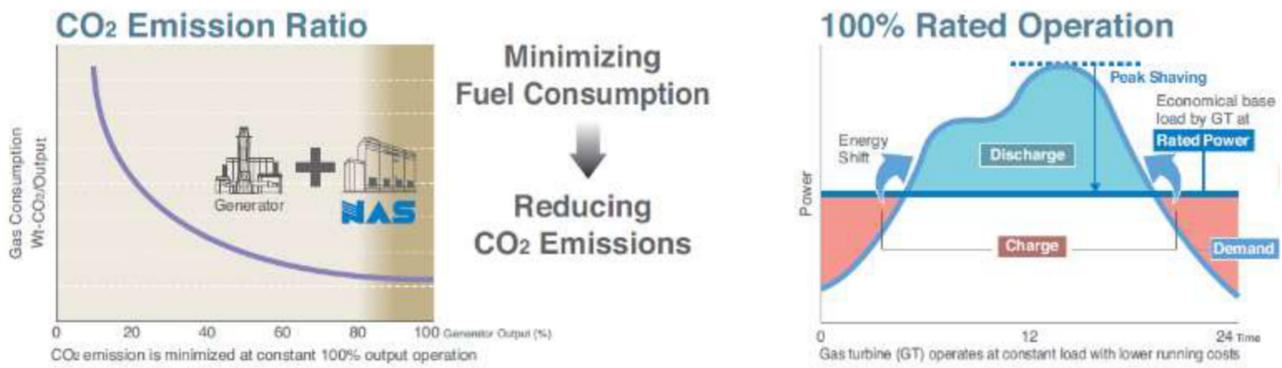

Fig. 3. Charge Curve Leveling

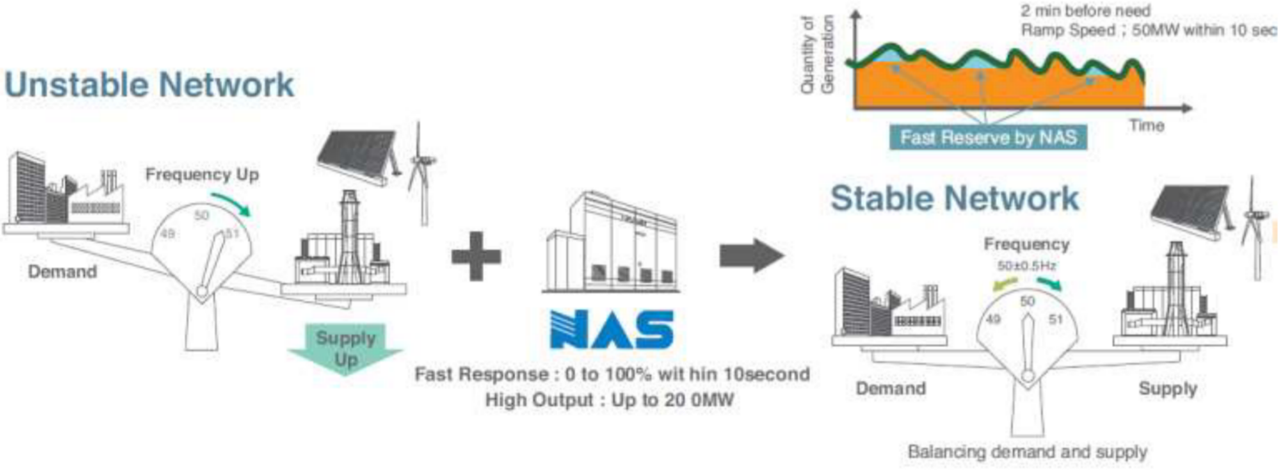

Fig. 4. Grid frequency leveling mode

In simulations the batteries constraints related to charge and discharge periods were not considered and only the restriction of minimum power produced for thermal plants was considered. Thermal power plants were grouped, including the solid waste thermal plant and the only restriction was the minimum power, equivalent to the minimum rotating reserve, considering the time horizon. Ramp rates were disregarded.

For battery operation, some assumptions were adopted to maximize wind resources and decreasing their wastes, accordind to next points presented.

4.1 General power higher than consumption

Whenever the sum of generated power exceeds the power consumption:

- If there is still battery capacity to store the remaining energy, battery stores it all, respecting its rated power limit
- If the remaining energy capacity of the battery is not enough to store all the energy, the exceeding energy is accounted as surplus

In Fig. 5 is graphically represented the method of calculation of power and energy in the next minute for each producing technology, and also the power and energy absorbed by the battery, with the respective losses through the charging process.

The different colors in Fig. 5 mean different production technologies and their power values are: PE – wind, PS – solar, PH – hydro, PT – thermal, PC – consumed power.

4.2 General power lower than consumption

Whenever the sum of the generated power is beneath the power consumption:

- If there is still energy stored in the battery, the battery provides de missing energy, respecting its rated power limit
- If the remaining energy in the battery is not enough to meet consumption, thermal power plants provide the missing energy

Fig. 6 represents graphically the method of calculation of power and energy in the next minute for each producing technology and also the power and energy provided by the battery, with the respective losses through the discharge process.

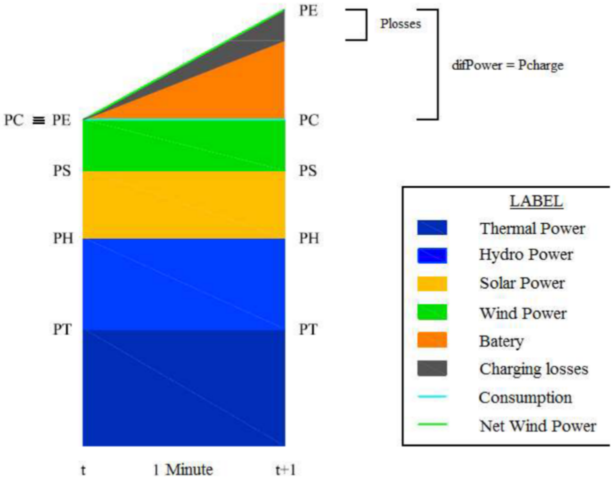

Fig. 5. Generated power higher than consumption

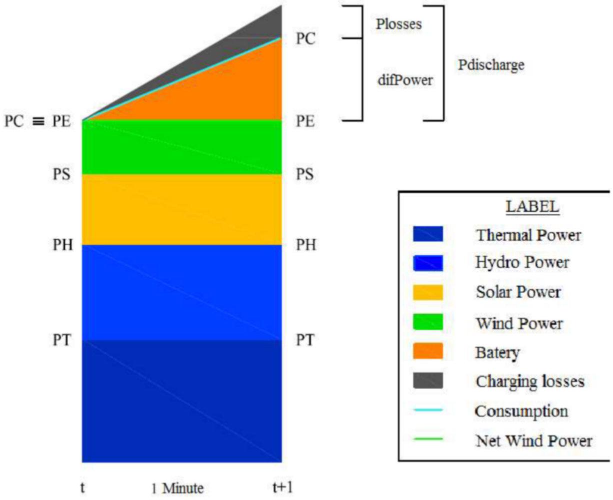

Fig. 6. Generated power lower than consumption

The power calculation process is based on the difference between power generation and consumption at every moment. For energy calculation we analyze the triangles and trapezoidal areas.

5. Power Dispatch Operation and Results

In this work a 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.

5.1 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.

In Fig. 7 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**

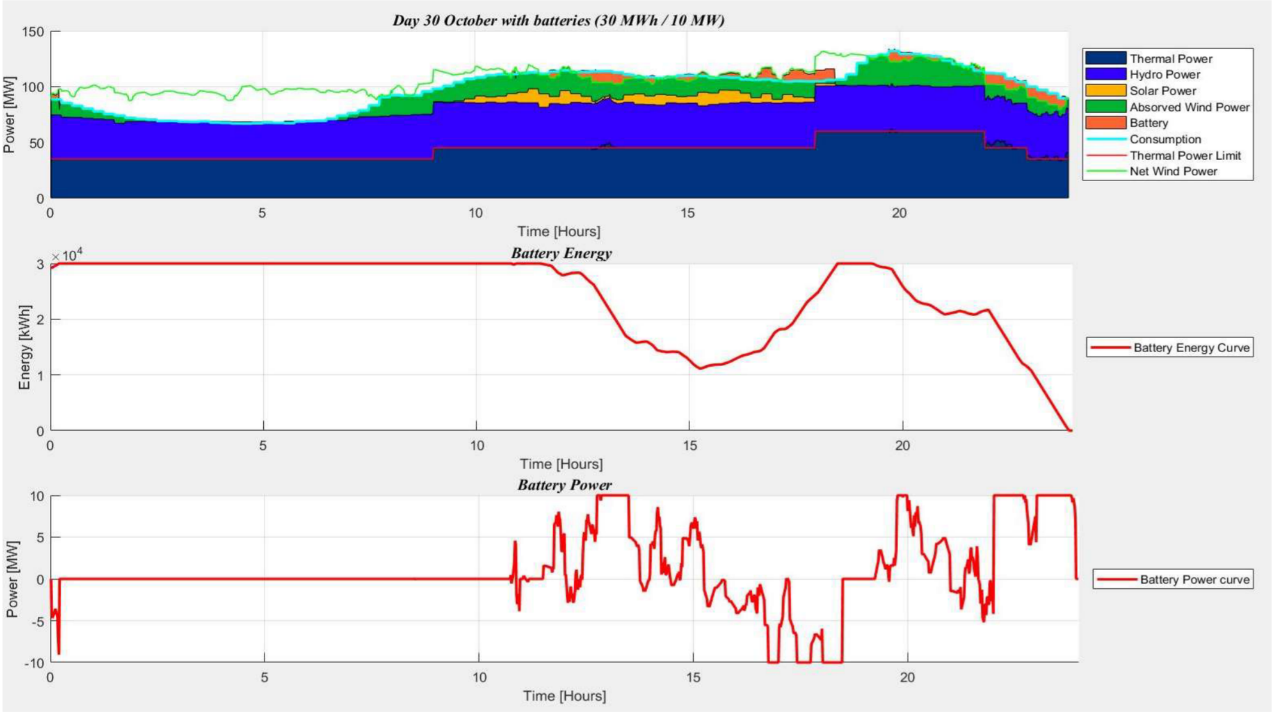

Fig. 7. Day 30th of October 30 MWh / 10 MW

5.2 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, 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.

Comparing the two presented scenarios the 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.

5.3 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.

5.4 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 [13]. Low carbon energy systems are a goal to be achieved by European Union and solutions that avoid GHG emissions [14] are very important and valuable [15].

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 CO2eq emissions since that are groups that use oil.

Results in Table 3 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 CO2eq. 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.

6. 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.

Table 3. Avoided CO2eq 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

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] Faizur Rahman, Shafiqur Rehman, and Mohammed Abdul-Majeed, "Overview of energy storage systems for storing electricity from renewable energy sources in Saudi Arabia," Renewable and Sustainable Energy Reviews, vol. 16, pp. 274-283, 2011.

[2] Haisheng Chen et al., "Progress in electrical energy storage system: A critical review," Progress in Natural Science, vol. 19, pp. 291-312, 2009.

[3] R. Sebastián and Peña Alzola, "Simulation of an isolated Wind Diesel System with battery energy storage," Electric Power Systems Research, vol. 81, no. 2, pp. 677-686, february 2011.

[4] J. N. Baker and A. Collinson, "Electrical energy storage at the turn of the Millennium," Power Engineering Journal, vol. 6, pp. 107-12, 1999.

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

[6] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems - Characteristics and comparisons," Renewable and Sustainable Energy Reviews, vol. 12, no. 5, pp. 1221-1250, 2008.

[7] M. Amiryar and K. Pullen, "A Review of Flywheel Energy Storage System," Applied Sciences, 2017.

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

[9] Florinda Martins, Teresa Nogueira, and Mira Smitková, "Sustainable Energy in Europe: the Wind Contribution," in 6th International Scientific Conference, Renewable Energy Sources, Tatranské Matliare, Slovak Republic, 2016, p. paper 685.

[10] Mário Rodrigues, Moacyr Brito, Teresa Nogueira, and Florinda Martins, "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, 2016, p. paper 650.

[11] International Electrotechnical Commission, "Electrical Energy Storage - IEC White Paper," Geneva, Switzerland, 2012.

[12] IRENA, "Battery Storage for Renewables Market Status and Technology Outlook," International Renewable Energy Agency, January 2015.

[13] N. Odeh and T. Cockerill, "Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage," Energy Policy, vol. 36, no. 1, pp. 367–380, 2008.

[14] Sheng Li, Lin Gao, and Hongguang Jin, "Life cycle energy use and GHG emission assessment of coal-based SNG and power cogeneration technology in China," Energy Conversion and Management, vol. 112, pp. 91–100, 2016.

[15] J Alic and D. Sarewitzb, "Rethinking innovation for decarbonizing energy systems," Energy Research & Social Science, vol. 21, pp. 212–221, 2016.