Feasibility Analysis of a wind pumped hydroelectric storage system on the Island of Brava

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***Abstract*— This work presents a case study on using wind pump hydroelectric storage system to maximize the penetration of wind energy in an island's power network. The proposed system reduces the dependence on fossil fuel and mitigates the effects of rising fuel prices on electricity. The system could be connected to an existing diesel-based power generating system that supplies electricity to the island. Simulations are performed over several scenarios which are defined by different sized equipment according to island's local infrastructure and energy demand. The results show that proper wind turbine selection has great impact on wind power generation, electricity price and return on investment. It is also noted that exceeding a certain share of wind energy in the power network can entail high energy costs and economically cripple the investment.**

Keywords—renewable energy; wind power; hydro pumped storage; hybrid energy systems;

I. INTRODUCTION

Most of the islands in the world depend on fossil fuel for most of their energy generating needs as well as for transportation. Due to their isolated locations, the infrastructure costs including energy are too high. For small islands, the costs of fossil fuels are quite substantial reaching over 15% of all their imports [1]. Fuel imports are thus a major source of capital expenditure and a major constraint on development; thus reducing social investment. To alleviate these effects on economy, islands around the world have generally sought to increase the penetration of renewable energies (RE), especially in the electricity grid. Although renewable energy sources are abundant and electricity conversion technologies are mature, there are still barriers and challenges limiting wide implementation of renewable energies in islands. Several research projects have been published over the years aiming to increase the penetration of RE sources in the general power network to levels reaching 100% [2]-[4]. However the greatest challenge to achieve that is to reduce or eliminate the instability of the electricity network caused by the injection of renewable energy sources [5]–[7]. Depending on the kind of renewable energy sources used on an island, this issue may be more or less difficult to achieve. Some islands have less energy consumption and acquire abundant water reservoirs and geothermal resources, which impose less problems on the stability of the general network [4]. This work presents a case study of using renewable energy sources for the Island of Brava in Cape Verde Archipelago. Wind pumped hydroelectric storage (WPHS) plant is proposed to be used for the island in order to maximize the penetration of renewable energies in the network. As well as to reduce the impact of using fuel on electricity tariffs and also to improve the island's energy security.

The article is structured as the following. Section II describes the island's natural energy resources and the potential of using them as energy sources. Section III proposes a wind-pumped storage power system to complement the existing diesel power station on the island. Section IV describes the components, the operation of the proposed system as well as the used simulation algorithm. Sections IV and V present the analysis of the results obtained and the conclusions of the work.

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II. HYDRO PUMPED STORAGE IN ISLAND'S POWER SYSTEMS

The instability of energy production of renewable energy sources, especially solar and wind, limits their penetration in the general electrical network due to frequency and voltage stability issues [5], [6]. Several strategies have been studied and implemented in order to increase renewable energies share in the electricity grid, such as demand management, hybrid renewable systems and energy storage [7]. However, employing energy storage strategy is the best way to significantly increase the penetration of RE into power network [1]. While comparing different energy storage technologies over parameters such as power level, storage capacity, cost, efficiency and response to discharge rate, it can be said that none of the current technologies have all the required characteristics for an optimal RE integration in the electric network. However, pumped hydroelectric storage technique is one of the most attractive options for RE integration as it is mature, commercial available and it can be used for large-scale storage systems. This system can store energy whenever there is excess of electricity produced and can be used as energy producer in the periods of lack of energy [8]. There is, however, a growing interest in reversible pumping hydro-power systems. In [9] it was proposed the installation of a hydro-wind storage system for the island of Gran Canaria, which showed that wind power penetration could increase by 1.93% (52.55 GWh/y) at a competitive cost of energy supplied (0.084 \$/kWh). In [10] a numerical study was presented to optimize the design of a wind power plant, in which it was concluded that the use of variable speed pumps is the most efficient and cost-effective solution to increase the amount of wind power stored into hydro energy. For the island of Ikaria, a proposal to take advantage of an existing water reservoir in the design of a new wind hydropower system with reversible pumping was presented in [11]. On the island of El Hierro, a hybrid hydro-wind based energy system with combined seawater desalination was recently deployed to achieve more than 80% of RE in the power grid [12]. Sea water as hydraulic fluid was introduced as the storage power systems in a pioneer project on the Japanese island of Okinawa [13]. In [14] same fluid is proposed in simulations of a wind-hydropower system, which resulted in annual wind energy penetration higher than 50%.

III. POWER SYSTEM IN BRAVA ISLAND

The island of Brava is located in the southwest of the Cape Verde Archipelago (West African Coast) and is the smallest of the country's ten islands, with an area of 67 Km^2. A single power plant, which is based on diesel generator, has 1056 kW total rated power [15]. A medium voltage network exists on the island with two voltage levels: a 6 KV line connecting the Harbour of Furna to Nova Sintra main village and another 20 KV line serving the rest of the island as illustrated in Fig. 1.

Two 250 KVA transformers connect the 6 KV line to the 20 KV line, at Nova Sintra substation. MV/LV stations distribute electricity in the main villages and in the EB3 and EB4 pumping stations. In 2016 the maximum demand reached 580 kW and the energy delivered to the grid was 2.7 GWh [15]. Consumption is expected to top 4.9 GWh by 2037, considering a growth of three percent per year for the island demand profile. The cost of fossil fuel used in electrical production is around \$290/MWh [15], which represents a huge impact on tariffs. In order to mitigate the cost of electricity, Brava used wind power for three years (1996-1998) in which a 150 kW wind turbine contributed up to 17.14% of wind energy in the annual electricity network balance [16]. This recent experience has proven the great wind potential available on the island, which registers annual mean wind speed above 7.630 m/s (Assuming Weibull distribution with: k=2.71, C=8.63m/s) and low standard deviation of 0.19 m/s) between annual averages. The island is located in a region of wind power density ranging from 300 to 370 W/m^2. The main advantages of using RE are reducing the import of fossil fuels and increasing energy security on the island.

IV. PROPOSED MODEL AND OPERATION

A wind pumped hydroelectric storage (WPHS) system is proposed aiming to increase wind power penetration levels in the electrical network. The proposed system, illustrated in Figure 2, considers the limits of resources and infrastructures existing in the island.

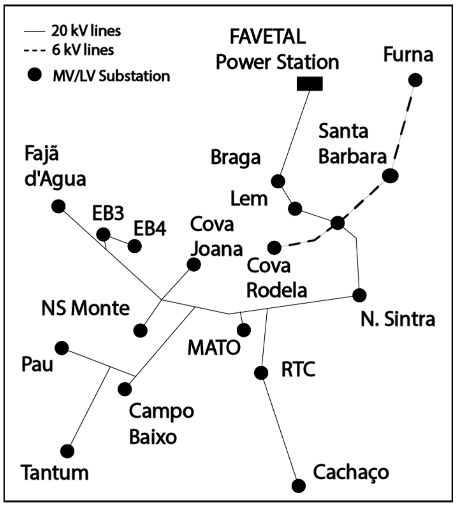

Fig. 1. *Electrical network at Brava Island*

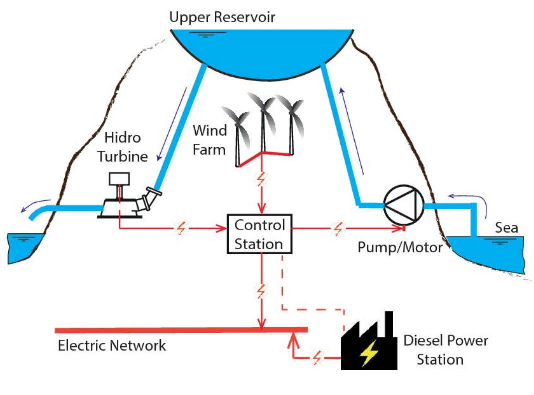

Fig. 2. *Wind Pumped Hydroelectric Storage System Proposed*

This system has two separated penstocks, one for pumping water and the other for generating electricity. Double-penstock system have more capacity to stabilize power voltage and frequency. Seawater is used as hydraulic fluid due to water scarcity on the island [16]. The advantage of using seawater is to avoid the construction of a second (lower) reservoir. However, it entails higher costs for maintenance, operation and risks to the environment [13].The wind pumped hydroelectric storage (WPHS) plant proposed consists of: (1) a wind farm (WF) located in the actual place with deactivated wind turbine with a good track record of wind power [17]; (2) a variable frequency and voltage pump set (PU); (3) hydro turbine unit (HT); (4) a seawater upper reservoir (UR) located near the current wind park and 110 m above sea level; and (5) a control station (CS), which manages the energy power flow and receives remote commands from the network operator. The WPHS system is connected to the electrical network that is also fed by a diesel power plant.

The main purpose of the proposed system is to increase the penetration of wind power in the public power grid by overcoming two drawbacks of wind power: (1) fluctuations and dynamic oscillations of power and (2) intermittency. The first issue can be mitigated by using variable speed pumps, which pump sea water to the upper reservoir. While the second drawback can be overcome by using hydro turbine for the water in the reservoir. Variable speed pumps is an effective strategy in power system primary frequency control and can also be very important in isolated networks [17]. In low required electricity situations with dominant and floating wind production, pump controllability is an important way to improve the response to power system disturbances. The controllability of the pump can be achieved using several strategies: (a) balancing power fluctuations by following the load; (b) frequency drop control; and (c) a combination of the first two schemes. So the stability of the power system is achieved by fast response of both pumping and generating modes. The operation of the WPHS system is as follows: 1) The utility operator sets maximum value for hydro turbine generation (E_H) and wind generation (E_{Wig}) into the grid. If the wind power reaches a 35% of the total demand threshold, the excess power is diverted to power the pump that direct the sea water to the upper reservoir. In case of full reservoir electrical resistances are activated to dissipate the excess power. At the same time, if there is sea water available in the UR, the HT generates electrical power and feed it to the grid to close the energy balance demanded from the diesel power plant. The diesel power engines can be switched off if the HT has enough power to replace it. The energy balancing and compensation is done by the hydraulic turbine and diesel generators, and both ensure the power system frequency and voltage control. The 35% threshold is justified by previous Brava's power wind project [16].

V. MATHEMATICAL MODEL

Hourly energy balance simulations are presented in this section. The simulations are conducted for several scenarios incorporating an economic analysis over a period of 20 years. Some parameters and variables are explained now:

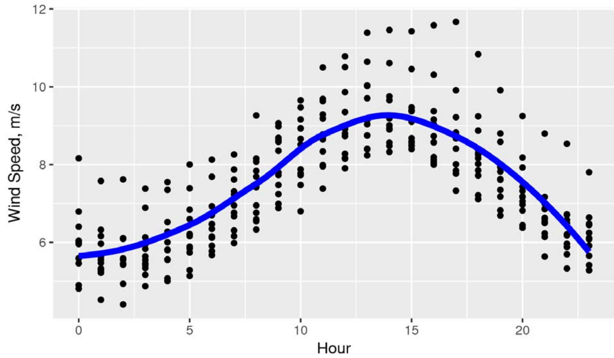

Fig. 3. Hourly wind speed (m/s) profile over 12 months

A. Wind speed

Hourly wind speed values are used in the simulation. These values are generated using local recorded average monthly wind speeds and Weibull parameters using correlation techniques of Weather Stations data in nearby Islands. The annual hourly wind speed are summarized in Fig. 3.

B. Wind turbines and electricity production

The existing wind farm (sized to hold a maximum of three wind turbines) is proposed to install the wind turbines. The island's harbor infrastructure and current access paths to the wind farm limit the weight and dimensions of the wind turbines to be used, i.e. up to 300 kW/unit [16]. Thus, three commercial wind turbines that fit the reality in the island are considered in the composition of several scenarios for later simulation: a) Nord Tank 150kW Wind Turbine; b) Nord Tank 300kW Wind Turbine; c) ACSA 27/225 kW wind turbine. The wind energy produced in each hour (kWh) is calculated using the wind speed data and the power curve of the wind turbines:

$$E_{wf} = \eta_w \cdot N \cdot P_w \tag{1}$$

where, E_{wf} is the total hourly produced energy of the wind farm; P_w is the hourly power of a single wind turbine; η_w is the wind farm overall efficiency (97%); and N wind turbine units;

C. Load demand

Brava has a typical rural load demand profile and a low annual growth. Load demand for 20 years ahead was estimated based on the current load diagram and assuming annual growth of 2.0 percent as shown in Fig. 4.

D. Pumped Hydro storage system

The pumped storage system with two separated penstocks, allows simultaneous pumping of sea water to the upper reservoir and electricity generation using sea water in the upper reservoir. The hydraulic reservoir absorbs the power of the pumps in case of excess wind energy and discharges the energy to hydro turbines to complete the energy balance. Investment and operational costs per kW and kWh are specified in Table I.

The simulations determine the required hourly power of the pumps that is needed to serve the system. The hydro turbine rated power is computed as the annual average power of the wind farm. Practical pump and turbine technologies can achieve a charging/discharge round-trip efficiency above 80% [18]. In this study a conservative value of 75% is assumed.

The upper reservoir is located next to the existing wind farm, taking advantage of the proximity coastal slope of 110 meters elevation above the sea level. The hydroelectric energy produced is given by:

$$E_R = h_{aut} \cdot E_d = \frac{\eta_h \cdot d \cdot V \cdot g \cdot h}{3.6 \times 10^6} \qquad (2)$$

where, E_R is the energy of the reservoir (kWh); h_{aut} are the hours of autonomy; E_d is the average hourly consumption; η_h is the hydro turbine efficiency; V is the volume of the reservoir (m3); d is the water density (1000 kg/m^3); g is the acceleration of gravity and h is the height of the reservoir above sea level (110 m).

E. Energy Balance Model

For each hour, the produced wind energy is divided into portions directly injected into the grid (E_{wig}), delivered to the pumps (E_p) and dissipated by the resistances (E_{dis}) in case the reservoir does not withstand any more sea water:

$$E_{wf} = E_{wig} + E_P + E_{dis} \qquad (3)$$

The energy sources supplied to the grid are the wind energy (E_{wig}), the hydraulic turbines (E_h) and by the diesel generators (E_{dg}) if necessary.

$$E_d = E_{wig} + E_{dg} + E_h \qquad (4)$$

The minimum operational power of diesel generators, when it is needed to close the energy balance, shall not be less than 128 kW due to generator sets manufacturer requirements. Diesel generators and hydro turbines assure the ultimate voltage and frequency control of the power system.

F.Description of the algorithm

The implemented algorithm uses the mathematical model explained above and performs technical/economical analysis of the overall system, based on empirical costs for all its main components (pumps, hydraulic turbines, wind turbines, reservoir and pipelines). The flowchart of the operation of the proposed system is explained in Fig. 5.

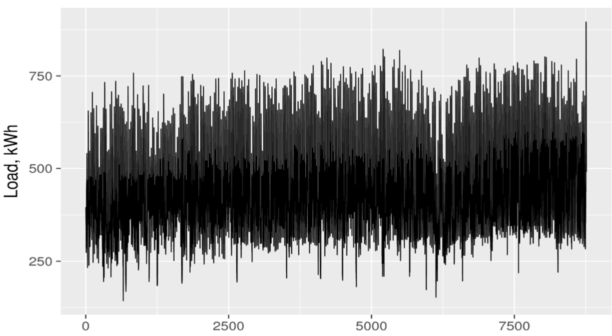

Fig. 4. Estimated load demand over 20 years

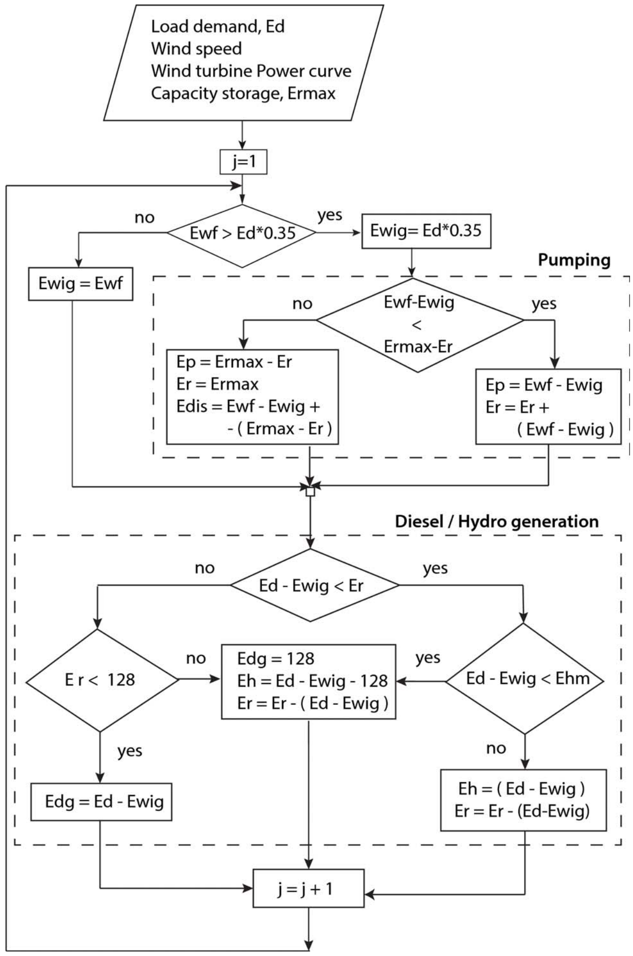

Fig. 5. *Algorithm flow chart*

If the wind power is less than 35% of the electrical load, it is injected directly into the electricity grid. Otherwise, a quantity of wind power equivalent to 35% of the load is injected into the power grid and the remainder is diverted to pumping or dissipated if the reservoir is full. After the injection of wind power, the energy balance is assured with diesel and /or hydro power. If there is not enough water to meet the remaining load (Ed-Ewig > Er) the diesel generator must be started. In this case, if the storage energy in the reservoir is below the minimum power of the generator (128 kW), only the diesel generator is driven (Edg = Ed-Ewig). Otherwise, the hydraulic turbine is also driven together with the minimum diesel production of 128 kW. On the other hand, if there is enough water in the tank to meet the load and the nominal power of the hydraulic turbine is large enough (Ed-Ewig < Ehm) only the hydraulic turbine is driven. If the hydraulic turbine does not have enough power, the diesel generator is also driven at its minimum value (128 kW). When the water is discharged the storage energy (Er) is updated.

G. Economic Evaluation

The economic evaluation of the project is based on eliminating the cost of diesel fuels by the injection of renewable power. Financial parameters, investment and specific O&M cost are presented below:

- *Loans: 70% ;*
- *20 years* loan payments with 4.0% interest rate;
- Discount rate: 14% ;
- State taxes: 20% over profit.
- Diesel price: $1.17/L (fixed) [19].

TABLE I. PUMPED HYDRO STORAGE COSTS

Item	Investment Cost	O&M Cost
Wind turbine (ref. 500 kW)	2,114.14 ($/kW)	0.024 ($/kWh)
Pump Station (ref. 350 kW)	1,057.95 ($/kW)	0.082 ($/kWh)
Hydro Station (ref. 350 kW)	1,469.38 ($/kW)	Accounted on pump station
Upper Reservoir (ref. 2000 m3)	88.25 ($/m3)	Accounted on pump station
Penstock (500 m)	5,7362.50	Accounted on pump station

Feasibility studies and tenders cost $56,554.48 and for several/unpredictable costs it is account additional 15% over total costs.

VI. SIMULATIONS AND RESULTS

Seven different configurations (see Table II) are considering estimated growth of load demand and constraints imposed by the infrastructure in the island. All configurations has a resulting storage capacity of 1.50 kWh per kW installed wind power.

TABLE II. PUMPED HYDRO STORAGE COSTS

Scen.	Wind Turbine			UR (m^3)
	Type	Qty.	Power (kW)	
1	NTK 150	2	300	1500
2	NTK 300	1	300	1500
3	NTK 150	3	450	2250
4	A27/225	2	450	2250
5	A27/225	3	675	3400
6	A27/300	2	600	3000
7	A27/300	3	900	4500

Simulations over 20 years were carried out for each configurations and all technical and economical values where calculated. Table III shows the pump and hydro turbine power rate for the seven scenarios.

TABLE III. PUMP AND HYDRO TURBINE POWER, KW

Scenario	1	2	3	4	5	6	7
Pump	251	230	425	382	601	569	895
Hydro	125	95	188	155	233	191	286

The simulations compute several parameters and they are summarized in Table III: RE share is the amount of wind and hydro energy injected in the grid over the total demanded load; energy loss is the excess wind power the reservoir could not store Also economic parameters are derived: Net Present Value (NPV), payback in years, Internal Rate of Return (IRR) and Levelized Cost of energy (LCOE).

TABLE IV. TECHNICAL AND ECONOMICAL RESULTS FOR DIFFERENT WPHS CONFIGURATIONS

Nr.	Inv. Cost (M$)	RE share (%)	Energy Loss,%	NPV ($$10^3$)	Pay back	IRR	LCOE,$/ MWh
1	1.48	26.3	5.3	426.5	5.8	0.241	176.5
2	1.40	20.4	4.0	207.3	9.0	0.189	197.5
3	2.21	36.8	11.8	381.5	8.3	0.198	202.8
4	2.10	31.1	9.4	221.2	11.0	0.172	212.3
5	3.12	43.6	16.1	15.6	19.3	0.133	236.7
6	2.80	35.5	16.7	-155.0	-	0.109	251.8
7	4.19	49.2	24.0	-615.7	-	0.071	283.1

It can be seen from the results that the maximum penetration of renewable energy reached was 49.2% for scenario 7 but it wasted more renewable energy (24%) due to full reservoir of water. Although the last two cases hold more renewable investment, they do not present favorable economic data with negative NPV and no payback (over 20 year evaluation), even though they present a LCOE ($251.8-$283.1/MWh) below diesel-based operation cost ($290/MWh). However, scenarios 3, 4, and 5 have the highest RE penetration with positive NPV, good IRR and more favorable LCOE. It can be noted that a good combination of the type wind turbine and related quantity is important to have a good RE share and economic return ratio.

Fig. 6 shows the contribution of each energy source in the power system. It is verified that wind power injected directly into the electric grid has on average a greater contribution than the hydraulic power, but the latter has more contributions when the installed wind power is higher (three last configurations). Fossil fuels contribution to electricity cost is actually $290/MWh, it follows that any of the scenarios, which have a LCOE below this value, results in a Weighted Average Cost less than the current cost. Scenario 3 (LCOE= $202.8/Mwh and 37% of RE share) gives a WAC of $269/MWh, which represents 11% decrease in electricity costs. Fig. 7 presents these amount cost reduction percentages for the other scenarios. It can be seen that scenario 7 has the smallest impact in lowering cost of electricity for a WAC of $286.6/ MWh (1.1% lower than actual cost).

VII. CONCLUSION

A pump hydroelectric storage power system is used to maximize the penetration of renewable energy in Brava Island's electric power system. The technical feasibility and economical sustainability of the system are investigated. Wind energy was adopted as the renewable energy source integrated with a pumped hydroelectric storage plant in order to enable sustainable power system for the island. The results showed that a high share of renewable sources in the power network may be economically unfeasible, although technically possible with energy storage technologies. Several scenarios were investigated by varying the wind power turbine and water storage reservoir capacities. Technical and operational restrictions of the proposed power system on the geographical location of the site were respected. The maximum renewable penetration achieved of the different scenarios on the island with economic return was 44% with positive impact on electricity production costs (up to 11% reduction). The simulations also showed that different wind turbines influence the overall power system efficiency and the economical outcome of the investment.

Finally, it can be said that renewable energy can play an important role to lower Brava's dependence on fossil fuels, increase energy security and mitigate rising prices of electricity production with better economical sustainability.

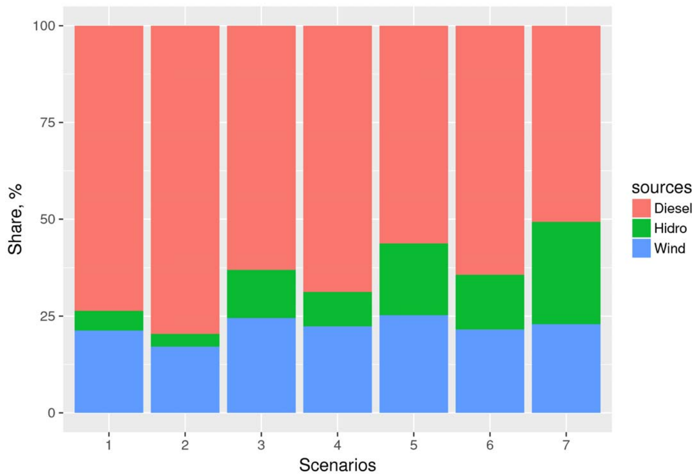

Fig. 6.Contribution of each energy source in the power system.

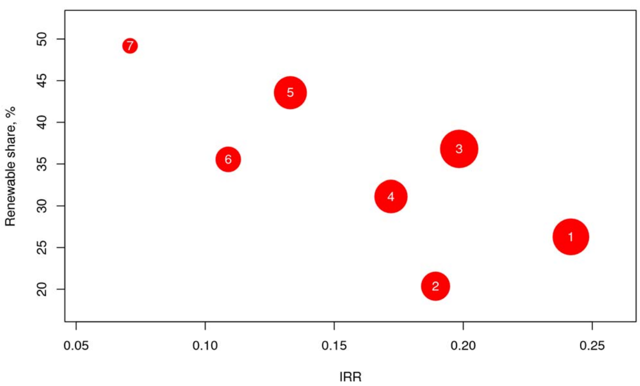

Fig. 7.Reduction of the final cost for electricity production in different scenarios.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

[1] N. Duic, J. P. Fonseca, M. G. Carvalho, *Increasing the penetration of renewable energy by merging energy and water supply systems: case study Corvo Island, Azores,* CD Proceedings of the 3rd Dubrovnik conference on sustainable development of energy, water and environment systems, Dubrovnik, 2005.

[2] Ćosić, Boris, Krajačić, Goran, et Duić, Neven. A 100% renewable energy system in the year 2050: The case of Macedonia. *Energy*, 2012, vol. 48, no 1, p. 80-87.

[3] Mason, Ian George, Page, S. C., et Williamson, A. G. A 100% renewable electricity generation system for New Zealand utilizing hydro, wind, geothermal and biomass resources. *Energy Policy*, 2010, vol. 38, no 8, p. 3973-3984.

[4] Duić, Neven et Da Graça Carvalho, Maria. Increasing renewable energy sources in island energy supply: case study Porto Santo. *Renewable and Sustainable Energy Reviews*, 2004, vol. 8, no 4, p. 383-399.

[5] Mukrimin Sevket Guney, Yalcin Tepe, Classification and assessment of energy storage systems, In Renewable and Sustainable Energy Reviews, Volume 75, 2017, Pages 1187-1197, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.11.102.

[6] T. Ackermann, *Wind Power in Power Systems*, Royal Institute of Technology Stockholm, Sweden, 2005.

[7] N. Duic, G. Krajacic, M. G Carvalho, R*enew islands methodology for sustainable energy and resource planning for islands,* Renewable and Sustainable Energy Reviews vol. 12, pp. 1032–1062, 2008.

[8] Connolly, David. *A review of energy storage technologies: for the integration of fluctuating renewable energy*. 2010.

[9] C. Bueno, J.A. Carta, *Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands,* Renewable and Sustainable Energy Reviews, vol. 10, pp. 312-340, 2006.

[10] J. S. Anagnostopoulos and D.E. Papantonis, *Pumping station design for a pumped-storage wind-hydropower plan,* Energy Conversion and Management, 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Vol. 48, pp. 3009-3017, 2007.

[11] M. P. Papadopoulos et al., *A Wind-Hydro-Pumped Storage Station Leading to High RES Penetration in the Autonomous Island System of Ikaria*, IEEE Transactions on sustainable energy, vol. 1, no. 3, 2010.

[12] R. Godina, E. Rodrigues, J. Matias, and J. Catalao,"Sustainable energy system of El Hierro island", in International Conference on Renewable Energies and Power Quality (ICREPQ'15). Renewable Energy and Power Quality Journal (RE&PQJ), vol. 13, 2015, pp. 46–51.

[13] A. Hiratsuka, T. Arai, and T. Yoshimura, "Seawaterpumped-storage power plant in okinawa island, japan", Engineering Geology, vol. 35, no. 3, pp. 237–246,1993, ISSN: 0013-7952.

[14] Katsaprakakis, Dimitris Al, and Dimitris G. Christakis. "Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential. A fundamental case study." *Energy* 66 (2014): 470-486.

[15] Electra SA. "*Relatorio e Contas*. Cabo Verde 2016". Available at: <http://electra.cv/index.php/2014-05-20-16-30-16/relatorios-norte>.

[16] GTZ, "Aproveitamento da Energia Eolica para o Abastecimento de Agua, Brava (Cabo-Verde) – Relatorio Final", GmbH, Tech. Rep., 1999.

[17] J.A. Suul, K. Uhlen, T. Undeland Variable speed pumped storage hydropower for integration of wind energy in isolated grids – case description and control strategies NORPIE/2008, Nordic workshop on power and industrial electronics (June 9-11, 2008).

[18] http://energystorage.org/energy-storage/technologies/pumped-hydroelectric-storage. Access:2017-10-18.

[19] http://www.are.cv/images/stories/combustiveis/histrico_011217.pdf. Access: 2017-12-27.