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# Techno-economic comparison of various renewable energy sources for hybrid system implementation

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**Abstract**: The current trends in electro-energetics indicate, that due to depletion of fossil fuels and the need of CO2 emission reduction, there is and will be a substantial development in the fields of renewable energy sources, decentralization and accumulation of electricity using battery energy storage systems in the near future. Along with the increasing power demand and penetration of renewables into electric grids, there is a need for energy mix expansion. Hybrid renewable energy sources (HRES) combine several renewables and energy storage into one system and can be used for micro-grid implementation for off-grid application or on-grid. The article is focused mostly on off-grid systems and provides an information about current state of renewable energy sources applications in HRES with techno-economic evaluation of net present cost and levelized cost of energy.

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***Abstract*** – *The current trends in electro-energetics indicate, that due to depletion of fossil fuels and the need of $CO_2$ emission reduction, there is and will be a substantial development in the fields of renewable energy sources, decentralization and accumulation of electricity using battery energy storage systems in the near future. Along with the increasing power demand and penetration of renewables into electric grids, there is a need for energy mix expansion. Hybrid renewable energy sources (HRES) combine several renewables and energy storage into one system and can be used for micro-grid implementation for off-grid application or on-grid. The article is focused mostly on off-grid systems and provides an information about current state of renewable energy sources applications in HRES with techno-economic evaluation of net present cost and levelized cost of energy.*

## 1 Introduction

Environmental and energy sustainability had become one of the biggest concerns in recent years, which made energy sources developers switch interest from conventional fossil energy sources to renewable energy sources and energy efficiency. The problem with renewables (like wind or solar) is the intermittency of their power production and availability at specific locations. Therefore, to increase their share in power supply, the distribution grid needs to be dynamic and more flexible than conventional grid. This need resulted in the development of distributed generation concept, like micro-grids or smart grids [1].

In contrast to a conventional centralized power generation concept, distributed generation utilizes smaller (in terms of rated power) energy sources scattered across distribution grid. In a lot of cases (esp. low rated power systems), the electricity is produced at the point of its consumption. The concept consists of numerous power generators, which supplies local loads, creating a micro-grid. The whole system is connected to distribution grid via a device called point of common coupling and can operate either in off-grid, on-grid or both modes [2,3]. Energy storage systems are widely implemented into micro-grids to overcome RES (renewable energy sources) power production intermittency. Optimal sizing and selection of a suitable energy storage system (ESS) technology is an important assessment to serve a desired purpose of ESS (peak-shaving, grid support, etc). [4]

Out of all renewables (i.e. solar, hydro, wind, biomass, ocean and geothermal), each has a specific benefits and application. The mentioned intermittency and unpredictability of these sources can cause an inability to produce a sufficient power to meet the load demand at each instant [5]. A hybrid energy system combines more than one renewable either with or without a conventional power sources (i.e. diesel generators) to obtain a more optimized power output. Out of the available renewables, wind and solar plants has seen the most attention and practical implementation. Therefore, they have the largest potential for supplying a major part of renewable energy for both large scale application and rural electrification [6,7].

The main drivers in hybrid renewable energy sources (HRES) implementation are economics, environment preservation, RES availability and advancements in technology etc. The greatest rise and investment in HRES technology occur in developing countries or remote areas, which do not have access to a reliable energy supply. These regions usually use diesel generators as the main source of electricity production. As the price of fossil fuels grows, the cost of operating and maintaining diesel generators gradually becomes economically less sustainable. Hence shifting focus towards investing in HRES [6,8]. The variations of sources for a possible HRES configuration can be seen in Figure 1.

This article is focused on analyses of techno-economic studies conducted in about last two years. Since Asian countries were found to have a dominant share in recent HRES implementation as well as publications, it was determined to focus the article on information from these studies. It has to be noted, that the economic evaluation in the studies is influenced by initial conditions and economic assumptions of the authors. Therefore, the values of investment costs can be outside of common European conventions and this fact has to be noted. This comparative report can serve as a foundation for a more global and complex research.

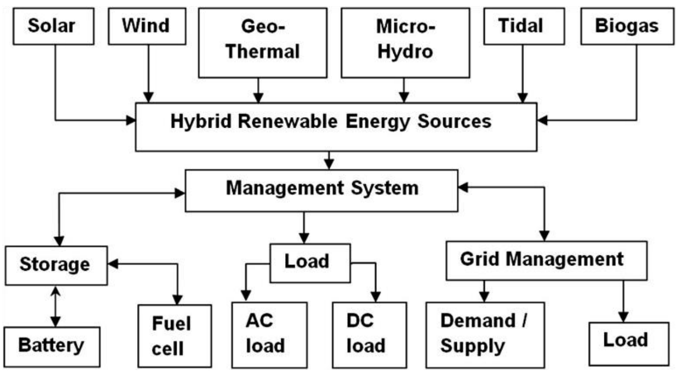

Figure 1: Diagram of hybrid power system [9].

## 2 Economic assessment

For hybrid system to be economically viable and profitable, an assessment has to be concluded. There are several economic

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indicators that can be evaluated, but the most important, which will be covered in this article are net present cost (NPC) and levelized cost of energy (LCOE).

To equate a total cost of a project over its life-time to the total cost today, while taking the time value of money into account, the net present value economic indicator is used. The advantage is that the investor will know, how much value an investment or project brings to an investor. However, if a system with no sales or incomes is assumed, which is the case in this article, it is common to use net present cost [10]. Net present cost is an indicator, which considers the total cost of installation and operation of a system throughout life-time of the project minus the present value of all the revenue earned over its lifetime. It is the main economic output to be minimized. The calculation is obtained from equation (1) [7,9]:

$$NPC = \frac{Total\ annualized\ cost}{CRF(i, R_{proj})}, \quad (1)$$

where *CRF* is capital recovery factor with interest *i* and project lifetime in years $R_{proj}$.

Levelized cost of energy indicates an average net present cost of energy production throughout lifetime of the project. LCOE can be calculated from equation (2) [9]:

$$LCOE = \frac{Annual\ capital\ cost + Annual\ operating\ cost}{Annual\ energy\ production}. \quad (2)$$

## 3 Renewable energy sources

This chapter discusses individual renewable energy sources considering the configuration in Figure 1. The sources are divided into five groups and each contains a description with examples of recent implementation along with economic assessment. Solar and wind energy sources share a combined subchapter since they are frequently used together in hybrid systems.

### 3.1 Solar and wind

As mentioned in introduction, the most common RES for hybrid renewable energy system consists of solar and wind energy generators. The system uses a wind turbine with a synchronous generator and photovoltaic panels operated with maximum power point tracking. Both sources are connected via their converters to DC bus usually along with battery storage, which is used to maintain energy balance in the system. Energy management system oversees and controls the power flow in different directions in order to supply the local load with demanded energy or supply the excess energy to the battery [11–13]. Diesel generator can be included in HRES off-grid system as a conventional power source for rural electrification. The diesel generator is working only if power supplied by both renewable sources and batteries cannot meet the load power demand [14,15].

Research [16] deals with analysis of hybrid system for an island, which used to be electrified by four diesel generators each of capacity 500 kW (running in turn for 24 hours) in parallel with a 40 kWp solar system. The average load power consumption is 4 076 kWh/day. The diesel generators were unreliable and solar system was insufficient, so upgrade was required. The stand-alone diesel, stand-alone solar/storage, solar/diesel, solar/diesel/storage hybrid systems configurations were analysed. From the simulation results, the lowest LCOE of 0,3569 $/kWh is found at the solar (200 kWp) and diesel (1 344 kW) configuration, which has also the NPC of 9 792 012 $.

Study [7] investigates a HRES deployment in Iran's coastal area. Various combinations of solar (10 kWp), wind (10 kW), diesel generator (100 kW) sources and li-ion battery (25 kWh) were analysed for a load power consumption of 11,25 kWh/day. Results show that the optimal HRES solar/wind combination generates a sufficient amount of electricity has the lowest NPC of 23 149 $ and LCOE of 0,44 $/kWh. Both studies [16] and [7] omit a battery storage, because of economic reasons (high NPC), even though it helps to reduce $CO_2$ emissions by as much as 30 %.

Development of optimal HRES model using solar/wind energy sources with battery storage to supply three Indian villages, with calculated power load consumption of 624,3 kWh/day, was conducted in [17]. The optimal system consists of 48 kWp of solar, 10 kW of wind and 154 kWh of battery capacity. Unlike previous studies, the solar and wind units generate such a fluctuating power output, that the optimal size of the battery had to be obtained to support peak load demand. The battery supplies 59,3 % of power for peak load demand in winter and 82,6 % in summer. The LCOE is 0,1032 $/kWh, which is almost three times lower than LCOE in [16] without battery storage. The value of NPC was not calculated.

Studies [18,19] chose a different approach in HRES design and analyses a PV/hydrogen fuel cell configuration instead of battery storage. The fuel cell converts hydrogen chemical energy into electricity via chemical reaction (fuel oxidation). To reverse the process, an electrolyser is used to consume electricity to generate hydrogen by electrolysis of water. The produced hydrogen is then compressed and stored in a tank to be used again in the fuel cell. In [18] the HRES to supply a desert community area in UAE with an average power consumption of 4 500 kWh/day. From results, the best obtained HRES configuration was 517 kWp solar, 750 kW fuel cell, 250 kW electrolyser with a 900 kg hydrogen tank. The electrical efficiency of the fuel cell was found out to be at 68 %. Total power production was 52 % from solar and 48 % from fuel cell. The total NPC is 3 070 000 $ and LCOE is 0,145 $/kWh. Therefore, the LCOE in this system is more than two times lower than LCOE in [16] and very similar to LCOE in [17].

Study [19] proposed a small HRES system for a household with an average daily power consumption of 12 kWh. The system consisting of 8 kWp solar, 1,5 kW fuel cell, 1,5 kW electrolyser with a 5 kg hydrogen tank has a LCOE of 0,52 $/kWh. In comparison to previous studies these results indicate, that HRES with fuel cell is not economically reasonable for a small scale/household application.

### 3.2 Hydro

To implement a hydro power in HRES, the location has to have a sufficient stream of water and other appropriate technical conditions to be suitable for power production, the survey of the area hydro potential is therefore necessary.

Study [20] provides a techno-economic analysis of different hybrid system to supply electricity to a typical Iraq rural village, which has an average daily load of 23,29 kW. Five configuration cases of solar, hydro, diesel generators and deep cycle lead-acid batteries are assessed. The simulation showed that energy system consisting of 13 kWp solar modules, 14,7 kW hydropower unit, 5 kW diesel generator and 55,52 kWh of battery storage is optimal solution with the lowest NPC of 113 201 $ and LCOE of 0,054 $/kWh.

On the other hand, in study [21] the HRES for rural electrification in Benin consists of solar and micro-hydropower station with a diesel generator unit and battery system. The wind power potential in the area is insufficient for energy generation, therefore this source is not considered. Instead, since the site is located 11 km far from a river suitable for a hydropower site, it is used for electricity generation with rated capacity of 247 kW. Simulation and sensitivity analysis of system configuration and sizing was conducted to assess the techno-economic feasibility of HRES in the area. Results showed that solar (150 kWp), diesel generator (50 kW) and lead-acid battery (637 kWh) configuration is the most cost optimal solution with NPC of 555 492 $ and LCOE of 0,207 $/kWh. A system, in which would hydro be present, would have LCOE of more than 0,32 $/kWh and NPC in range of 860 000 to 930 000 $. According to results it also has to be noted that the grid extension from the site to the hydropower station has to be installed, which is an extra investment, that makes the proposed system less cost-effective than using just the PV, diesel generator and battery. Therefore, the remoteness of the area from hydro site is an issue. In contrast to [20], since the area uses a much larger diesel generator unit and doesn't consider hydro production, the LCOE is about four times higher. In conclusion, the availability of this energy source doesn't have to be an appropriate solution for HRES, economically.

Studies [22,23] suggest a HRES with a pumped-hydro storage (PHS) to use it as an energy storage system. The upper reservoir can be used not only to store water, but also to harvest rainwater from roofs [24], which then can be allowed to run down through hydro turbine to produce electrical power. Lower reservoir collects the water and in time of surplus energy from renewables, the pumps store it back into upper reservoir. The water in reservoirs has to be replenished either by natural inflow or from rainfalls. This implies that this kind of HRES configuration is more suitable for locations with a large number of rainy hours in a year or tropical locations in general.

In [22] the study proposes two PHS based HRESs for a South Korean island with an average power consumption of 24 720 kWh/day. System A was designed to have the lowest NPC, respectively the lowest LCOE in system B. Both systems consist of 2 000 kW wind turbine, hydro turbine in PHS of 1 020 kW and 2 504 kWp of solar in system A or 3 157 kWp in system B. The size of PHS in system B is also larger than in A, more details on design in [22]. Therefore, the results of the study estimate an NPC for system A of 11,3 million $, respectively 17,6 million $ for system B. On the other hand, the investment in larger PHS results in lower LCOE of 0,122 $/kWh in comparison with 0,159 $/kWh in system A. Study also compared the economics of PHS against battery storage. In both systems because of its scale, the PHS was a cheaper option.

Similar study [23] proposing a solar, wind, hydropower station with PHS was carried out in central China. According to the results, the best cost-effective HRES combination achieved was solar (13 786 kWp), wind (4 500 kW), hydro (5 377 kW) with PHS. The optimized system has LCOE of 0,2345 $/kWh, which is a bit more expensive to [22], NPC is not stated so it cannot be compared.

Research [24] analyses HRES with PHS to harvest rainwater and electrify a household with an average 3,032 kWh/day power consumption. The system was designed to be less dependent on installed battery storage and solar power capacity. After analysing multiple cases with and without PHS, the most optimal system consists of 1,7 kWp solar, 125 W hydro, 3,13 kWh battery storage, which also has the lowest LCOE of 0,443 $/kWh. Compared to [22] and [23], which demonstrate a large-scale implementation of PHS, the LCOE is about two times higher. In conclusion, similarly to systems [18,19] with hydrogen storage, an implementation for a single household results in higher LCOE. The NPC of both [23] and [24] is not stated.

### 3.3 Biomass

The biomass resources come from agricultural crop residues, wood residues or animal waste. Biomass is usually burned or gasified into biogas and used as a combustible in power generators. For this renewable sources to be cost-effective at specific locations, there has to be a sufficient agricultural development and production. If the site is suitable for this energy source, it can be used as a replacement of standard diesel generators. However, the biomass from agricultural waste has to be processed in some kind of fuel to be used in biomass generators, which increases the LCOE in the system. Implementation of biomass into HRES occurs in studies [25–29].

Research [25] optimizes a HRES for small rural community in Saudi Arabia of 267 kWh/day average load consumption. The best design consists of 71 kWp solar, 160 kW biomass, 20 kW wind and 288 kWh of nickel-iron batteries, which has the NPC of 581 218 $ with 0,254 $/kWh LCOE.

Study [26] analyses a comprehensive HRES based on combination of solar, wind, biomass, biogas sources either with or without fuel cell and battery to power three rural villages in India of 724,83 kWh/day average power consumption. According to results, the lowest NPC of 856 013 $ and LCOE of 0,163 $/kWh were achieved in a system consisting of 100 kWp solar, 50 kW wind, 50 kW biomass generator, 60 kW biogas generator, 200 kWh battery, 57 kW fuel cell with 50 kW electrolyser and 300 kg hydrogen tank. Compared to [25] it seems, that the addition of fuel cell can decrease the systems LCOE.

Study [27] analyses a HRES with 104 kWp solar, 30 kW wind, 50 kW biomass with 331 kWh lead acid batteries for rural village electrification in China with an average of 620 kWh/day power consumption. The proposed system has a LCOE of 0,201 $/kWh and NPC of 587 013 $. Both values are very similar to previously mentioned studies. The area is not connected to main grid, the investment in HRES was compared against

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investment in grid extension and HRES came out as a more economically viable solution.

Research [28] proposes a small scale hybrid system of 3 kWp solar, 1 kW biomass generator with 15 kWh of battery storage in Bangladesh. The system can be also connected to grid if HRES production for load is either insufficient or surplus. The NPC of this system equals 39 421 $ and LCOE, which was derived from figures, is varying from range of 0,4 to 0,6 $/kWh. Like in studies with PHS and solar, fuel cell configurations, the small scale implementation results in higher LCOE.

### 3.4 Geothermal

When it comes to geothermal energy, the possibility of this source for HRES implementation is not much explored yet. This is due to not only limited number of suitable geographical locations but also due to the physical principle of the technology itself being difficult and expensive to build and also the temperatures of working fluid have to be sufficient for electricity production. Only a limited amount of researches [30–32] were recently conducted. In [30,31], the geothermal energy in HRES have been used only to produce heat, therefore they are not further discussed in this article.

In [32] the researchers were able to use a geothermal plant to produce steam by heat exchanging to generate electricity for a village in Pakistan with 7 350 kWh/day average power consumption. The geothermal plant acts as a 250 kW base load plant with more than 70 % share on power production. The rest of the system consists of 250 kWp solar, 100 kW wind and to meet the load high power demand, the system is on-grid. This optimized design has the NPC of about 1,5 million $ with LCOE of 0,048 $/kWh. If the load power demand increases, the electricity can be purchased for about 0,0768 $/kWh or sold for 0,0512 $/kWh, if the generated power is higher. The results of LCOE are comparable to [20], which has hydro power plant instead of geothermal acting as a base load plant. Because the power production in both is stable, the LCOE reach to lowest values compared to systems with solar, wind or biomass sources.

### 3.5 Tidal and wave

Tidal sources produce energy from rise and fall of ocean. Therefore, tidal sources can be utilized in HRESes located close to shores. The tidal energy generators function basically as sea wind turbines, that generate electricity from the energy of moving water [34]. Since it is not vastly expanded energy sources, only a few researches were conducted recently, for example studies [33,34] recently dealt with implementation of tidal sources into HRES, however with no economic evaluation.

Research [35] is one of few which looks for an economically optimal combination of solar/wind/tidal and battery system in a stand-alone area in France of average power consumption 16 MWh/day. According to results, the best combination was achieved using only wind turbines of 4,6 MW total rated power with 59,74 kWh of battery capacity. This combination has the lowest LCOE of 0,0942 $/kWh and NPC of 3 488 082 $, although the system depends a lot on weather and load demand. The study compares two HRES designs with tidal turbines, one design uses a 2,3 MW wind turbine and a 500 kW tidal turbine. This design has an NPC of 4 522 475 $ and LCOE of 0,1221 $/kWh. The second design contains 3 MW total of tidal turbines and 285 Wp of solar, which has LCOE of 0,2647 $/kWh and NPC of 9 802 707 $. The study also analyses a design combining 3,14 kWp solar, 2,3 MW wind, which has lower both LCOE (0,1003 $/kWh) and NPC (3 711 676 $) than designs implementing tidal turbines. The largest renewable potential with lowest cost at the studied area therefore have wind turbines.

Feasibility study of on-grid solar/wave HRES in three different locations on the shores of Persian Gulf in Iran, was conducted in [36]. The system, consisting of 12 kWp solar and 3 kW oscillating water column generator for wave energy transfer, was analysed. The share of wave generator on power production was determined to be less than 5 %. The system simulation resulted in excessively high LCOE due to unrealistic initial conditions, therefore the value is not stated in this article. In conclusion based on the power production share of wave generator, the investment in this technology is not economically feasible.

## 4 Summary

To put all the numbers about HRESes mentioned from studies above in perspective, table 1 provides a summary of every HRES combination in chronological order of appearance in the article with focus on presence of different renewable energy sources. The information about the rated power of individual energy sources or capacity of energy storage (if present) and total rated power of all sources in the system is provided as well as NPC and LCOE. Some of the studies does not have available data of systems NPC, therefore marked N/A in the table. Because the article analyses HRESes of different sizes, in terms of rated power, the Cost to rated power indicator was calculated to better asses the different sizing of hybrid systems.

## 5 Conclusion

Based on the survey regarding hybrid renewable energy systems, the largest implementation has occurred in eastern (Asian) countries recently. The need for rural electrification and creating off-grid systems have been the major drivers, as well as reliability and cost of HRES.

Solar and wind energy sources are and will be dominant in most of the systems, due to its availability and lower cost of technology. Systems which combine these two sources usually result in the lowest NPC. The LCOE in these systems depend on presence of energy storage system. The implementation of ESS results in significant NPC increase as well as decrease of LCOE. Both battery and hydrogen storage follow this trend. Therefore, the optimal HRES configuration can differ based on the assessed economic indicator (NPC or LCOE). A hybrid system combined with diesel generator often occurs as the most optimal solution in simulations due to its price/performance ratio regarding NPC, but resulting in increase of LCOE.

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Table 1: A summary of HRESes and economic indicators

| HRES configuration | Rated Power [kW] | Total Rated Power [kW] | NPC [$] | LCOE [$/kWh] | Cost to rated power [$/kW] |
|---|---|---|---|---|---|
| Solar/Wind [7] | 10/10 | 30 | 23 149 | 0,440 | 1 158 |
| Solar/Diesel gen. [16] | 200/1 344 | 1 544 | 9 792 012 | 0,357 | 6 342 |
| Solar/Wind/Battery 154 kWh [17] | 48/10 | 58 | N/A | 0,103 | N/A |
| Solar/Fuel cell 750 kW [18] | 517 | 517 | 3 070 000 | 0,145 | 5 938 |
| Solar/Fuel cell 1,5 kW [19] | 8 | 8 | N/A | 0,520 | N/A |
| Solar/Hydro/Diesel generator/Battery 55,52 kWh [20] | 13/14,7/5 | 32,7 | 113 201 | 0,054 | 3 462 |
| Solar/Diesel generator/Battery 637 kWh [21] | 150/50 | 200 | 555 492 | 0,207 | 2 778 |
| Hydro/Diesel gen. [21] | 247/40 | 287 | 885 302 | 0,330 | 3 085 |
| Solar/Hydro [21] | 50/247 | 297 | 935 669 | 0,349 | 3 150 |
| Solar/Wind/Hydro with PHS - System A [22] | 2 504/2 000/1 020 | 5 524 | 11 300 000 | 0,159 | 2 046 |
| Solar/Wind/Hydro with PHS - System B [22] | 3 157/2 000/1 020 | 6 177 | 17 600 000 | 0,122 | 2 849 |
| Solar/Wind/Hydro with PHS [23] | 13 786/4 500/5 377 | 23 663 | N/A | 0,235 | N/A |
| Solar/Hydro/Battery 3,13 kWh [24] | 1,7/0,125 | 1,825 | N/A | 0,443 | N/A |
| Solar/Wind/Biomass/Battery 288 kWh [25] | 71/20/160 | 251 | 581 218 | 0,254 | 2 316 |
| Solar/Wind/Biomass/Biogas/Fuel cell 57 kW/Battery 200 kWh [26] | 100/50/50/60 | 260 | 856 013 | 0,163 | 3 292 |
| Solar/Wind/Biomass/Battery 331 kWh [27] | 104/30/50 | 184 | 587 013 | 0,201 | 3 190 |
| Solar/Biomass/Battery 15 kWh [28] | 3/1 | 4 | 39 421 | 0,4 - 0,6 | 9 855 |
| Solar/Wind/Geothermal [32] | 250/100/250 | 600 | 1 500 000 | 0,048 | 2 500 |
| Wind/Tidal [35] | 2 300/500 | 2 800 | 4 522 475 | 0,122 | 1 615 |
| Solar/Tidal [35] | 0,285/3 000 | 3 000,285 | 9 802 707 | 0,265 | 3 267 |
| Solar/Wind [35] | 3,14/2 300 | 2 303,14 | 3 711 676 | 0,100 | 1 612 |

Other renewable sources have to meet certain technical conditions at specific locations to be implemented in HRES. Implementation of hydro power in HRES increase NPC significantly, but it acts as a base load plant with stable power output. If the location of hydro generator is located close to HRES, it results in one of the lowest LCOE. For energy storage, a PHS can be included.

According to studies including PHS in their systems, the results compared to other studies show a moderate LCOE and significant increase of NPC. Therefore, with implementation of this technology, the positive environmental effect should be taken **into** consideration, for PHS to be economically reasonable. Implementing biomass in HRES results in moderate both NPC and LCOE. If the location has a sufficient sources of biomass, it can act as a preferable substitution of diesel generators. Geothermal source in HRES is not much explored and suitable locations are limited. According to study mentioned in the article, the addition of geothermal plant results in one of the lowest LCOE of all studied systems. However, the NPC, considering the installed rated power of the system, is one of the highest. According to studies, tidal and wave energy sources for HRES implementation are not really explored. Results showed very little share on power production. Compared to HRES with only wind and solar sources, it resulted in much higher NPC and also LCOE. From these results, it can be concluded that designs using tidal or wave energy are not economically feasible.

In the end, for the reader to have a clear and organized view of the hybrid systems economics, Table 1 provides a complete summary with addition of Cost to rated power indicator to compare different size HRESes more easily.

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