Quantifying the Market Value of Wave Power compared to Wind&Solar – a case study

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Abstract

This study discusses the market value of electricity production by different sustainable sources, and shows how it is influenced by the correlation between electricity market price and energy production. The generic discussion is accompanied by a case study comparing the value of wave, wind and solar power using time series data for production and prices generated by grid and market simulations. The study has shown that simplified common-practise approaches (which do not consider correlation) fail to correctly reveal the market value of electricity production. It has also been shown that wave power can achieve a market value that is significantly higher than wind and slightly higher than solar. These differences in market value have been explained through correlation between electricity production and price, which is different for different energy sources. The study has identified competitive advantages of wave power towards the dominant sustainable energy sources, that need to be taken into account when competitiveness and profitability are to be assessed.

1 Introduction

The potential of wave power is large, making it a suitable candidate for being an essential part of the world's power supply in a sustainable future. However, wave power technology is still at an early stage, and the maturity is not comparable to wind power or solar power (in this article, solar power refers to photovoltaic technology). New technology is always expensive, and so are wave power converters at the moment. This is neither surprising nor important; the important question is if wave power in the future can compete wind&solar.

This competitiveness depends on two aspects, the cost and the value. Costs are important and often addressed, but not the topic of this study. Instead, this article concerns the value:

How much market value can wave power deliver?

Wind&solar power and wave power are weather-driven sources that cannot store their primary energy carrier (unlike e.g. hydro power with a large reservoir). These weather-driven power plants adjust the quantity of their product offered on the market according to the resource availability. High wind speed and/or strong solar radiation lead directly to more supply on the market. This significantly influences the shape of the bid-curve, which is one of two factors (the other being the demand curve) setting the electricity market price. These weather-induced fluctuations of the marked supply result in market price fluctuations. Both wind&solar are big enough market players, that their supply bid significantly influences the market price; wave power is not in that position (not now, neither in the near future).

The correlation between energy production and market price is negative (more power supply leads to lower prices). This is a *disadvantage* for the big weather-driven market players (wind&solar power). It is, however, a competitive *advantage* for wave power, or any other new technology, which does not rely on wind speed or solar radiation. The relevance of this correlation is steadily increasing with rising shares of wind&solar power. The market price fluctuations in general are also increasing with rising shares. This will gradually increase the competitive advantage of wave power, giving it a higher value (per kWh) on the market than its direct competitors. The hypothesis here is:

Wave power delivers more market value than wind&solar

And if wave power delivers more value, it may well be more expensive, but it still can be economically competitive. Higher cost might be less of a problem than otherwise anticipated.

2 Determining the Market Value

This study considers the *idealised market value* of electricity production, computed as the revenue obtained in an ideal, single electricity market. The rather complex system of real electricity markets that are split into several sub-markets (e.g. day-ahead, intra-day), influenced by subsidies and taxes that differ between countries and change over time, is not addressed here. The real revenue a power plant owner will make selling electricity on the real electricity market system can differ significantly from the *idealised value* from the ideal market. This idealised value is used to grasp the generic and universal aspects of 'value', to reflect the interest of society rather than an investor.

2.1 Levelised Cost of Energy

Levelised Cost of Energy (LCoE) is a well-established measure for comparing electricity costs. It intends to capture the energy-average electricity production cost (considering both investment and operation cost) over the entire life-time. Using LCoE, the cost per kWh of different electricity sources can be compared. Sustainable electricity production technologies are usually assessed based on this measure.

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To define the LCoE, it is first necessary to define the *discount function* $q(t)$ (a common financial book-keeping concept), which is a way to compare future values with present values:

$$q(t) = \frac{1}{(1+Q\tau)^{t/\tau}} \tag{1}$$

This is based on the discount rate Q that reflects the general interest rate and has the units $\%/\tau$, with τ being the compounding period (normally one year). This discount function $q(t)$ is used to obtain the *present value* of costs C by calculating the total discounted cost over the life time T:

$$C = \int_{t=0}^{T} c(t) \cdot q(t) dt \tag{2}$$

The *present value* of the energy production can be expressed in the same manner:

$$E = \int_{t=0}^{T} e(t) \cdot q(t) dt \tag{3}$$

Now, the LCoE can be formulated:

$$\text{LCoE} = \frac{C}{E} \tag{4}$$

2.2 Levelised Value of Energy

To capture not just the cost, but also the market value, the concept of *Levelised Value of Energy* (LVoE) has been proposed [1]. It is defined in a similar manner as the LCoE, but with cost C replaced by value V:

$$\text{LVoE} = \frac{V}{E} \tag{5}$$

The value V can be defined similar to the cost C in Equation 2. Considering an ideal electricity market, the value v is the product of energy production e and market price p.

$$\text{V} = \int_{t=0}^{T} v(t) \cdot q(t) dt = \int_{t=0}^{T} p(t) \cdot e(t) \cdot q(t) dt \tag{6}$$

The *discounted energy production* is introduced:

$$\epsilon(t) = e(t) \cdot q(t) \tag{7}$$

Expressing the energy E (Equation 3) in terms of ϵ yields:

$$E = \int_{t=0}^{T} \epsilon(t) dt = T \cdot \frac{1}{T} \int_{t=0}^{T} \epsilon(t) dt = T \cdot \bar{\epsilon} \tag{8}$$

Expressing the value V (Equation 6) in terms of ϵ yields:

$$\text{V} = \int_{t=0}^{T} p(t) \cdot \epsilon(t) dt \tag{9}$$

Any function $x(t)$ can be expressed in terms of the mean value $\bar{x} = \frac{1}{T}\int_0^T x(t)dt$ and the deviation $\Delta x(t) = x(t) - \bar{x}$. When using this notation for $p(t)$ and $\epsilon(t)$, the value integral can be written as:

$$\begin{aligned} V &= \int_{t=0}^{T} [\bar{p} + \Delta p(t)][\bar{\epsilon} + \Delta\epsilon(t)] dt \\ &= \int_{t=0}^{T} \left[\bar{p}\bar{\epsilon} + \bar{p}\Delta\epsilon(t) + \Delta p(t)\bar{\epsilon} + \Delta p(t)\Delta\epsilon(t)\right] dt \\ &= \bar{p}\bar{\epsilon} \underbrace{\int_0^T dt}_{=T} + \bar{p} \underbrace{\int_0^T \Delta\epsilon(t) dt}_{=0} + \bar{\epsilon} \underbrace{\int_0^T \Delta p(t) dt}_{=0} + \underbrace{\int_0^T \Delta p(t)\Delta\epsilon(t) dt}_{C_{p\epsilon}(0)} \\ &= \bar{p} \cdot \bar{\epsilon} \cdot T + C_{p\epsilon}(0) \end{aligned} \tag{10}$$

$C_{p\epsilon}(t)$ is the cross-covariance of p and ϵ (at time lag t), which is a measure that captures the dependency between p and ϵ. Considering Equation 8, the value V can be expressed as:

$$V = \bar{p} \cdot E + C_{p\epsilon}(0) \tag{11}$$

Now inserting this version of the value into Equation 5 yields:

$$\text{LVoE} = \frac{V}{E} = \frac{\bar{p} \cdot E + C_{p\epsilon}(0)}{E} = \bar{p} + \frac{C_{p\epsilon}(0)}{E} \tag{12}$$

The LVoE can be expressed as the sum of *average* electricity market price $\bar{p}$ and another term based on the cross-covariance.

2.3 Simplification

The cross-covariance of two series is zero if the series are non-correlated. When assuming no correlation between electricity market price $p(t)$ and the other two terms of the value integral in Equation 6 (energy production $e(t)$ and the discounting function $q(t)$), the cross-covariance $C_{p\epsilon}(0)$ becomes zero, leading to a simplified expression for the LVoE that equals the time-average of the electricity market price:

$$\text{LVoE}^* = \bar{p} \tag{13}$$

Using this simplified version is tempting (and common practise), but highly problematic: it would only work if there was no correlation, which is not the case (anymore).

2.4 Correlation

The simplified approach ignored correlation of the electricity price $p(t)$ with the discount function $q(t)$ and the energy production $e(t)$. The investigation of the price-production correlation is the main focus and contribution of this study. This correlation is different for all three considered energy sources and therefore important when comparing them. Price-discount correlation is briefly discussed in Section 5, but not in focus.

2.5 Approach

Correlations between production and price are increasingly important, as the market shares of sustainable energy sources are growing. This undermines the premises on which this simplified approach is based. In a sustainable future, the simple approach breaks down and it is incapable of demonstrating the benefit of alternative sources (such as wave energy) that anti-correlate or correlate less with the dominant sources (wind&solar).

To correctly assess the market value of wave power, and to compare it to wind&solar, it is essential to use the original version for the LVoE (Equation 12) which correctly takes the correlation between energy production and electricity market price into account. Effectively, it calculates the *weighted* time-average price, with the weights being the energy production at the time. It can be interpreted as an energy-average: *for what price can the average* kWh *be sold?*

Determining this LVoE is not straight-forward, as knowing only average values is not sufficient input. A full time series of production and price is needed, containing all the dependencies between the two. As such a time series is not easily available, it has been generated through simulation for a future scenario.

3 Power Grid and Market Simulation

3.1 Simulation Tool

The power grid and market simulations were performed using the open-source Python package PowerGAMA[2], which represents the power system as a linear programming optimisation with the objective to minimise total cost of generation for each time-step. Constraints represent transmission line capacity limits, generator capacity limits, and power flow equations. Each generator has a marginal cost that depends on its type: For fuel-based generators, it is determined by fuel cost, efficiency and taxes. For renewable generation without storage, it is nearly zero. For hydro power with large storage, the marginal cost represents the *storage value* rather than the actual costs, i.e. the marginal value of keeping energy in the storage. The available renewable power and power demand is provided by time-series input. The inclusion of energy storage requires the problem to be solved sequentially for each time-step.

The power *grid* is represented by the linearised power flow equations which relate transmission line power flow, impedances and power generation and load. The power *market* is represented by the system cost minimisation, an idealised market where all energy is traded in a single market with no forecast errors.

The simulations create a power price time series in each node of the network. Country-wide prices have been computed as a weighted average of these nodal prices with power demand used as weights. Of course, the simplified representation of the electricity market limits the accuracy of the output, and the price time series will differ from prices formed in a real electricity market. However, the *correlation* between weather (wind and solar radiation) and prices is captured, which, as discussed above, is crucial for the calculation of the LVoE.

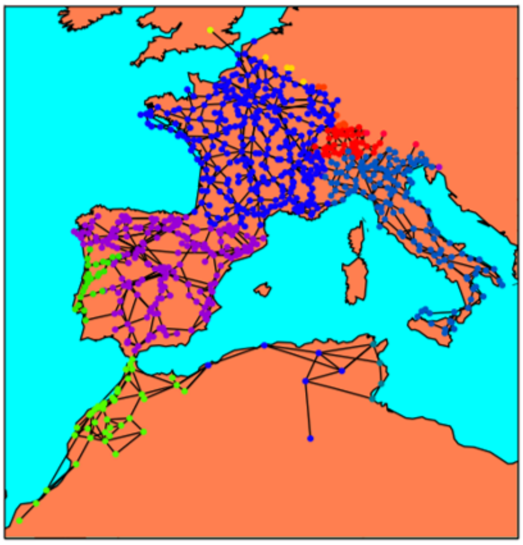

Fig. 1: Simplified western-Mediterranean grid model. Different colours for different countries.

Table 1 Assumed generation capacity and average load (GW)

	Hydro	Solar	Wind	Wave	Thermal	Load
PT	4.7	5.6	8.3	0.008	7.7	6.4
ES	15.1	16.9	35.7	0.0	21.7	37.4
FR	21.8	13.9	47.4	0.0	62.8	59.0
CH	20.1	0.8	0.6	0.0	4.5	8.6
IT	19.2	28.2	25.2	0.0	69.3	37.6
MA	2.0	4.0	4.0	0.0	13.4	9.4
DZ	0.2	10.0	2.0	0.0	27.8	16.0
TN	0.07	2.0	1.7	0.0	7.7	4.6

3.2 Study Case

To determine the LVoE for wave, wind and solar power in a future scenario, a case study based on a western Mediterranean 2030 scenario has been conducted; 2030 as a target year for commercial utilisation of wave power plants, and the western Mediterranean because of the location of the MegaRoller prototype in Portugal. The geographical extent and grid granularity of the study is illustrated in Figure 1.

A detailed description of the scenario is provided in reference [2], but a brief summary is as follows: Per-country power demand and generation capacity per technology was specified according to the *EC Trends to 2050 Reference Scenario 2013* [3] for 2030, see Table 1. Hourly power demand profiles per country are based on historical values. The grid model is based on an open European grid model [4] with some modifications. Generator capacities and loads have been scaled up or down according to the scenario. The simulation has been run for a year with hourly resolution.

3.3 Weather data

Wind, solar and wave power production time series were created based on historical weather data. A data set within the

MegaRoller project (not published) [5] contained wave height and frequency data for the relevant location on the Portuguese coast, whereas Wind speed and solar radiation were obtained from a global reanalysis data set [6]. By selecting synchronised data (the same years), correlations should be contained correctly, even though the data stems from different data sets. Wind varies significantly from year to year, while solar and wave do not. To grasp these long-term wind variations as well, three different weather years were considered (1997, 1998 and 1999).

4 Results

Based on the time series for electricity price and production, the LVoE can be calculated for wind, solar and wave power. For comparison, also the unweighted time-average electricity price has been calculated. The results are displayed in Table 2.

Table 2 Levelised Value of Energy

Market participant	Relative Price/Value
Demand	101,0 %
Wave power	95,9 %
Solar power	94,1 %
Wind power	89,8 %
Unweighted time-average	100,0 %

It can be observed that wave power performs slightly better than solar power and significantly better than wind power. Also interesting is the fact that the demand sees a higher price than the simple approach would tell. This seems logical, as high demand drives the prices, giving the high-price-moments a heavier wheight in the calculation of the average, than when considering the unwheighted average.

4.1 Diurnal pattern

Production and demand are not constant, but they fluctuate over time. One dominant mode is the diurnal fluctuation, displayed in Figure 2. This daily profile is obtained by computing the mean values for each hour of the day.

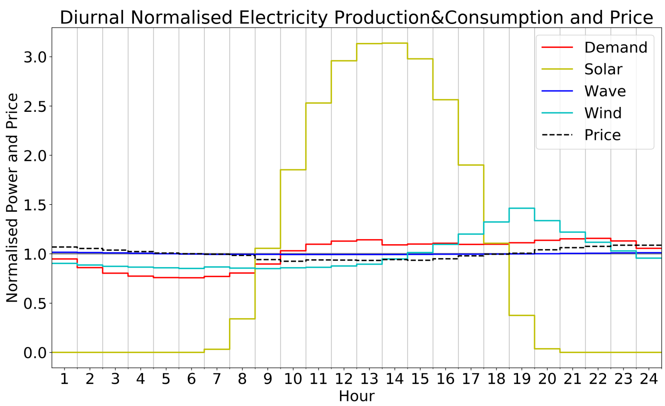

Fig. 2: Diurnal pattern of power production and demand

As expected, solar power has the most prominent diurnal pattern. Also demand and wind power show a pattern, however, not as pronounced. Somewhat surprisingly, wave power shows almost zero diurnal pattern, with only a marginal increase at night. This might not generally be true, but it is at least for the Portuguese Atlantic coast data used here.

Demand has also been included, as its fluctuations influence the electricity price just like the energy source fluctuations do. These diurnal power patterns cause a diurnal pattern for the electricity price. To what extent they influence the price depends on the market shares. Especially the pronounced solar pattern is dominant, causing the power price to be lower during the day and higher during the night.

How the different sources perform on the market during the average day is displayed in Figure 3. Wind and wave power show a similar pattern as the price itself, however located lower, with wave performing better than wind. Solar actually realises a revenue close to the market price, but only during the daylight hours when the market price is low.

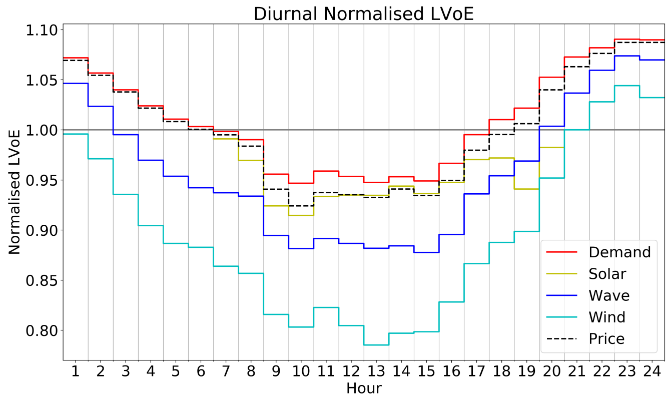

Fig. 3: Diurnal LVoE pattern of electricity price and LVoE

4.2 Seasonal pattern

The other dominant mode of fluctuation is the seasonal pattern, shown in Figure 4. The extraction of the fundamental (twelve month) seasonal pattern has been done by applying a very-close-to ideal implementation of an ideal low-pass filter with a filtering cut-off time period of eight months.

Also here, solar power shows (as expected) a clear pattern, due to more sunny weather during the summer, while demand and wind power are less pronounced . However, in some regions of the world (very warm/very cold) the seasonal demand pattern can be much stronger than observed here. Noticeably, the strongest seasonal pattern is by far wave power, where power production during winter is about four times as large as compared to summer.

These seasonal power patterns cause a seasonal electricity price pattern: in general, electricity is cheaper during spring/early summer and more expensive during autumn/winter. This is mostly caused by the combination of more solar power production and less demand during summer. The very

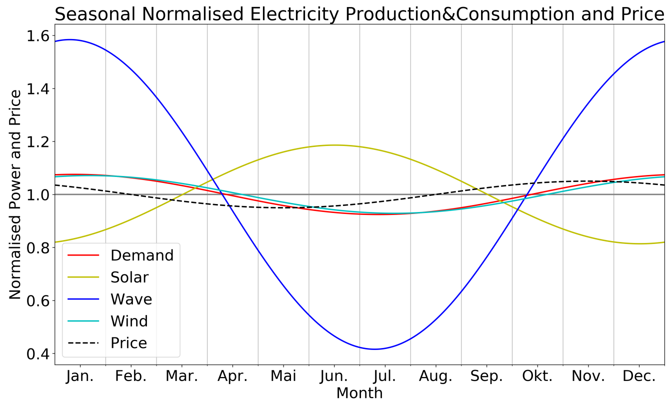

Fig. 4: Seasonal pattern of power production and demand

pronounced seasonal pattern of wave power would theoretically push the price pattern in the opposite direction (high power production would lower prices in the winter). However, as the 2030 case does not include large amounts of wave power (in contrast to wind and solar), wave power does not influence the power price. On the seasonal scale, wind and wave power correlate positively with the electricity price, while solar correlates negatively.

How the different sources perform on the market in comparison with the average market price, i.e. the LVoE relative to the seasonal average price, is displayed in Figure 5. In this figure, the grey reference line (at 1.0) depicts the average electricity price *at that time of the year*, and corresponds to the black dashed line in Figure 4.

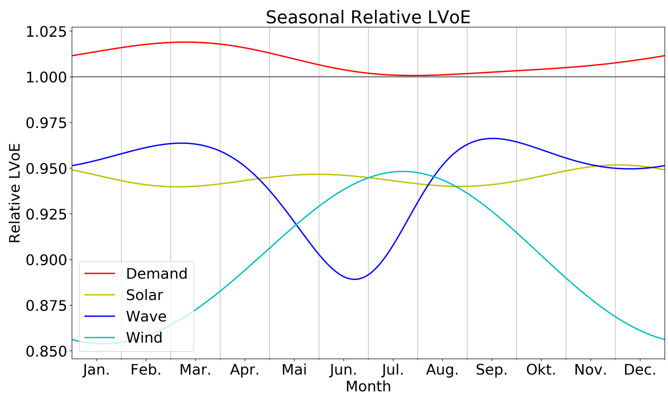

Fig. 5: Seasonal pattern of electricity price and LVoE

The deviations with regards to the grey reference line visualise the error that results from the simplified value assessment. Demand is always slightly above the average price, while solar is around 5 % below. Wind and wave show a seasonal pattern in market performance, with wind performing well and wave performing worse during summer. Considering the power production profiles, this is in favour for wave power, as the period of bad market performance is the time of the year, where production is low anyhow, while for wind, bad market performance and high production coincide.

5 Discussion

The results from the case study support the hypothesis (wave power delivers more market value than wind&solar). This is mostly due to the aforementioned (now quantified) negative correlation between production and price for wind&solar, but also in the positive correlation between waves and demand.

Wave power does not follow a clear day-night pattern (unlike solar power), but it has a clear summer-winter pattern: the waves are larger in the winter. This is positively correlated with electricity prices which are higher during the winter, caused by less available solar power and more load (at least in non-tropical regions). With this beneficial seasonal pattern that *positively* correlates with electricity demand, wave power would actually be expected to "score" above 100 % with regards to the unweighted average. This is, however, not the case, and the explanation lays in the correlation between wind and waves.

5.1 Correlation between wave and wind

Waves depend on wind (wind is the main cause for waves), in the same way that wind depends on solar radiation (the main cause for wind). So in the end, all three energy sources correlate. As wind and waves are positively correlated (corr=0.21), and as wind and market price are negatively correlated (corr=-0.42), wave power *inherits* some negative correlation (corr=-0.18) to the electricity market price from wind power.

This inherited wave-price correlation is smaller then the original wind-price correlation, because the wind-wave correlation is rather small. The dependencies of waves on wind function (for the considered wave power plant at the Portuguese coast) on the scale of the Atlantic ocean. Locally, they can be rather loose, where big ocean waves can hit the coast without wind being present right here right now. These waves might have been created (by wind) days ago and far away. The phenomenon is similar to wind also existing at night, without the solar radiation being present.

This means: wave power is affected by the electricity price depression that large amounts of wind power cause, but to a smaller degree than wind power itself. This is fortunate for wave power. The location of the considered wave power plant at the very large Atlantic ocean reduces that correlation, resulting in a competitive advantage for wave power. On small water surfaces like a lake, correlation between wind and waves is much stronger, reducing that competitive advantage.

This inherited correlation causes wave power to "score" below 100 %, but still higher than wind power itself. Overall, this means: in the studied case, wave power is valued significantly higher than wind and slightly higher than solar, in the sense that 1 kWh of wave power on average gives higher income.

5.2 Case-dependency

The LVoE numbers calculated for the given case are only valid for that case. Even though the principles generally apply, the quantified numbers do not. The choice of the case has significant influence, where three main influencing factors are the *target year*, the *geographic location* and the *amount of wave power*.

Target year: Basically all future scenarios forecast rising shares of wind and solar power, also beyond 2030. Considering higher shares of wind and solar will significantly decrease their market value (even more than in this case study). This is good news for wave power, as it increases its competitive advantage.

Geographic location: Another relevant aspect is the location at the Portuguese coast. Continental Europe has a very large power system, with rather stable electricity prices. Freak phenomena like the occasional negative electricity prices in Germany do exist, but they are regulation induced, and do not reflect the socio-economic value of electricity as considered here. In such a stable electricity system, differences between the different forms of electricity production are less pronounced, which is a less friendly environment for wave power. Other locations at smaller, weaker electricity systems (e.g. on an island) will likely show stronger price fluctuations, resulting in larger differences between the sources. It can be expected that this would create a better case for wave power.

Amount of wave power: Another aspect of the case that does have relevant influence is the amount of installed wave power. Everything simulated and calculated here is valid under the premise that there is only a small amount of wave power ($P = 8\mathrm{MW}$), so that the market bid of wave power does not significantly influence the electricity price. Large scale deployment of wave power would lead to the situation where the market power of wave power will influence the market prices. This will lead to a similar depression of market value as experienced by wind and solar. It will decrease the competitive advantage of wave power. However, this is not problematic, since the scenario of large-scale wave power deployment is only a relevant future scenario if wave power already is competitive.

5.3 Influence of discounting

The inclusion of the discount (Equation 1) reduces both cost and energy production as compared to calculating the non-discounted total over the life time. The production is, however, affected stronger than the cost, as only the operating cost are discounted in a similar way as the energy production, while the upfront investment cost at $t = 0$ remains unaffected. This means that discounting directly increases the LCoE, where sources with heavy investment cost (sustainable sources) are affected stronger than sources with heavy operation cost (fuel based sources). The higher the discount rate Q, the stronger is the effect on the LCoE. This creates a bias that favours fuel-based sources, as it affects how sustainable sources compare with them. However, this bias affects wave, wind and solar in the same manner, and therefore does not influence the competition between them.

Correlation of the discount function with the electricity price and production (long-term price and weather trends) has implications for the LVoE. The simplified approach to value assessment ignored also these correlations, while they can be relevant. It remains challenging though to forecast how sustainable weather-based energy production will be affected by climate change and how electricity prices develop in the long run, making it difficult to consider these trends properly.

6 Conclusions

The case study has shown that wave power can achieve a significantly higher market value than wind power and a slightly higher market value than solar power, when considering the revenue per kWh. This difference has been explained through correlation between electricity production and electricity price, which is different for different energy sources. Other influencing factors (e.g. predictability, ramp-rates) might increase the value of wave power even more, but these effects were not accounted for in this study. The findings should also apply to other energy sources that anti-correlate or correlate less with wind speed and/or solar radiation, and that correlate with electricity demand.

Simplified approaches to assess the market value are common practise, where just the average electricity price is considered, while correlation is ignored. The study has shown that these approaches do not correctly reveal the value of electricity production, and that they give a pessimistic view that might hinder deployment of wave power.

This study can by no means prove that wave power will be profitable, but it gives a reminder that a too strict focus on the LCoE is not meaningful. In a sustainable future, we will more and more need to look at the LVoE, as both LCoE and LVoE are relevant to determine which technologies are competitive.

Acknowledgement

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References

[1] C. Park, F. Bigler, et al. Feasibility analysis of the power-to-gas concept in the future swiss distribution grid. *24th International Conference & Exhibition on Electricity Distribution (CIRED)*, 2017. doi:10.1049/oap-cired.2017.0214.

[2] H. G. Svendsen and O. C. Spro. Powergama: A new simplified modelling approach for analyses of large interconnected power systems, applied to a 2030 western mediterranean case study. *Journal of Renewable and Sustainable Energy*, 8(5), 2016. doi:10.1063/1.4962415.

[3] European Commission. Energy, transport and ghg emissions: Trends to 2050 – reference scenario 2013, 2013.

[4] N. Hutcheon and J. W. Bialek. Updated and validated power flow model of the main continental european transmission network. In *2013 IEEE Grenoble Conference*, pages 1–5, 2013. doi:10.1109/PTC.2013.6652178.

[5] European Commission. Megaroller - developing the pto of the first mw-level oscillating wave surge converter, 2018. URL `https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/tidal-wave-hydropower/megaroller`.

[6] E. Kalnay, M. Kanamitsu, et al. The ncep/ncar 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77(3):437–472, 1996. doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.