Enhancing system resilience and security with tidal stream energy

Daniel Coles, Richard Coyne and Jon Miles

***Abstract*—This research investigates the impacts of tidal stream in enhancing energy system security and resilience, when installed alongside solar PV and wind. Energy security is defined as 'the uninterrupted process of securing the amount of energy that is needed to sustain people's lives and daily activities while ensuring its affordability'. Energy resilience is defined as 'the ability of a system to survive strong and unexpected disruptions and to recover quickly afterwards'. As demonstrated in this paper, wind-droughts are common occurrences that present potentially significant risks to energy security/resilience. The Energy System Model for Remote Communities (*EnerSyM-RC*) is adopted to build on previous research of the Isle of Wight energy system. Energy system modelling is based on resource, demand and electricity price data from 2021, when a known wind-drought, and rising electricity prices, were observed. The study also considers 2022 electricity supply, when prices demonstrated significant volatility. Results show that the inclusion of tidal stream capacity alongside solar and wind enhances supply-demand balancing to reduce annual reliance on imported electricity by 30%, relative to cases systems that install solar PV and offshore wind only. The inclusion of tidal stream reduces the electricity import cost by over 60% in months with low wind and high electricity prices.**

***Index Terms*—Tidal stream, energy system modelling, energy security, energy resilience, solar PV energy, offshore wind energy**

I. Introduction

Achieving net-zero carbon emissions requires a transition away from dispatchable fossil fuel generated electricity, to distributed, weather dependent, variable, renewable power. Currently, a surge in electricity demand may be balanced by turning on/up a gas fired power station. Future net-zero energy systems can no longer rely on these conventional, widespread types of dispatchable power. The primary sources of renewable power generation in the UK are and will be solar PV and offshore wind. They are variable sources of renewable power generation, whose power output depends on weather conditions, which are uncorrelated to electricity demand. National Grid have identified maintaining system resilience during periods of high demand and low wind and solar output as a key challenge in the future [1].

Energy system resilience is defined as the ability of a system to survive strong and unexpected disruptions and to recover quickly afterwards [2]. Energy system security is defined as 'the uninterrupted process of securing the amount of energy that is needed to sustain people's lives and daily activities while ensuring its affordability' [3]. This research is motivated by recent events that have brought into question the UK's energy system security/resilience. During autumn 2021, high global gas demand driven by post-covid-19 lockdown activity led to a 400% increase in imported wholesale gas prices in the UK (Figure 1a). This coincided with (i) an extended period of low wind resource during September, when wind turbines provided 60% less energy than typical levels for the time of year (Figure 1b), (ii) low nuclear power availability (Figure 1c) and (iii) depleting domestic natural gas reserves. These simultaneous events led to high dependency on expensive imported fossil fuels for electricity generation. As a result, UK wholesale electricity prices more than doubled (Figure 1d). The 2022 military and political impact of Russia's invasion of Ukraine has led to additional increases in imported fuel prices.

These types of energy system disruptions are being seen in other locations also (e.g. Texas 2021), and have the potential to cause rolling blackouts, resulting in significant social damage (e.g. welfare) worth years of sector revenues [2], [4]. In the future, energy security and resilience challenges must be overcome whilst also achieving net-zero to limit global warming to within 1.5 degrees Celsius above pre-industrial levels, whilst electricity demand at least doubles [5].

Our research to date shows that tidal stream has the potential to complement solar PV and offshore wind to help enhance energy system security and resilience [6]–[8]. Adopting tidal stream alongside wind and solar enhances the correlation between annual renewable supply and demand. This maximises the proportion of local renewable power that is used directly to balance demand. During periods when demand exceeds renewable power, reliance on energy imports and/or stored energy is reduced. During periods when renewable power supply exceeds demand, the need to store excess renewable energy, export renewable power and/or curtail renewable power also reduces. Reduced reliance on energy storage helps to reduce efficiency losses.

Our research also shows that the magnitude of surplus renewable power is reduced by adopting tidal stream alongside solar PV and wind capacity. This

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D. Coles and J.Miles are with the School of Engineering, Computing and Mathematics at the University of Plymouth, Drake Circus, Plymouth, PL4 8AA (e-mail: daniel.coles@plymouth.ac.uk)

R. Coyne is with the School of Energy, Geoscience, Infrastructure and Society at Herriot Watt University, Campus The Avenue, Edinburgh EH14 4AS

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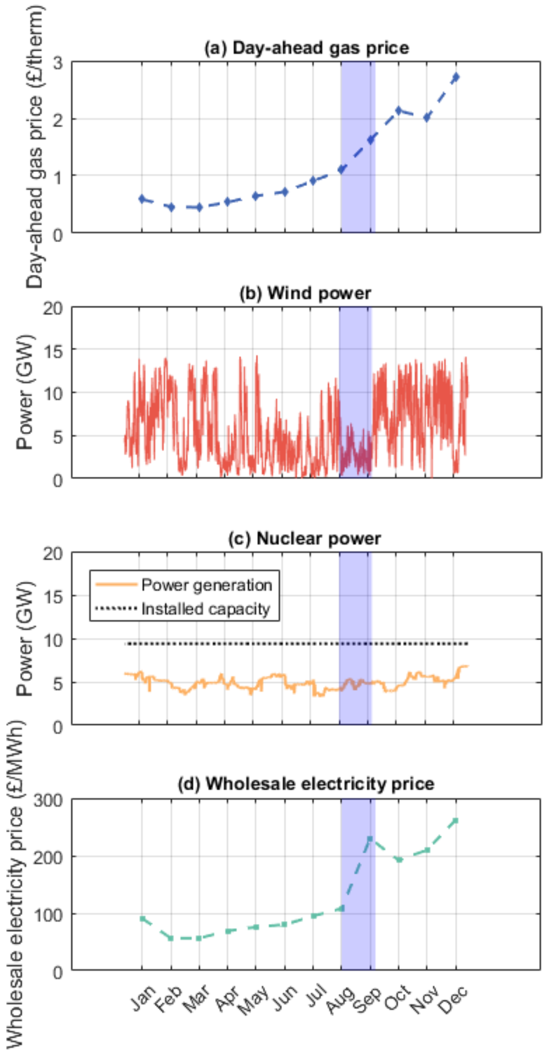

Fig. 1. 2021 UK time series of (a) Day-ahead gas price, (b) Wind power, (c) nuclear power, and (d) wholesale electricity price. Shaded regions highlight the start of the autumn 'energy crisis' period.

helps to limit the necessary capacity of the distribution grid and energy storage to deal with excess renewable power, and their associated costs.

Finally, our research shows that the semi-diurnal cycling of tidal stream power is highly compatible with short duration storage. The combined effect of installing tidal stream and short duration energy storage together is an additional enhancement in supply-demand balancing. This is less/not achievable with solar PV and wind respectively, as in general, they exhibit higher persistence, which has a detrimental impact on the load factor of the storage system, making it a less economically viable technology to implement to enhance balancing. Given that short duration energy storage is the cheapest form of storage, it is argued that in some cases, the levelised cost of tidal energy premium may be outweighed by these system cost benefits it provides, to make it an economically viable technology.

In this paper, we build on progress to date to provide novel insights into the potential contributions of tidal stream energy to system security/resilience enhancement during wind-drought periods. The Energy System Model for Remote Communities (*EnerSyM-RC*) [8] is adopted to simulate the Isle of Wight's energy system. We build on previous research by focusing the modelling on the aforementioned 2021 period, when known wind droughts occurred. In doing so we focus this research on monthly periods when the energy system experiences high weather related stress. We quantify the energy system performance during these specific periods, based on scenarios with high renewable energy penetration using solar PV, offshore wind and tidal stream.

II. Renewable energy variability

Figure 2 shows the annual variability in solar PV, offshore wind and tidal stream capacity factor, between 2012 and 2020. The data has been derived using Isle of Wight-specific resource data.

The annual power capacity of solar PV, offshore wind and tidal stream generation vary between 15 - 17%, 44 - 51% and 39 - 42% respectively. Offshore wind shows the greatest range in annual capacity factor; the most energetic year yields 16% more energy than the least energetic year. This is followed by solar, which exhibits 13% higher energy yield in its most energetic year relative to its least energetic year. Low wind generation can occur both during low wind periods (typically wind turbines have a cut-in speed of around 5 m/s), and when wind speeds exceed the cut-out limit, which is typically 25 m/s. Low wind speeds account for between 96 - 99% of low generation events [9], [10]. Tidal stream demonstrates the narrowest annual capacity factor range; its most energetic year yields 8% more energy than its least energetic year. This annual variability in the tidal stream energy resource is driven mainly by the 18.6 year lunar nodal cycle [11]. This phenomenon causes variation in the gravitational force (and therefore the tide generating force) between the Earth and Moon as a result of variation in the inclination of the Moon's orbital path relative to the equatorial plane of the Earth.

The monthly variability in the solar PV, offshore wind and tidal stream resources are presented in Figure 3. As with annual variability, offshore wind exhibits the greatest monthly capacity factor variability. During the high resource, winter months, the capacity factor of offshore wind varies between 40 - 80%, depending on the year. Both energy production and annual variability in monthly generation reduce during the summer months, when monthly capacity factor falls between 23 - 52%. In general the seasonal offshore wind resource is positively correlated with the Isle of Wight's demand.

These results are consistent with UK-wide wind energy resource studies, which demonstrate persistent low energy production for periods in excess of a week [10], [12]. Potisomporn et al. (2022) [10] concludes that the likelihood of prolonged periods of low wind energy varies seasonally, with autumn and winter being less common than spring and summer. Their results show

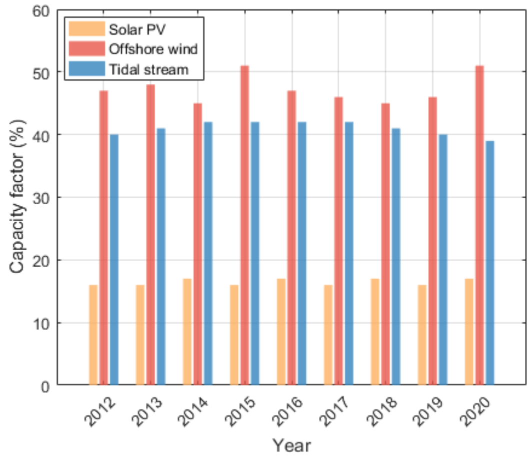

Fig. 2. Annual variability in solar PV, offshore wind and tidal stream power capacity factor between 2012 - 2020, derived from resource data specific to the Isle of Wight.

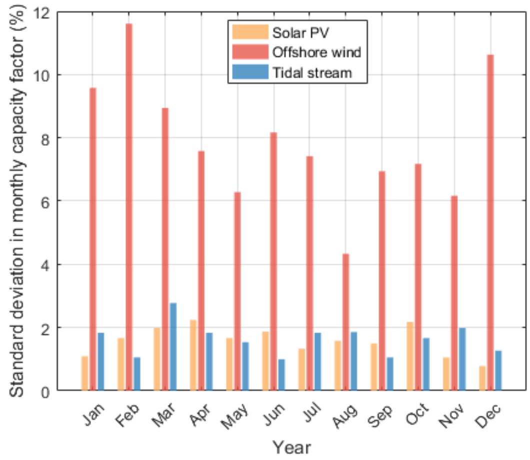

Fig. 4. Standard deviation in monthly capacity factor of solar PV, offshore wind and tidal stream power capacity factor between 2012 - 2020, derived from resource data specific to the Isle of Wight.

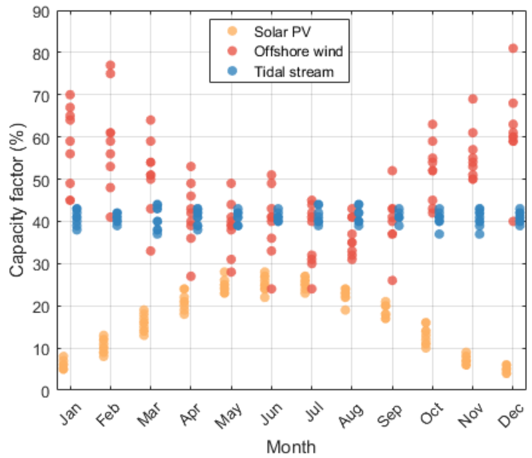

Fig. 3. Monthly variability in solar PV, offshore wind and tidal stream power capacity factor between 2012 - 2020, derived from resource data specific to the Isle of Wight.

that whilst geographic diversification of offshore wind generation reduces the likelihood of prolonged periods of low energy production compared to that for individual wind farms, the correlation in wind generation between wind farm pairs remains significant over the regions that contain the majority of the UK's offshore wind farms (an area covering around 500 km). This national scale wind drought was observed during the aforementioned autumn 2021 period shown in Figure 1. Reliance on geographically diverse wind power generation requires adequate grid to transmit power long distances, between regions with high and low wind power generation.

Monthly solar PV energy production is negatively correlated with the Isle of Wight demand. Solar PV also exhibits significantly lower capacity factors than offshore wind, which is attributed the relatively low efficiency of solar PV panels (<25%), relative to the rotor efficiency of wind turbines (>40%). Monthly solar PV capacity factor exhibits relatively low variability.

Results presented here, based on historic data specific to the Isle of Wight, demonstrate that local wind power variability is significant across monthly and annual timescales. This makes wind variability an important consideration when designing future energy systems.

III. Methods

This research uses the Energy System Model for Remote Communities (*EnerSyM-RC*), which is openly available; https://github.com/danielcoles/EnerSyM-RC. The model was first presented in research that this conference paper builds upon. A brief description of the model is presented here. The reader is pointed to the original presentation of the model ([8]) for further information.

Figure 5 provides a schematic of the *EnerSyM-RC* architecture. Solar PV, offshore wind and tidal stream are the primary sources of power. 10% electrical losses are assumed between the renewable generators and the Isle of Wight grid demand. A storage system is modelled, which stores excess renewable power during periods when renewable power exceeds demand. The storage system has a power capacity of 75 MW, and an energy storage capacity of 300 MWh (i.e. 4 hour duration storage). If the battery is fully charged during these periods of surplus renewable power, the surplus renewable power is exported or curtailed. The battery also helps balance supply with demand during periods when demand exceeds renewable supply. If the battery is fully discharged during these periods, power must be imported from the reserve energy source, which we assume is located on mainland UK, with a subsea cable connection.

A range of cases are modelled in this research, where in each case, the proportion of solar PV, offshore wind and tidal stream capacity is varied. In each of the capacity cases, the total annual energy production from the renewable capacity is kept equal to the Isle of Wight's annual demand, of 501 GWh. Figure 6 provides the range of solar PV, offshore wind and tidal stream capacities in each case. In the case of low wind and tidal stream capacity, their low energy production

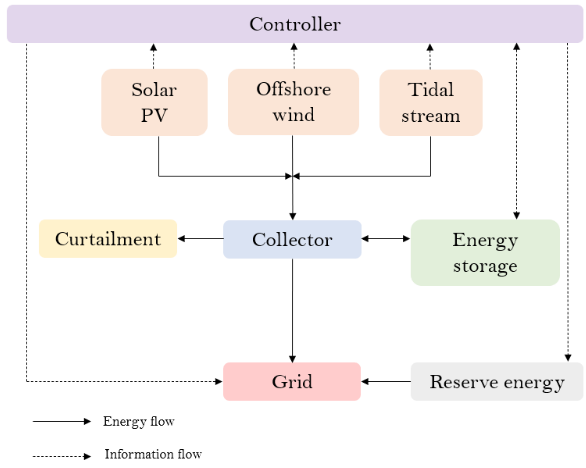

Fig. 5. *EnerSyM-RC* schematic [8].

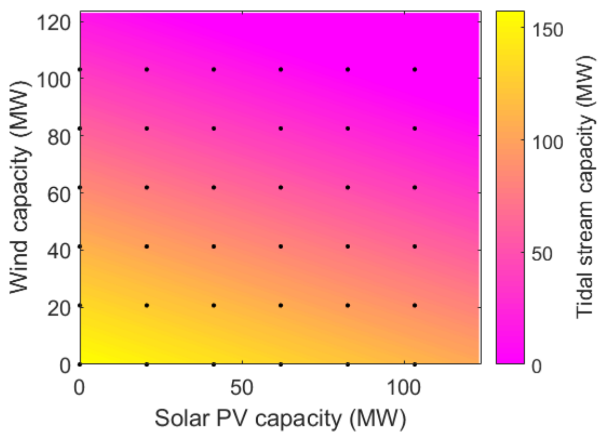

Fig. 6. Capacity cases, with varying proportions of solar PV, offshore wind and tidal stream capacity used to produce the Isle of Wight's annual electricity demand.

contribution is overcome by installing a high amount of solar PV capacity, for example. Solar PV and offshore wind capacity range between 0 - 120 MW. Tidal stream capacity is varied between 0 - 160 MW, in order to fulfill the annual deficit in net annual power generation left by solar PV and offshore wind in each capacity case. The black markers show the 42 capacity cases considered in the research.

The model is run over the whole of 2021 using a 1 hour timestep.

A. Model inputs

Solar PV and offshore wind power timeseries were obtained from the global Modern-Era Retrospective analysis for Research and Applications (MERRA-2) project datasets, which are made available through the renewables.ninja tool [13], [14]. The solar PV power data was derived by assuming no tracking, a panel tilt angle of 35° and an azimuth of 180°. The offshore wind power was derived based on a Vestas V164 9500, with a hub height of 105 m. Tidal stream velocities were obtained from Acoustic Doppler Current Profiler data collected at St Catherine's point, at the southern end of the Island. The data was harmonically extrapolated to cover 2021. Tidal stream turbine power was derived by assuming a power coefficient of 0.41, a rotor diameter of 20 m, a cut in speed of 1 m/s, and a rated power of 1 MW.

B. Energy system optimisation

EnerSyM-RC adopts a simple brute force optimisation approach, where by the wide range of capacity cases are run independently. *EnerSyM-RC* quantifies key energy system performance metrics for each capacity case, so that they can be compared to establish the most suitable system design. Performance indicators presented in this research are annual energy shortage and surplus, and the cost of importing electricity from mainland. These metrics are quantified on both an annual and monthly basis.

The advantage of this brute force approach is that it allows the user to consider a wide range of often conflicting performance indicators. For example, the system design (i.e. the installed capacities of solar PV, offshore wind and tidal stream) that minimises annual energy shortage may not also minimise overall system cost. It is important to consider a wide range of system performance indicators to establish a design solution that is practical across a wide range of criteria, which requires compromise.

IV. Results

A. Supply-demand balancing

Figure 7 shows the annual (a) energy shortage and (b) energy surplus for each of the 42 capacity cases. The red markers highlight the capacity case which minimises annual energy shortage and surplus, which is achieved with a total installed capacity of 180 MW, with an even 60 MW contribution from solar PV, offshore wind and tidal stream respectively (i.e. a ratio of 1:1:1). In this case the annual energy shortage and surplus are minimised to 63 GWh and 55 GWh respectively. This represents 13% and 11% of the Isle of Wight's annual electricity demand respectively. Interestingly this proportion of solar PV, offshore wind and tidal stream differs from a similar analysis carried out based on an increased future demand [8], and renewable resources in 2019. In this case the tidal stream capacity that minimises annual energy shortage/surplus is slightly lower than that of solar PV and offshore wind, with a ratio of 1:1:0.8. These differences are as a result of different solar and wind resources over the two years, and the different energy storage specifications considered.

In Figure 7 the blue markers highlight the capacity case that minimises annual energy shortage/surplus when installing solar PV and offshore wind only. 80 MW of solar PV and 100 MW of offshore wind results in annual energy shortage being minimised to 91 GWh, and annual energy surplus being minimised to 86 GWh. This represents a 44% and 56% increase in annual energy shortage and surplus, relative to the capacity case that includes tidal stream. Again, this proportion of solar PV and offshore wind that minimises annual energy shortage and surplus is different to that based on 2019 resource data and future demand, which concluded 100 MW of solar PV and 250 MW of offshore wind to minimise annual energy shortage and surplus [8].

Figure 8 shows the monthly energy shortage for each of the 42 capacity cases. Red and blue markers highlight the capacity case that minimises annual energy shortage with and without tidal stream respectively. The capacity case that minimises monthly energy shortage differs considerably throughout the year. As expected, the cases that include high solar PV capacity minimise energy shortage during summer months. Similarly, the cases that include high offshore wind help minimise energy shortage during winter months. The two highlighted cases that minimise annual energy shortage with/without tidal stream show that there is a reduction in monthly energy shortage when tidal stream is adopted, across all months of the year.

In general this reduction in monthly energy shortage that results from adopting tidal stream capacity is most noticeable during spring and autumn month. This is most notably the case in April, September, October and November, when monthly energy shortage falls between 27 - 62% as a result of using tidal stream. In general the difference in monthly energy shortage is less significant in summer and winter months.

This result is particularly interesting given the 2021 temporal variability in gas and electricity prices displayed in Figure 1. Prices increased dramatically in the second half of 2021, and stayed high after peaking around September/October. The combination of low autumn wind resource and high energy prices is of particular relevance with respect to energy security and resilience. Results presented here demonstrate that the diversification of renewable power through the inclusion of tidal stream alongside solar PV and offshore wind may provide an opportunity to enhance energy security and resilience during wind-drought periods. The diversification of renewable generation technologies enhances the correlation between overall renewable power supply, and electricity demand. The enhanced correlation reduces energy shortage. In doing so, energy system security and resilience is enhanced through reduced reliance on imported, and potentially expensive, power. This is especially the case during wind-drought periods that can last multiple weeks. This is explored further in Section IV-B by estimating the cost of importing power during wind-drought periods.

B. Economics

Figure 9a shows the monthly average UK wholesale electricity price over 2021 and 2022. As already discussed, 2021 exhibits a significant increase in electricity price, that gradually rises from January when electricity price was 50 £/MWh, and starts to increase in gradient in August. There is a local peak in electricity price in October, of 120 £/MWh, and the year ends with its highest price of 190 £/MWh. 2022 exhibits higher electricity prices than 2021. The year starts similar to how 2021 ended, with electricity prices around 175 £/MWh. There is a gradual increase in electricity price between January to May, when the price reaches 200 £/MWh. There is then a significant increase in electricty price between May and August, peaking at 400 £/MWh. This represents a 700% increase in electricity price over a 20 month period between January 2021 and August 2022. Between September 2022 and December 2022 there is a reduction in electricity price, to 275 £/MWh at the end of the year.

Figure 9b shows the annual cost of importing wholesale electricity to balance supply with demand during periods of power shortage, during 2021 and 2022, using each of the 42 capacity cases. Results show that during 2021, the cost of importing electricity using the optimal cases with and without tidal stream is 5.6 £m and 8.1 £m respectively. The inclusion of tidal stream reduces the electricity import cost by 2.5 £m, or 30%. In 2022, when wholesale electricity prices were significantly higher than 2021, the cost of importing electricity using the optimal cases with and without tidal stream are 15.7 £m and 23.9 £m respectively. This represents an 8.2 £m reduction in the cost of imported electricity across 2022 by including tidal stream alongside solar PV and offshore wind.

Monthly breakdowns of imported electricity cost during 2021 and 2022 are presented in Figures 10 and 11 respectively. In 2021, the impact of introducing tidal stream energy is greatest in September, October and November, as a result of significant imported electricity volumes and high wholesale electricity prices. During these months the monthly cost of electricity imports reduces by 35 - 60% by introducing tidal stream.

The monthly cost of importing electricity during 2022 (Figure 11) is significantly higher then 2021, which is mainly due to the higher wholesale electricity price. During 2022 more material reductions in imported electricity cost are observed as a result of introducing tidal stream capacity vs. neglecting it, than was seen during 2021. Again this is most evident during September, October and November, as a result of high reliance on imported electricity (driven in September by the wind-drought), and very high 2022 wholesale electricity prices.

V. Conclusions

This research has investigated the ability of tidal stream energy to deliver energy security and resilience enhancement during wind-drought periods.

Results from the Energy System Model for Remote Communities (*EnerSyM-RC*) demonstrate that tidal stream compliments solar and wind by enhancing supply-demand balancing, thereby reducing reliance on imported energy, and providing protection against high and often volatile imported energy prices. This is a clear mechanism for tidal stream to enhance energy security and resilience, assuming the cost benefits from installing tidal stream outweighs its relatively high levelised cost of energy at present.

At annual resolution, results show that the inclusion of tidal stream reduces the annual electricity import cost by approximately 30%, relative to the best performing system that adopts solar and wind only. The

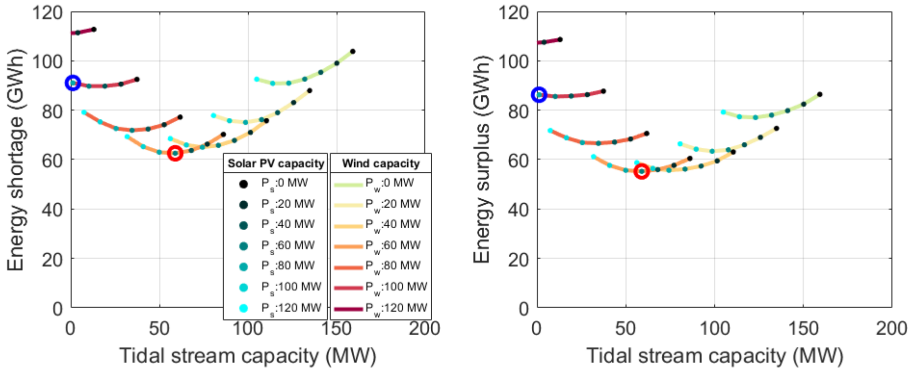

Fig. 7. Relationship between solar PV, offshore wind and tidal stream capacity and net annual (a) energy shortage, and (b) energy surplus. Red markers highlight the capacity case which minimises annual energy shortage/surplus. Blue markers highlight the capacity case which minimises annual energy shortage/surplus in the absence of tidal stream capacity.

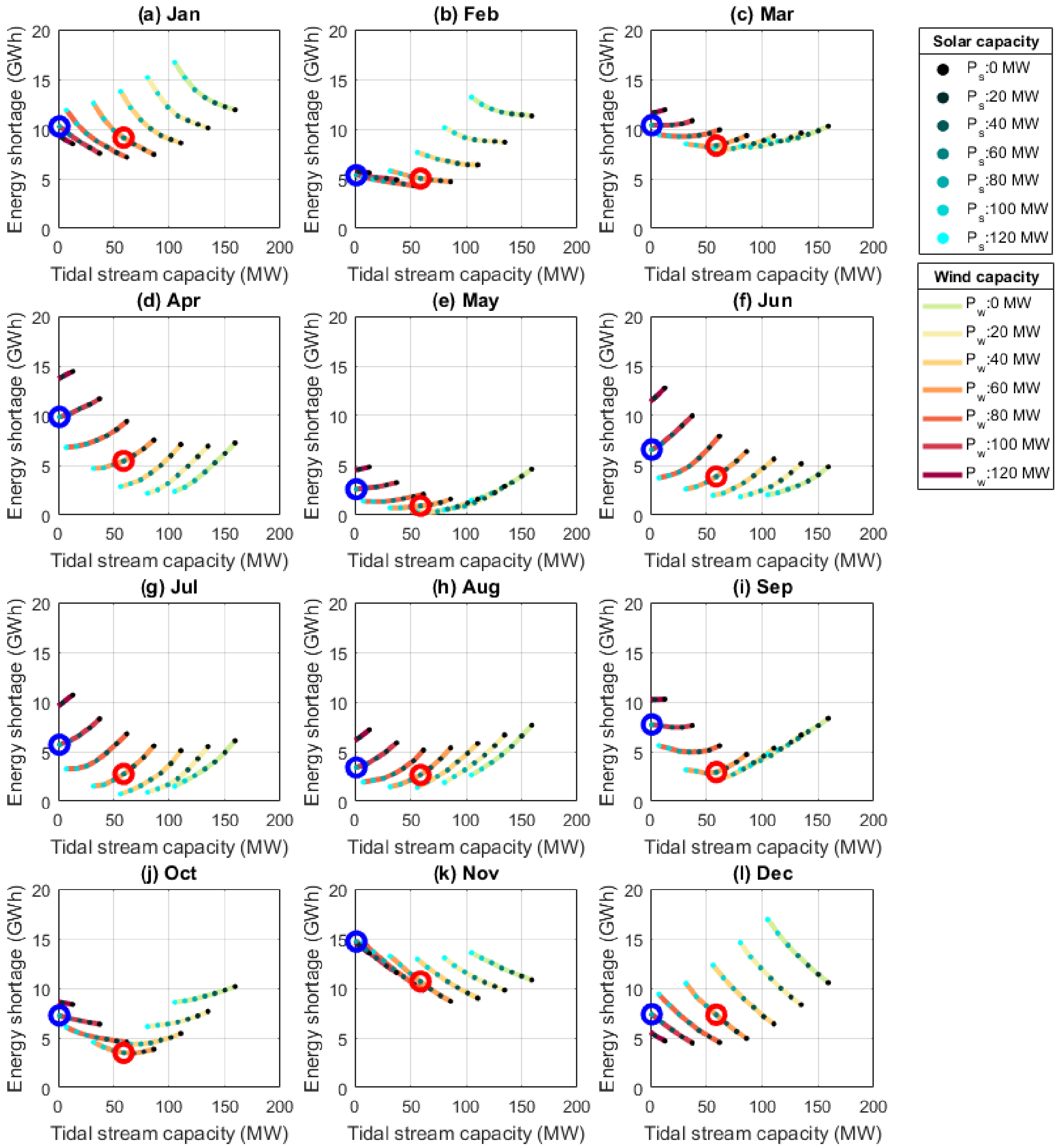

Fig. 8. Relationship between solar PV, offshore wind and tidal stream capacity and monthly energy shortage. Red markers highlight the capacity case which minimises annual energy shortage/surplus. Blue markers highlight the capacity case which minimises annual energy shortage/surplus in the absence of tidal stream capacity.

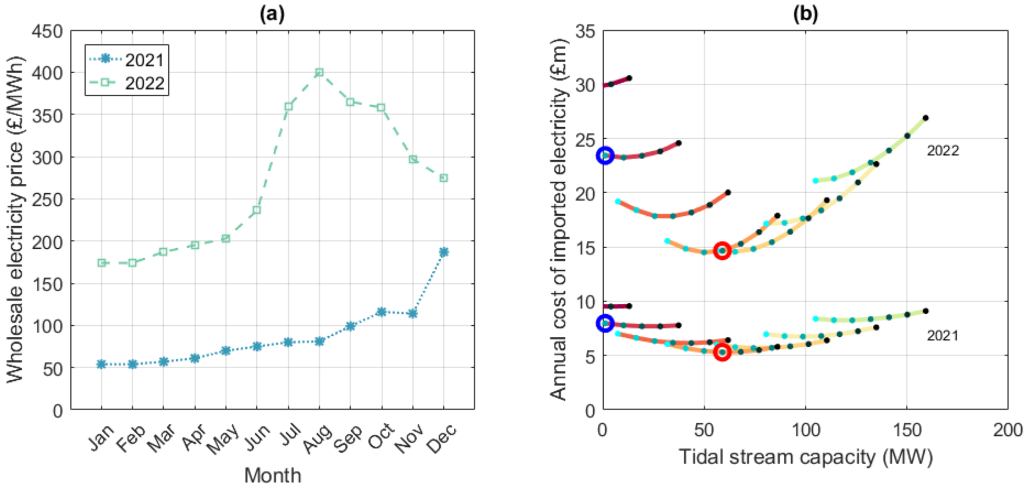

Fig. 9. (a) Monthly variation in UK wholesale electricity prices during 2021 and 2022, (b) Relationship between solar PV, offshore wind and tidal stream capacity, and net annual cost of imported electricity during 2021 and 2022. Red markers highlight the capacity case which minimises annual energy shortage/surplus. Blue markers highlight the capacity case which minimises annual energy shortage/surplus in the absence of tidal stream capacity.

most significant imported energy cost savings are seen in 2022, when wholesale electricity prices were highest. In this case the annual cost of electricity imports is reduced by over 8 £m by including tidal stream capacity.

Results demonstrate that during months with low wind resource and high wholesale electricity prices, the inclusion of tidal stream reduces monthly electricity import cost by over 60% in some cases, relative to the best performing solar+wind system.

The next stage of this research will carry out an economic assessment of the energy systems to address questions such as; how cheap does tidal stream need to be to deliver energy security?

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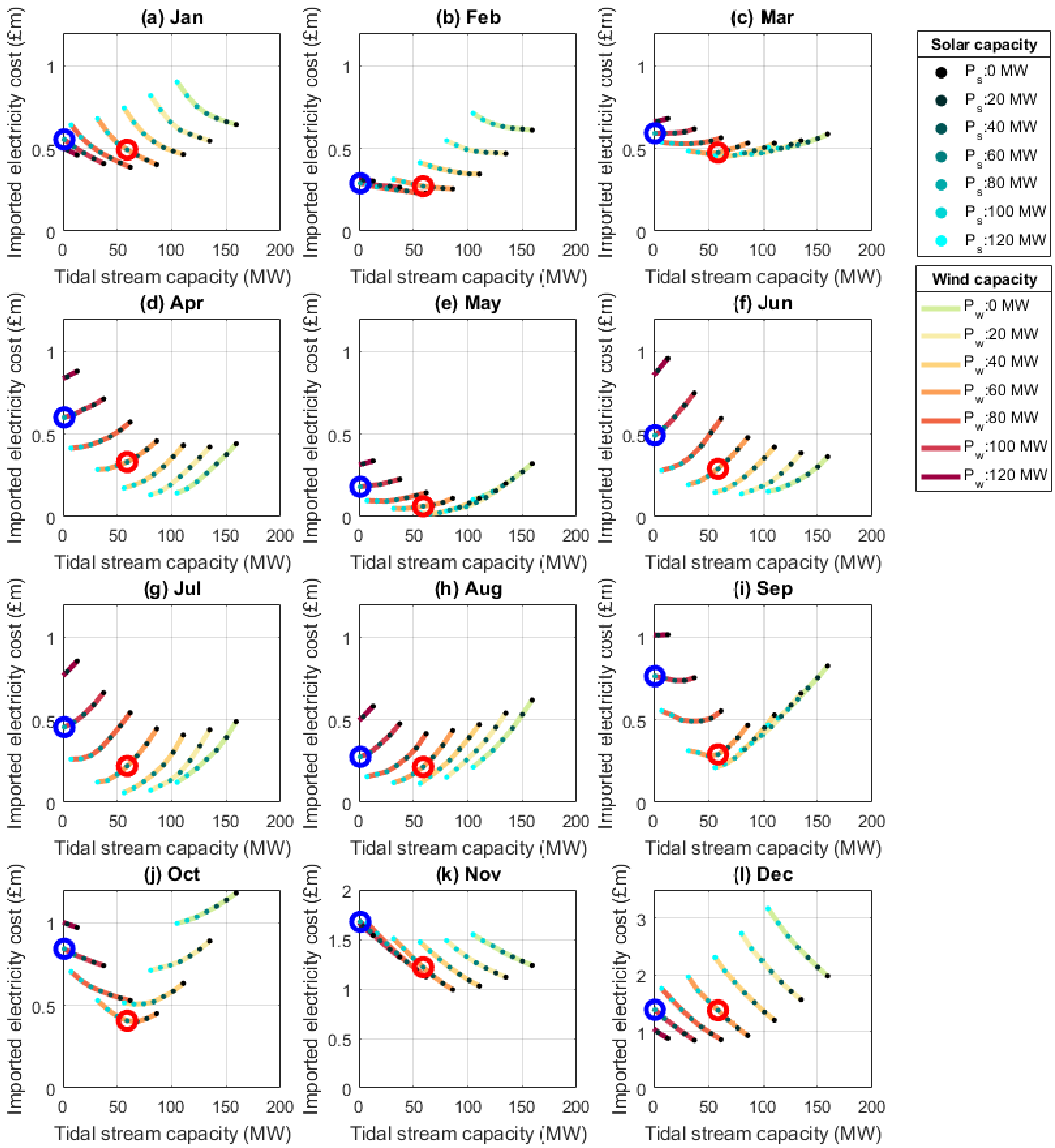

Fig. 10. Relationship between solar PV, offshore wind and tidal stream capacity and monthly imported electricity cost during 2021. Red markers highlight the capacity case which minimises annual energy shortage/surplus. Blue markers highlight the capacity case which minimises annual energy shortage/surplus in the absence of tidal stream capacity.

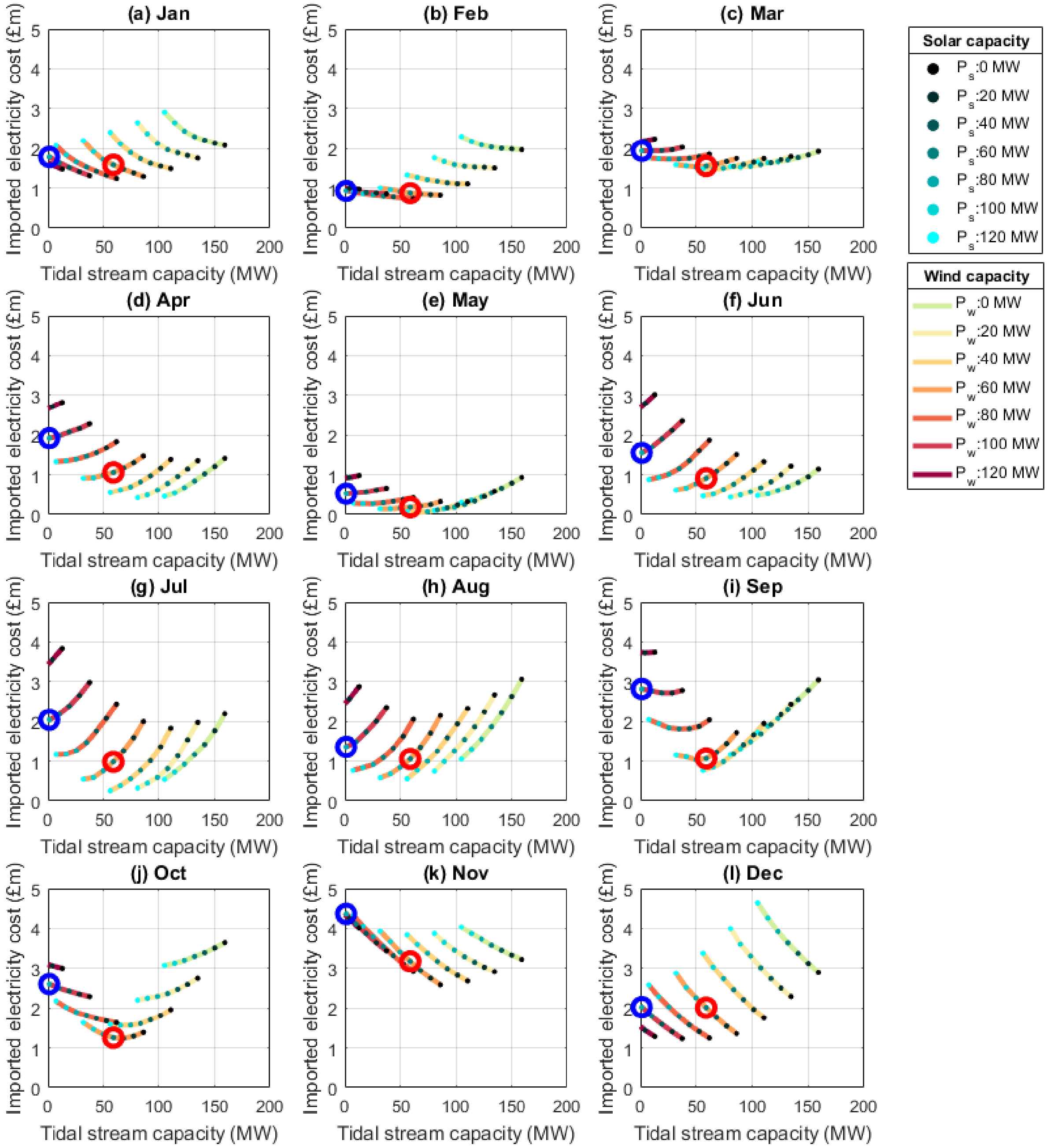

Fig. 11. Relationship between solar PV, offshore wind and tidal stream capacity and monthly imported electricity cost during 2022. Red markers highlight the capacity case which minimises annual energy shortage/surplus. Blue markers highlight the capacity case which minimises annual energy shortage/surplus in the absence of tidal stream capacity.