Exploring the Viability of Hybrid Wind-Solar Power Plants

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***Abstract*— As renewable energy in power grids increases, a discussion on the potential advantages of hybrid power plants (HPPs) has been ongoing [1]–[6]. This study focuses of HPPs consisting of wind, solar and possibly storage technologies. Foreseen advantages relate to system integration cost-efficiency, environmental and economic factors. The evolving digitalisation of renewable energy plants is expected to unleash the full potential of such hybrid cases. Currently, the number of existing HPPs, under development or already operating, is very limited. As a result, it is extremely difficult to access reliable data, not only due to the early age of the projects. Their business case is still under development and/or evaluation which makes developers and operators reluctant to sharing crucial information. This study explores the business case of HPPs, to identify drivers and barriers and to make policy recommendations for boosting their development, in case potential advantages appear considerable.**

Keywords-hybrid power plants, wind, solar, storage, co-location

INTRODUCTION

As renewable energy in power grids increases, a discussion on the potential advantages of Hybrid Power Plants (HPP) has been ongoing [1]–[6]. This study focuses of hybrid power plants consisting of wind, solar and possibly storage technologies. Foreseen advantages relate to system integration cost-efficiency, environmental and economic factors. The evolving digitalisation of renewable power plants is expected to unleash the full potential of such hybrid cases.

Currently, the number of existing HPPs, under development or already operating, is very limited. This makes it extremely difficult to access reliable data, not only due to the early age of the projects. Their business case is still under development and/or evaluation which makes developers and operators reluctant to sharing crucial information.

The present study explores this new promising opportunity, creates awareness and builds knowledge around HPPs. The authors assess existing HPPs globally, in different locations, fitting different purposes, developed under different conditions. An online database with HPPs is created and made publicly available. An assessment of certain case studies follows to identify factors and barriers rendering a HPP viable or not, compared to pure wind or solar projects.

Based on this overview and assessments, the authors draw some conclusions on the viability of HPPs identifying drivers and challenges. Finally, this paper presents a set of policy recommendations that could unlock the potential benefits from HPPs.

I. THE MOTIVATION BEHIND HYBRID POWER PLANTS

Hybrid power plants, combining wind and solar, can present numerous advantages when compared to pure wind or solar power plants.

From a societal point of view, HPPs can reduce infrastructure investment costs as a single grid connection point needs to be set up in most cases [7]. This fact reduces overall grid investment costs and the subsequent grid tariffs paid by grid end-users. Secondly, land is used more efficiently since installed capacity and energy output per square meter of used land increases. Based on these facts and a potentially better utilisation of the site's resources, HPPs could have lower Levelised Cost of Electricity (LCoE) and thus require less economic support to be profitable. Indeed, developers harvest synergies within the development and permitting process, by using just one grid connection, using land in a more efficient way and deploying joint operation and maintenance strategies.

From a system integration point of view, given the phasing-out of conventional plants, HPPs can offer a more firm capacity alternative (higher yearly capacity factor and more stable power output over time), compared to pure wind or solar plants, with high flexibility potential. This applies when the wind and solar irradiation profiles in the respective site are negatively correlated (they need to be complementary over daily periods, which is often the case) so that ramping issues and instantaneous peaks are avoided.

Thanks to the co-existence of generation units and digital technologies with different capabilities, HPPs are a good partner to the grid in terms of flexibility but also resilience when storage is included. The latter can lead to reduced balancing costs and less renewables' (RES) curtailment, both beneficial from a societal point of view.

From a developer's point of view, hybridising an existing wind power plant could maximise the utilisation of the grid connection's total capacity. In most cases, the converter connecting the RES power plant to the grid is oversized in order to fulfil the worst-case scenario. However, the latter may occur less than 5% of the operation time. In certain conditions, it is meaningful to monitor the utilisation of the converter's capacity with the existing technology and connect complementary renewable generation to it. In this way the sizing of the HPP can be optimised. Although such design might lead to minor energy spills, it certainly plays a role in making viable a hybrid wind-solar plant.

II. THE SCOPE OF THIS STUDY

Firstly, this study aims at building knowledge and creating awareness in the renewable energy sector regarding HPPs including wind, solar and potentially storage technologies. Such projects can be classified in terms of different parameters which impact their business case and their interaction with the power system.

The authors have mapped existing and under development HPPs and statistically assessed them in function of market and system integration parameters. Finally, an online database has been created[1]. The latter will be regularly updated with new HPPs worldwide.

Secondly, this study assesses whether the expected value propositions of developed HPPs have been validated. The authors collected and evaluated feedback by pioneer hybrid power plant developers. The study presents drivers and barriers that may render such projects viable or not.

Finally, this study develops policy recommendations for boosting the development of HPPs in frameworks where their potential advantages appear considerable.

III. BUILDING KNOWLEDGE ON HYBRID POWER PLANTS

Certain countries (e.g. India, Australia) have been planning to support hybrid projects s by setting up hybrid-specific auctions or hybrid-friendly auctions [8]–[11]. As governments roll out their plans and industry develops various designs and control configurations, it becomes relevant to create a clear regulatory framework, starting with the definition of the HPPs. This paper proposes the following scope and definitions.

Regarding wind, all existing types of wind turbines are considered while for solar, the focus here is on photovoltaic (PV) installations. Regarding storage technologies in HPPs, the scope of this study is narrowed down to Electrical Energy Storage (EES) as defined by the IEC 62933-1 standard [12] "*Installation able to absorb electrical energy, to store it for a certain amount of time and to release electrical energy during which energy conversion processes may be included*". [2]

For classifying HPPs, we suggest that the following aspects are principally considered:

- Grid connection configuration and plant operation (types of co-location, unless standalone plant)
- Total capacity and capacity share of technologies (wind, solar, storage)
- Functionalities and services to deploy
- LCoE and market value

A. *Grid connection configuration and operation modes:*

For HPPs integrated in the power system, multiple connection configurations can be considered, in terms of RES co-location and RES/storage co-location.

Co-location of RES:

Two configurations are the most common ones and a third one may be considered under specific conditions. Table 1 outlines the principal advantages and disadvantages of the three configurations.

A. Co-location of wind and solar sharing the same substation and coupling point to the grid: the advantage of this solution is that wind and solar share the same grid connection and substation. This fact is expected to reduce, significantly in most cases, capital expenses (CAPEX) and permitting times in the development of the plant. The Annual Energy Production (AEP) per m^2 also increases which maximises the utilisation of the land and of the local grid. Moreover, overall development, site assessment and O&M costs result lower due to combined strategies for wind and solar.

B. PV panels integrated at the wind turbine level or closely located to the turbines: the advantage of this solution compared to the previous one is that the solar inverter can be eliminated. A hybrid converter sourcing AC & DC power together can be used. The combination of the technologies allows a more effective utilisation of the converter. The AEP per m^2 of the wind farm increases without requiring a nameplate capacity increase, including long permitting approval times in certain cases.

The advantage of both previous cases is that a single grid connection needs to be set up (or probably upgraded if existing). Currently, the connection procedure of HPPs is still quite new to most local authorities and system operators; this might induce some delays and complexities. As the number of HPPs increases, the permitting procedure will become more streamlined resulting in both cost and time savings.

In the case of PV panels integrated at the turbine level, shading of the PV panels by the blades is a disadvantage. A solution to this could be installing the PV panels further apart from the turbines. However, this solution would increase cabling cost, which might be very significant in some countries, and induce line losses, both in terms of active and reactive power. Maximum Power Point Tracking (MPPT) techniques are necessary to maximise power extraction under all conditions. Another disadvantage of this configuration, in case it is applied in an existing wind farm, is the space limitation for PV panels and the potential capacity limitation due to the existing wind turbine converter.

Another challenge in both cases relates to metering requirements. Metering concepts are not standardized or

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[1] WindEurope, "WindEurope's online database of co-located projects," 2017. [Online]. Available: https://windeurope.org/about-wind/database-for-wind-and-storage-colocated-projects/.

[2] In certain systems, only a part of the storage capacity is reserved for storing and releasing electrical energy. The rest of the capacity might be reserved for storing electrical energy, converting it to a different energy form and then using it in non-electrical applications. In such cases, the present study considers only the capacity that is reserved for storing and releasing electrical energy. This is not the case with the WindEurope database which includes information for the entire storage system.

formalized for HPPs but subject to bilateral negotiation and agreement with the relevant system operator, in most countries. If one of the RES plants is subsidized, it needs to be metered separately. Adding a storage device may even endanger subsidy payments in certain cases (suspicion of "grey" power supplied by the plant rather than "green" power).

Apart from these two configurations, best adapted to unlock the potential benefits from HPPs, a third case can be considered:

C. Co-location (in the same site) of wind and solar with separate substations and coupling points to the grid: the advantage of this solution compared to the previous ones is that the permitting process is the common one, well-known to local authorities and system operators. Building separated power plants in the same site may present some advantages compared to virtual power plants. The latter could relate to system integration issues such as higher capacity reserve for local congestion management or frequency restoration services or local reduction of imbalances in case storage is integrated. It might also facilitate the development process, when different developers are involved per RES technology. Also in this case, overall development, site assessment and O&M costs might result lower as the developer and operator can combine strategies for the different RES plants. The disadvantage of this solution, in terms of HPP development, is that no cost or time savings are achieved as in the previous cases, since two grid connection points are set up and two substations are needed.

Co-location of RES-storage:

Three different configurations are considered:

D. ESS as a supplementary component: the storage unit is linked to at least one of the generating units and cannot be independently controlled. In this case, the storage unit is only used as a supportive element to the generating units.

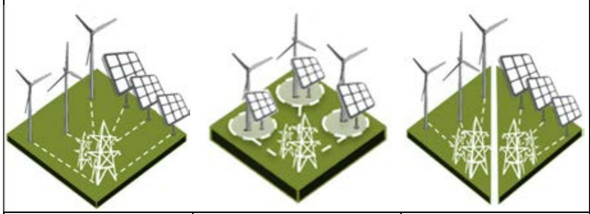
E. ESS as an independently operated component: the storage unit is operated independently from the generating units. In this case the storage unit can be used either to support the operation of the generating units or to provide ancillary services to the grid (by storing energy from the grid or directly supplying stored energy to the grid).

F. ESS as a partly supplementary component and partly independent component: In this case a share of the storage capacity is reserved (and should be registered) as a supplementary component only enabled when the generating units operate. The remaining part of the capacity is reserved (and should be registered) as an independent component directly interacting with the grid.

B. Total capacity and capacity share of technologies:

The total capacity of HPPs and the share of the different technologies vary depending on the developer's needs, the local conditions and the planned functionalities. Fig. 1 presents the capacity share of wind, solar and storage technologies in existing and under development HPPs. The total capacity is computed as the sum of nominal wind and solar output capacities.

TABLE 1: CO-LOCATION CONFIGURATIONS OF GENERATION UNITS IN HYBRID POWER PLANTS

	Source: GE Renewable Energy [13] 		
	Same substation and grid connection	**PV panels integrated with the turbines**	**Different substation and grid connection**
√	- Reduced CAPEX and permitting time thanks to one common grid connection point and substation - Maximised utilisation of the grid connection capacity - Easier to optimise the sizing of the substation to the most possible range of power output, but necessary to carefully consider curtailment		- Common well-known permitting and metering process - Easier to manage the works of different RES/storage developers, avoid conflicts
	- Simpler and more flexible configuration to develop and size, especially when storage is integrated - PV capacity not limited by turbines' converters - No shading from the blades to the PV panels	- The solar inverter can be eliminated	
	- Joint development and O&M works can be deployed thanks to the geographical co-location of RES/storage		
X	- Connection and metering processes quite new to authorities, not yet standardised and streamlined	- Connection and metering processes quite new to authorities, not yet standardised and streamlined - Potential shading of PV panels from the blades. - In existing wind farms, PV capacity to be installed limited by the turbines' converter capacity and by space	- Two grid connections and substations although generating units in the same site. - This choice needs to be justified by specific conditions. Otherwise its benefits compared to virtually linked power plants are not obvious

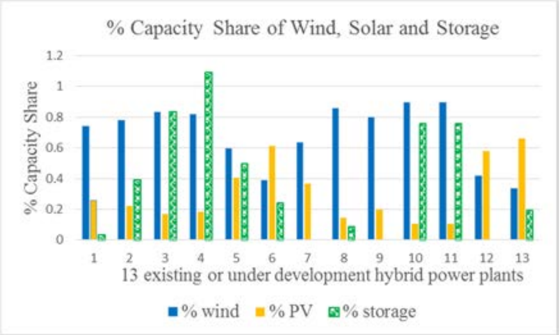


Fig. 1. Capacity share of wind, solar and storage in thirteen existing and under development hybrid power plants

C. *Functionalities and services to deploy:*

HPPs have been gaining momentum because they can serve a set of different functionalities. The most common ones are the following:

- Capacity firming (more stable power output, reduce ramps and imbalances)
- Remote/isolated area
- Increase island self-sufficiency
- Weak power grid
- Frequency restoration services
- Other ancillary services (black start, reactive power control, voltage control…)

Along with the increasing share of RES in the power grid, the functionalities of HPPs are expected to multiply for serving different flexibility and resilience needs of the grid. Most HPPs are built to serve more than one functionality, multiplying in this way their revenue streams. Based on existing and under development cases, Fig. 2 presents a statistical overview of principal functionalities of existing HPPs.

D. *LCOE and market value*

The existing plants have been very recently built or are still in the development phase. Developers are still evaluating the business case of such projects while quantitative data are very limited. This study presents a set of qualitative conclusions regarding market integration of HPPs in the following *Lessons Learned* section.

IV. CREATING A DATABASE

In 2017, WindEurope developed and made publicly available a database of co-located power plants with wind and storage technologies [13]. For creating awareness and building knowledge around HPPs, the authors have complemented this database[3] with HPPs including wind, solar and potentially storage. Please note that the database includes all kinds of energy storage, even installations that store electrical energy from a RES plant and then convert and release it in a different form.

One screenshot of the database under development are presented in the following figures. Fig.3 illustrates the global map with HPP locations and types. Orange dots represent HPPs with wind, solar and storage and blue dots represent HPPs with only wind and solar. Green dots represent co-located power plants with wind and storage (information on these projects has been already published online in the existing database [13]).

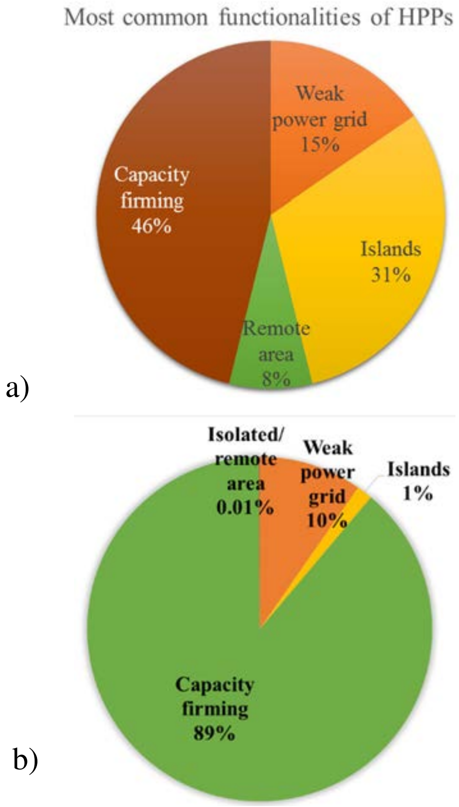


Fig. 2. Most common principal functionalities of existing HPPs (a) % of total number of assessed cases, b) % of total installed RES (wind + solar) capacity)

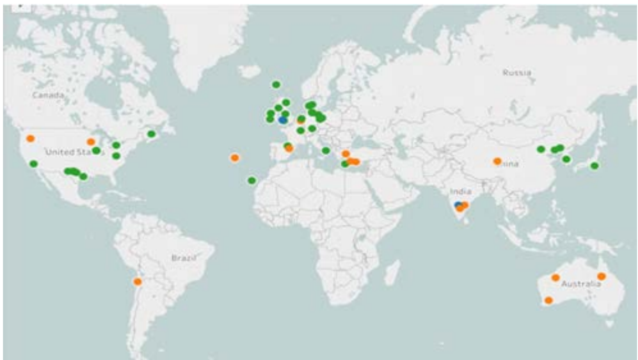


Fig. 3. A screenshot of the WindEurope database of HPPs

V. ASSESSING CASE STUDIES

For creating and updating the presented database, the authors have collected and assessed the maximum available information on existing, under development and announced HPPs worldwide. The following paragraphs outline indicative case studies from pioneer HPP developers.

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[3] WindEurope, "WindEurope's online database of co-located projects," 2017. [Online]. Available: https://windeurope.org/about-wind/database-for-wind-and-storage-colocated-projects/.

A. *Cynog Park, United Kingdom*

The *Cynog Park* is Vattenfall's first solar PV and wind HPP (Fig.4), developed as a strategic project for gaining experience [14]. In this pilot project, a solar PV farm of 4.95MWp has been installed, in 2016, in the 3.6 MVA onshore *Cynog* wind farm, built in South West Wales since 2001. The HPP has a grid connection capacity of 4.1MVA (co-location type A, see paragraph III. Building knowledge on hybrid power plants).

According to Vattenfall, negative correlation of wind and solar irradiation has been observed at the site, on monthly, daily and 10-min basis. This fact has been positive for firming the output capacity of the plant thus for maximising the utilisation of the grid connection capacity. Adding a battery could further shape or smoothen the production profile.

In terms of challenges, the PV power curtailment has been higher than anticipated. The developer highlighted the importance of deploying curtailment simulations on a 10-min or 15-min basis for having reliable estimates. When sizing the HPP, the ratio of wind and PV capacity is crucial but necessarily site-dependent. Some losses have been monitored due to conflicting settings of controllers for active and reactive power. In case of power over supply, a fast reaction of the controllers is primordial.

Fig. 4. The *Cynog Park*; Vattenfall's first solar PV and onshore wind HPP (Source: Vattenfall [14])

B. *Haringvliet, The Netherlands*

The *Haringvliet* is Vattenfall's first HPP combining wind, PV and battery storage (Fig.5) since its early development [14]. The plant consists of 21MW of wind (Nordex N117/3675 turbines), 41 MWp of solar and 12MWh/ 12 MW of battery storage. The grid connection capacity is of 50MW (co-location type A, see paragraph III. Building knowledge on hybrid power plants).

The objective of the developer is to combine the three technologies, since early development, to stay competitive in the future. The permitting and the Dutch Renewable Energy Grant Scheme (SDE+) have been secured for the plant since 2017. The construction will start in 2019 and the plant is expected to be commissioned in 2020. The revenue streams of this HPP are expected through participation in the wholesale electricity market and Guarantees of Origin (GoO), Frequency Containment Reserve services and time shifting services.

Fig. 5. The *Haringvliet*; Vattenfall's first HPP combining wind, solar and battery storage since early development (Source: Vattenfall [14])

C. *Minnesota Community Site, United States of America*

The *Minnesota Community Site* is the first wind and integrated solar HPP developed in the USA (Fig.6). The project has been developed by Juhl Energy for a local municipality. The installed system is a GE WiSE system with one 2.0-116 wind turbine and 500kWp of solar [15] (co-location type B, see paragraph III. Building knowledge on hybrid power plants). The system has been installed in December 2018 and is currently being commissioned.

In terms of development and operation challenges, it has been estimated that power curtailment will not be an issue for this plant [16]. Grid connection compliance has been a challenge not due to technical reasons but mainly due to the innovative character of the project. Indeed, local authorities and developers have been gaining experience from this first development. The total output of wind and solar will be limited to the nameplate capacity of the wind turbine converter, necessarily in such a co-location type.

Fig. 6. The GE 2.0-116 rotor being lifted in place (Source: North American Wind Power)

D. *La Muela, Spain*

The *La Muela* power plant (Fig.7) is a prototype that was inaugurated by Siemens Gamesa in 2015. This off grid HPP consists of a Gamesa G52 850kW wind turbine, 816 photovoltaic modules providing a total capacity of 245kWp, three 222kW diesel generators and a battery system of 429 kW [17]. The prototype was designed to deliver reliable, green power to remote areas without access to the main electricity grid. According to the developer, the HPP has been operating successfully since January 2016 helping end-users to make significant savings over conventional diesel-based generation [18].

Fig. 7. The *La Muela*; Siemens Gamesa's off grid HPP prototype inaugurated in 2015 (Source: MTU Report [18])

VI. LESSONS LEARNED

A. *Technical priorities and challenges*

Based on the feedback from first developments, firming the output capacity of an HPP is primordial. To this end, the choice of the specific site to install a plant needs significant attention. Wind and solar irradiation profiles need to be as complementary (negatively correlated) as possible on 10-min or 15-min basis. This allows optimally sizing the converters, maximizing the utilisation of the grid connection capacity and reducing power curtailment. As a matter of fact, curtailment estimation studies need to be deployed on 10-min or 15-min basis to be reliable for decision making. Picking the right sites is a major factor in HPP design because it will result in both CAPEX and OPEX reduction. Firming the output capacity of a plant will also increase its value in a PPA.

Investing on high quality reliable forecasting of energy production is also very significant. The complementarity of different RES can mitigate the variability of the power output potentially leading to lower imbalance costs. However, if one of the assets is subsidized, it needs to be metered separately from the rest of the technologies. This is a challenge that may increase costs and administrative complexity.

When Guarantees of Origin (GoO) are required, the operator might need to trace real RES power output separately from power supplied from stored grid energy ("green" power versus "grey" power). Otherwise, as is the case in certain countries, adding a storage device in an existing subsidised power source may endanger subsidy payments [14].

In terms of development complexities, a multi-disciplinary team is required with expertise on wind and solar generation technologies, storage devices and the interoperability between them [14]. The project management is also more complex compared to pure wind or solar plants as the developer needs to align different development schedules e.g. wind permitting process is usually lengthier than solar). To manage such complexities, continuous adjustment of internal organisation and project steering are required.

When it comes to AEP, if PV panels are integrated at the wind turbine level or are closely located to the turbines, shading from the blades will be an issue. A solution would be to install PV further apart from wind turbines but this would increase cable cost and induce line losses, both in terms of active and reactive power. Maximum Power Point Tracking (MPPT) techniques are necessary to maximise power extraction under all conditions.

Finally, in some countries, solar PV systems cannot be installed on farm land which might limit co-location opportunities. At the same time, *Agrophotovoltaic* is becoming an established practice to increase land efficiency, and further deployment of this type of solutions can increase HPP opportunities [19].

B. *Policy recommendations*

HPPs generally need to rely on support schemes given that their LCoE has not yet reached grid parity in most countries; especially when storage is integrated, inducing high CAPEX not offset with equivalent incremental revenue streams [7].

In today´s RES support schemes, it is a challenge for HPPs to get support for the full concept even in case of technology-neutral auctions. As previously mentioned, adding ESS in an existing plant induces complexities in terms of metering and RES traceability that may put in danger already rewarded subsidies for the existing wind or solar system. Furthermore the societal benefits from HPP (mentioned in paragraph I. The motivation behind hybrid power plants) is not fully rewarded in today´s support schemes. A solution to this challenge could be the implementation of RES auctions supporting developments that match the needs of the local grid.

In case subsidies are granted to HPPs, policy makers need to ensure that the incentives of the developer are aligned with market dynamics, by introducing a premium on top of the wholesale electricity price or introducing a reward scheme for the electricity supplied to the grid [7]. No taxes and tariffs shall apply on electricity used or stored behind the grid metering point (used instead of curtailment) [2].

Another issue are the metering concepts for HPPs. In most cases they are not standardized or formalized but subject to bilateral negotiation and agreement with the relevant system operator. This leaves the project developer with significant economic and regulatory uncertainty and often the local system operator with suspicion for grey electricity supply [7]. To mitigate such uncertainty, it is imperative to standardize metering concepts for HPPs or co-located power plants in general, at least at national level.

When capacity markets are present, HPPs should be allowed to participate along with conventional generation sources. In such case, another incremental revenue opportunity will arise for HPPs. More generally, HPPs should be allowed to provide different services at the same time, thus improving the profitability of the project through several revenue streams.

VII. CONCLUSIONS AND RECOMMENDATIONS

This study highlights that HPPs could provide significant RES system integration benefits. Moreover, based on pioneer developments, it seems that that HPPs also have a business case, but the setup is more challenging than in case of pure wind or solar plants. Therefore, support schemes and regulation need to develop further. The development and success of HPPs would benefit from more hybrid-friendly RES auction design supporting developments that match the needs of the local grid. Thanks to digitalisation and in particular virtual metering strategies, requirement for one metering point in HPPs should be considered sufficient in terms of standardization. HPPs should also be able to participate in existing capacity mechanisms. No taxes and tariffs should be imposed on behind-the-meter stored energy and sector coupling. In return existing grid infrastructure and land would be used more efficiently and curtailment compensation expenditures can be reduced. The respective savings can be re-invested in grid infrastructure upgrades and improvements.

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