LDES Council

A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements

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Contents

Acronyms

API	Application programming interfaces
Capex	Capital expenditure
CO_2	Carbon dioxide
EAC	Energy attribute certificate
EU ETS	European Union Emissions Trading System
ESG	Environmental, social, and governance
gCO_2eq	Grams of carbon dioxide equivalent
GHG	Greenhouse gas
GW	Gigawatt
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
Li-ion	Lithium-ion
LDES	Long duration energy storage
MW	Megawatt
MWh	Megawatt-hour
Opex	Operational expenditure
PPA	Power purchase agreement
PV	Photovoltaics
RES	Renewable energy sources
SBTi	Science-based targets initiative
TSO	Transmission system operator
TW	Terawatt
TWh	Terawatt-hour
T&D	Transmission and distribution
UK	United Kingdom

Preface

The LDES Council is a global, executive-led organization that strives to accelerate decarbonization of the energy system at lowest cost to society by driving innovation and deployment of long duration energy storage (LDES). Launched at COP26, the LDES Council provides fact-based guidance to governments and industry, drawing from the experience of its members, which include leading technology providers, industry and services customers, capital providers, equipment manufacturers, and low-carbon energy system integrators and developers.

LDES is defined as any technology that can be deployed competitively to store energy for prolonged periods and scaled up economically to sustain electricity provision, for multiple hours, days, or even weeks, and that has the potential to contribute significantly to the decarbonization of the economy.

This report focuses on corporate Power Purchase Agreements (PPAs) that, if properly designed, can become a key lever to capture the value of LDES technologies and accelerate their deployment. It excludes the analysis of other complementary measures such as regulatory instruments, new market designs, or financial incentives. These topics will be covered in upcoming LDES Council reports.

The following organizations form the Council (Exhibit 1).

Exhibit 1

LDES Council members

Technology providers

Anchors

Industry and services customers

Capital providers

Equipment manufacturers

Low-carbon energy system integrators & developers

The report has been prepared by the members of the LDES Council in collaboration with McKinsey & Company as knowledge partner.

Key messages of the report

A new form of Power Purchase Agreement (PPA) — the 24/7 clean PPA — promises dramatic increases in the effectiveness of emission reduction efforts in the power generation sector and for corporate off-takers. 24/7 clean PPAs have the potential to address key problems in balancing supply and demand for power as renewables contribute an increasing proportion of generation capacity. In the process they can help providers and off-takers accelerate the overall decarbonization of the power sector.

24/7 clean power PPAs measure electricity consumption and greenhouse gas emissions on a granular basis — e.g., by the hour — **and provide time-matched clean power.** They represent an improvement from today's scope 2 decarbonization with pay-as-produced renewable PPAs, which balance supply and demand on an annual basis and only achieve 40 — 70% decarbonization[1] of the off-taker's actual electricity consumption. Time-matched clean power provided through 24/7 clean PPAs addresses both problems by using a combination of renewables and flexible capacity to create a more granular match between renewables supply and demand.

Current barriers to wider adoption of 24/7 clean PPAs include cost and a lack of agreed standards, but these can be overcome. Achieving 100% actual decarbonization with today's storage technology is often considered to be prohibitively expensive as the levelized cost of electricity from a wind / solar and lithium-ion (Li-ion) hybrid system exceeds 200 USD per MWh in most regions. But solutions based on novel energy storage technologies like long duration energy storage (LDES) are expected to reduce the cost of 24/7 renewable power to below 100 USD per MWh in the near future if deployment accelerates. 24/7 clean PPAs are an essential non-regulatory tool to support this acceleration by enabling investments in clean, dispatchable capacity that will drive down costs.

The industry can accelerate decarbonization by applying a standardized assessment allowing for different levels of ambition; to this end, a quality assessment framework within which the industry can define a set of standards for 24/7 clean PPAs is proposed in this report. This will establish a pathway to 24/7 clean PPAs with increasing levels of clean supply-demand matching. "Entry Level" 24/7 clean PPAs are defined to have low entry barriers and cost in the range of today's average power market prices in many regions (around 70 USD per MWh), which should accelerate adoption. At the other end of the scale, "Platinum" PPAs represent the highest ambition level (approaching 100% clean supply-demand matching) and are designed for those looking to accelerate decarbonization and technology deployment: the cost levels of those high-quality 24/7 clean PPAs is expected to decline by 30 — 40% over the next 10 years as technology matures and scale increases, closing the gap to market prices.

To maximize decarbonization impact, 24/7 clean PPAs would benefit from being officially certified by an independent organization based on up-front validation of contract terms and / or proposed sizing of the designated assets. In addition, continuous validation of the actual level of clean supply-demand matching throughout the PPA lifetime ensures consistent execution.

The assessment shows that full clean supply-demand matching is not always the optimal target: the compromise between 24/7 load matching and system-level decarbonization would need to be carefully considered when structuring the contracts. A case example shows 10 — 30% cost reduction potential and an uplift of around 100% system-level CO_2 abatement when dispatch is partly based on power market prices and hourly marginal grid emissions factors. This shows that deviations from consumers' 24/7 load matching can unlock system-level benefits and avoid sub-optimal solutions that may emerge from 100% load matching for each off-taker.

1 Range estimated based on a solar / wind generation profile and baseload demand; actual decarbonization impact depends on the load shape and market-specific emissions intensity.

Executive summary

The rising share of renewable power in the global generation mix-driven by the need to reduce greenhouse gas (GHG) emissions — has created new challenges in managing electricity supply and demand. In particular, the inherent intermittency of wind and solar power creates a need to balance supply and demand, for example by using fossil fuel power to fill gaps. The search is on for a solution that will further reduce the need for fossil fuels, increase decarbonization, and improve risk management. **One answer is 24/7 clean Power Purchase Agreements (PPAs).**

Today's standard renewables PPAs enable new clean generation capacity but do not support full system decarbonization due to a temporal mismatch between generation and demand

- As companies aspire to decarbonize their operations, corporate renewable PPA volumes are increasing.
- Although these PPAs drive the deployment of new renewables capacity, they do not lead to full grid decarbonization as the carbon accounting for energy procured is insufficiently granular: matching supply and demand on an annual basis is sufficient to claim full decarbonization of power supply according to current carbon accounting standards, while in reality only 40 — 70%[2] of emissions are addressed due to a temporal mismatch between renewables supply and off-taker demand.
- Current 100% renewable pay-as-produced PPAs also do not fully hedge price volatility risk for the off-taker, which is accentuated by high penetration of variable renewable energy sources and volatility of commodity prices.
- While there are multiple solutions that can address both these challenges, 24/7 clean PPAs are amongst the most immediately impactful as these only rely on a contractual relationship between buyer and PPA provider.

Lack of standards and high cost premium relative to average power market prices are key barriers to deploying 24/7 clean PPAs today

- **Lack of standards:** The lack of industry-agreed definitions of 24/7 clean PPAs creates a significant barrier to consistently rewarding players that procure 24/7 clean power.
- **Cost:** 24/7 renewables procurement with clean supply-demand matching based on Li-ion storage comes at a significant cost premium (for example, in the California case example[3] the cost would increase by min. 5x compared to average power market prices). LDES has the potential to significantly lower this cost premium; however, more widespread deployment of these technologies is needed to drive down the cost curve.

A standardized quality assessment framework can help reward industry players to move beyond standard PPAs, while different quality levels help to support affordability

- PPA providers and buyers would benefit from a 24/7 clean PPAs benchmark based on a standardized assessment framework and classify different quality levels to ensure that decarbonization leaders get the appropriate recognition (e.g., for adding new clean capacity on the grid).
- Attention needs to be paid to five quality dimensions: the level of clean supply-demand matching, time granularity, geographical granularity, and additionality of renewables and flexible or clean dispatchable capacity.

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2 Range estimated based on a solar / wind generation profile and baseload demand; actual decarbonization impact depends on the load shape and market-specific emissions intensity.
3 Based on CAISO (California Independent System Operator).

- Given that corporates' procurement strategies vary based on decarbonization and risk appetite, several quality grades are proposed with progressively higher requirements to encourage companies to go beyond pure hedging strategies and aim for greater system decarbonization impact:
  - Entry Level aims to lower barriers for energy-intensive users to adopt 24/7 clean PPAs. Basic requirements include a minimum of 80% clean supply-demand matching and one-hour time granularity, with assets and load to be in the same balancing / bidding zone;
  - Silver is designed for players that seek to further accelerate the transition and support new capacity deployment: this includes requirements such as additionality of renewables and flexible capacity;
  - Gold and Platinum levels set higher ambitions, with Gold requiring a minimum of 90% supply-demand matching and Platinum calling for matching higher than 98%.

Today, 24/7 clean PPAs come at a premium, but cost levels are expected to become competitive as technology costs come down due to scaling of novel flexibility technologies

- By 2025, meeting the "Silver" quality rating (minimum supply-demand matching of 80%) implies only a 10 — 15% cost-premium relative to today's average wholesale market price and clean power certificates (based on a 2021 CAISO example, which would result in a Silver PPA cost of around 70 USD per MWh). For Platinum requirements with 100% supply-demand matching, the estimated cost premium would rise to 40 — 50%.
- In addition, over time, 24/7 clean PPA costs are expected to decrease rapidly due to progress in technology maturity, scale effects, and further improved economics as flexibility assets tap into additional revenue streams: technology-related cost alone is expected to decline by 30 — 40% over the next 10 years for Platinum PPAs.
- Achieving attractive cost levels for 24/7 clean PPA solutions requires optimization of the technology mix, ideally using a portfolio of wind and solar power as the generation sources. The analysis shows that using solar-only generation can lead to 3 times higher cost of electricity compared to a solar-wind-hybrid setup in case of a baseload demand profile. In general, the correlation between load shape and available renewable supply is a relevant cost driver. For example: switching from a baseload profile to a typical office load profile could imply a cost increase of around 25% in a wind-dominant region like the United Kingdom (UK), and a cost decrease of around 5% in a solar-dominant region like California.

In some markets, CO_2 impact and cost would benefit from optimized dispatch patterns not focusing on load-matching. To increase attractiveness and consistency, 24/7 clean PPAs would need to be officially certified by an independent organization based on validation of contract terms and / or proposed sizing of the designated assets

- The assessment shows that often there is a compromise between full clean supply-demand matching and system decarbonization. If the operator has the option to optimize dispatch based on power market prices and hourly grid emissions, costs can be reduced by 10 — 30% and system-level CO_2 abatement increased by around 100%. This is possible through market arbitrage and surplus generation optimization in markets where market prices and emissions intensity are highly correlated. Thus, once the system has been designed and certified off-takers could consider lowering the load-matching constraint, e.g., to 80 — 90%, to amplify system-level impact while keeping the Platinum rating.

- It is proposed that an independent certifying body assesses 24/7 clean PPAs to assign a quality rating for their public announcement. Two major options exist to verify that 24/7 clean PPA contracts adhere to a certain quality standard:
  - Contractual obligations for the provider to deliver clean power consistently with the certified quality level, and clear provisions in the event of non-delivery.
  - Modeling the designated PPA capacity against a standardized set of weather data to ensure system design can meet the requirements.
- Hourly tracking of the demand and supply could be carried out to certify the contractual terms are being met and to demonstrate system impact. Furthermore, players may also choose to optimize emissions by tracking the marginal carbon intensity of the grid.

Five actions could support the widespread adoption of 24/7 clean PPAs:

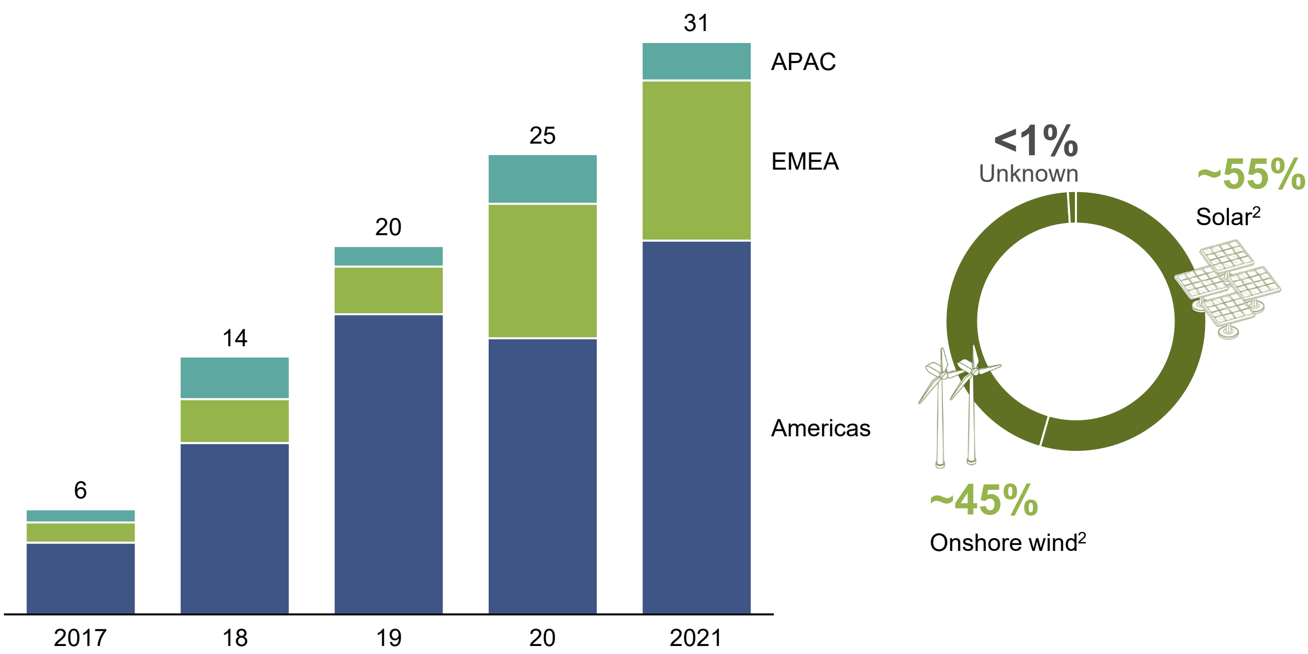
- Establishment of an agreed international framework overseen by an independent governance body;
- Creation of incentives to spur wider corporate adoption, for example through inclusion of 24/7 PPAs in carbon accounting standards;
- Development of a transparent data ecosystem, with supportive regulation;
- Creation of supportive regulations to eliminate barriers and catalyze deployment;
- Definition of measures that lower barriers to entry for smaller and less sophisticated corporate players, including innovative business models that enable asset sharing and the involvement of intermediaries or aggregator platforms.

Power Purchase Agreements 101

What are Corporate PPAs?

Corporate Power Purchase Agreements — PPAs — are **legally-binding long-term contracts** between a **seller and a buyer** that define all the commercial terms for the purchase of electricity. The buyer, also called off-taker, is usually a commercial or industrial end-consumer, but can also be a government entity. In renewables Corporate PPAs, the electricity is obtained from renewable sources like solar or wind.

Announced renewables Corporate PPAs annually[1]
GW



1. On-site PPAs excluded. APAC volume is an estimate. Pre-reform PPAs in Mexico and sleeved PPAs in Australia are excluded.
2. Excludes 2021 data

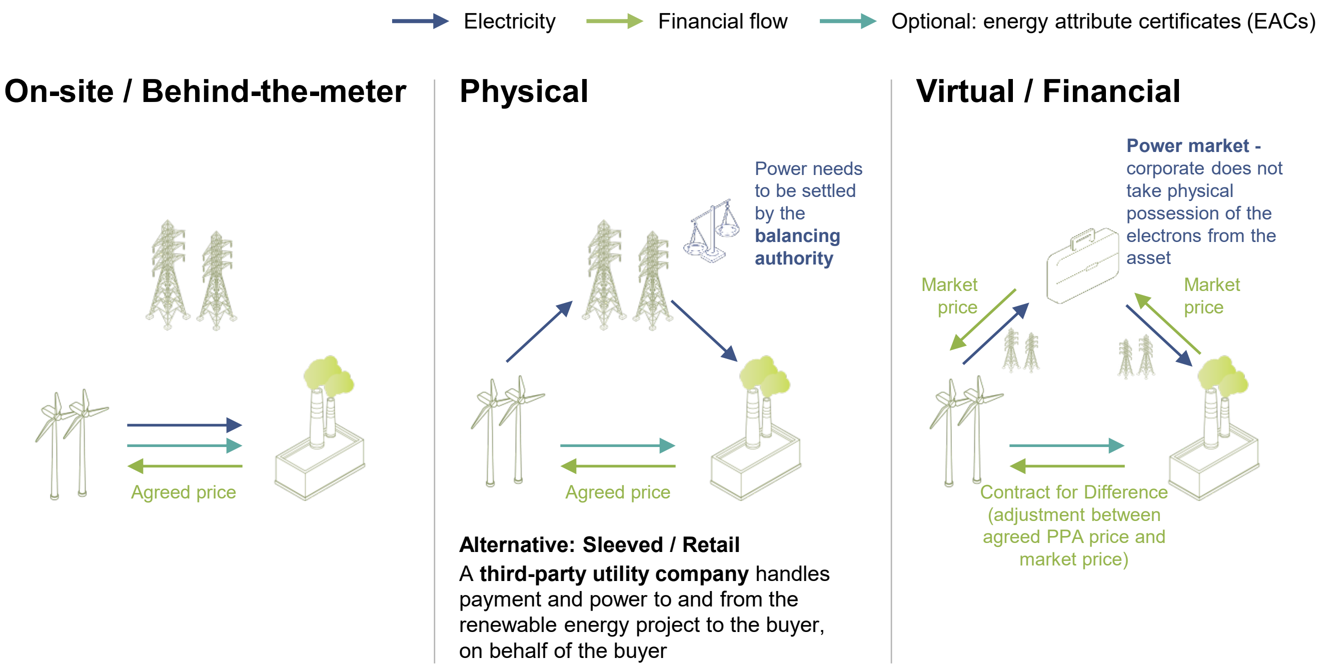
Source: BNEF

What are the most common set-ups?

There are three principal varieties: On-site or behind-the-meter, physical and virtual or financial PPAs. They differ in how the power is delivered to the corporate. Currently, the **majority of transactions in** the **United States are virtual PPAs, while Europe has a broader mix of transactions**. A common alternative version of Physical PPAs are Sleeved PPAs, where an intermediary utility provides the “sleeving” service.

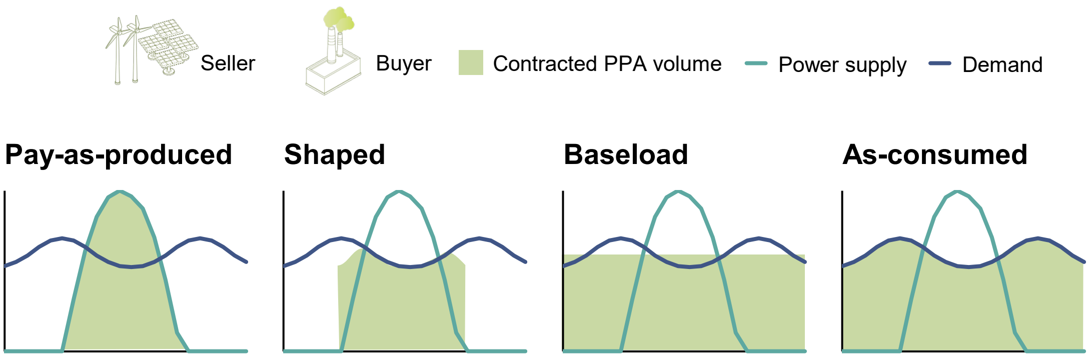
Energy Attribute Certificates (EACs)

They offer proof of the source of energy by creating a unique certificate that represent the environmental attributes of one megawatt-hour (MWh) of supplied power. They can be unbundled from the electrons and traded.



What are the most common structures?

The most typical PPA structures are: pay-as-produced, shaped, baseload, and as-consumed. In pay-as-produced PPAs, the off-taker buys the gross generation from the assets, thereby bearing the price risk. Because of this, the remaining three structures are increasingly in demand. In these cases the seller has to settle the difference between the power produced and the load — currently transparency on the source of the power filling the gap is quite limited and may be sourced from fossil-based flexibility sources.



	Pay-as-produced	Shaped	Baseload	As-consumed
Description	The consumer buys the gross generation from the assets.	The seller converts the gross generation from the assets into a fixed shape over a year.	The seller converts the gross generation from the assets into a monthly/ annual baseload volume.	The PPA volume is the actual off-taker demand.
It has a higher price risk for…	The buyer, as the generation from the renewable assets is not fully predictable.	The seller, as it has to settle the difference between actual volume produced and the fixed shape at the market (resulting in a gain or cost).	The seller, as it has to settle the difference between actual volume produced and the baseload at the market (resulting in a gain or cost).	The seller. Only sellers with a large generation portfolio and flexibility assets can offer this type of PPA.

I.

The need for 24/7 clean PPAs

While current renewables PPAs drive the deployment of new solar and wind generation capacity, they only address the annual supply-demand balance and do not incentivize full grid decarbonization.

Current renewables PPAs have helped to unlock private investment into new clean capacity

Renewables power purchase agreements (PPAs) are a key mechanism for deploying new renewable energy sources (RES) projects. From the standpoint of the energy seller, they enable the generation plant to seek financing from capital markets (e.g. providing the project with bankability); from the perspective of energy buyers, they enable corporates and major off-takers to meet their clean electricity targets and obligations.

RES PPAs are a key lever for businesses aiming to decarbonize their Scope 2 emissions from purchased electricity, heat, and steam. When corporates contract renewable PPAs, they buy power generated from carbon-free assets as well as the assets' corresponding Energy Attribute Certificates[4] (EACs), which the companies then use in their carbon accounting to demonstrate clean power consumption. The RE100 initiative, with over 300 members across 175 markets that have pledged to use 100% renewable electricity, is a notable example of this trend.

However, even though companies use 100% renewable PPAs to procure sufficient renewable power to cover their annual consumption, the hour-by-hour loads are typically co-supplied by fossil assets

Due to the variable nature of RES, in the absence of clean flexibility solutions or massive capacity overbuilding, renewables can only cover a fraction of a consumer's load profile. When the supply of wind or solar power drops below the load, the gap is usually filled by power derived from a mix of renewable and fossil sources. Conversely, when the supply exceeds load, businesses sell the surplus RES back to the market.

However, since EACs can be temporally and physically unbundled from the electricity supply,[5] corporates can use the EACs from periods of surplus RES to offset their emissions when there is no wind or sun. Consequently, businesses matching their annual load with RES pay-as-produced PPAs (i.e., 100% renewable PPAs) do not accurately account for the timing of emissions and currently have little incentive to do so.

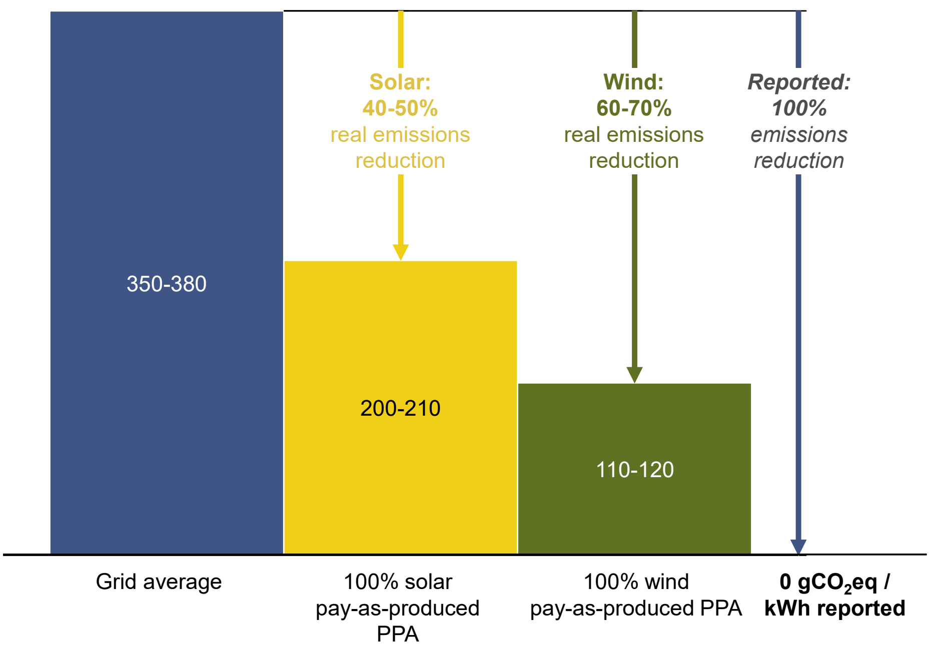
For example, consumers procuring a solar or offshore / onshore wind pay-as-produced PPA matching their annual load in Germany or California are actually being supplied by carbon-emitting electricity during renewables 'under-supply' periods. If a consumer has a baseload profile similar to that of a datacenter, its resulting average annual carbon intensity would be above 200 gCO_2eq per kilowatt-hour (kWh) consumed for a solar-based PPA, and more than 110 gCO_2eq per kWh for a wind-based PPA in both locations.[6] This creates a mismatch with the direct emissions reported under current accounting rules, which would be 0 gCO_2eq[7] in this case (Exhibit 2).

4 One EAC represents the environmental attributes of a one megawatt hour (MWh) of energy produced.
5 EACs can be redeemed up to 12 months after the production of the electricity unit, and can be used within certain market limits that are not always linked to the grid area into which the power is injected.
6 Based on: hourly, average grid emissions and solar and offshore wind generation data for Germany (2021) and a 100 MW demand with a baseload profile.
7 Excludes supply chain emissions.

Exhibit 2

Emissions of 100% annual matching PPAs that uses unbundled renewable certificates to cover grid consumptions

Emissions intensity of different power procurement options [1]
gCO_2eq / kWh



A baseload with a **100% solar or wind PPA matching annual consumption, would still have a carbon intensity** of 200-210 or 110-120 gCO_2eq / kWh respectively.

Reported emissions, however, are 0gCO_2eq per kWh consumed.

The off-taker **uses the surplus energy attribute certificates from times of wind or solar over-supply,** to compensate emissions from grid consumption **during times of under-supply.**

1. Based on 2021 average grid emissions and RES generation data for Germany and California. Emissions intensity of the grid and wind PPA: lower range applies to Germany (offshore wind), and upper range to California (onshore wind). Emissions intensity of solar PPA: lower range applies to California, upper range to Germany.

In addition to decarbonization solutions, off-takers need solutions that reduce their exposure to increased power price volatility, resulting in part from increased renewables penetration.

Current 100% renewable PPAs do not fully hedge price volatility risk, which is accentuated by high penetration of variable RES and volatility of commodity prices

Allocating the various risks is a critical component of the PPA negotiations. The contract's structure largely determines that risk allocation. In a baseload structure, the PPA provider typically bears the price risk as it has to settle the difference between the actual volume produced and the baseload with the market. On the contrary, in pay-as-produced PPAs, the off-taker is liable for complementing its PPA purchase from the market at periods of under-supply.

In markets with high RES penetration, the price peaks at periods of low renewable production tend to be higher because the clearing — or market — price is often augmented by strategic bidding of thermal generation owners to help them recover their investment. Increasing carbon prices increase the costs even further: the price in the European Union Emissions Trading System (EU ETS) is expected to grow by 40% by 2030, to around 110 EUR per ton of CO_2 on average.[8]

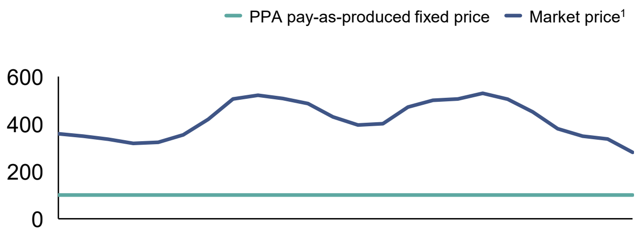
8 Carbon Pulse analyst poll (data as of Q1 2022).

As a result, players are becoming exposed to increasing market price fluctuations and periods of high prices. In the case example shown below, with baseload consumption under a pay-as-produced PPA matching its annual consumption, the load will be exposed to market prices when the offshore wind is not sufficient to cover the consumption. The PPA does not hedge the off-taker's exposure to market price fluctuations (Exhibit 3).

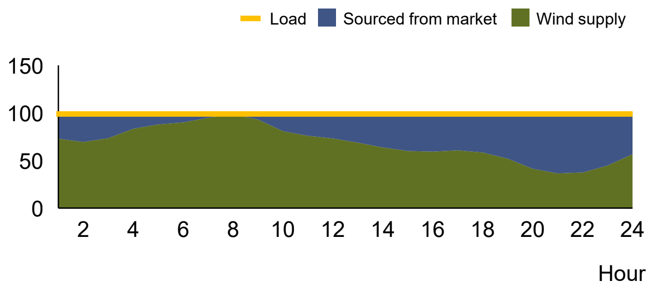
Exhibit 3

Case example of a baseload with a pay-as-produced offshore wind PPA, hourly price, and power supply components

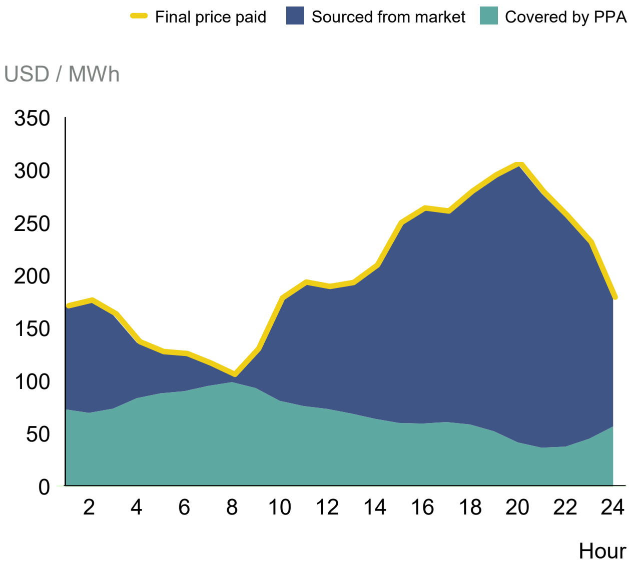
Price
USD / MWh



Power
MW



Hourly price paid for a baseload with an offshore wind pay-as-produced PPA in Germany[1]
2021



1. Based on market price data and offshore wind capacity factors of Germany, 22.12.2021.

Solutions exist today to minimize exposure to electricity price volatility via risk management products. However, not all approaches reduce emissions

Players can hedge price risk through commodity markets. Both buyers and sellers can manage risk on these markets by trading on energy exchanges: for example, by leveraging Futures, Forwards, Swaps or hourly Options to minimize price risk.

However, these products do not effectively address the decarbonization issue as off-takers can still decouple their carbon accounting (e.g., via EACs) from their actual electricity procurement. This may result in lower environmental, social, and governance (ESG) ratings due to a lack of direct links between electricity supply and consumption.

While other solutions can address grid decarbonization and market risk challenges, 24/7 clean PPAs are amongst the most immediately impactful.

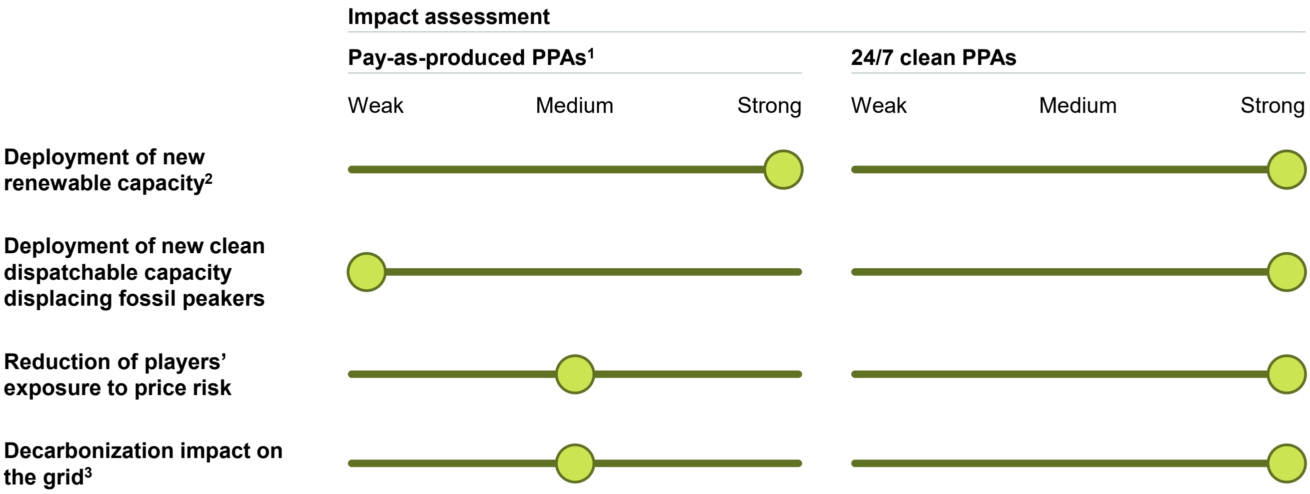
24/7 clean PPAs increase the decarbonization impact of clean electricity on the grid and reduce the market risk for corporates

A solution to the decarbonization and market risks challenges is 24/7 clean power procurement. Purchasing round-the-clock clean electricity primarily acknowledges that temporality matters when it comes to clean electricity generation. 24/7 clean PPAs are a key instrument in this regard, as they focus on supplying sufficient clean power to match the actual load and incentivize investments in enabling technologies. 24/7 clean PPAs:

- **Have a higher decarbonization impact than current 100% clean annual-matching PPAs:** 24/7 clean PPAs switch the emphasis from electricity emissions offsets (mainly through unbundled EACs) to time-monitored power procurement bundled with EACs. The higher temporal granularity of these PPAs results in an increased decarbonization impact, as it drives new clean supply at the hardest-to-decarbonize times currently served by non-clean assets.
- **Incentivize the deployment of enabling clean flexibility solutions like LDES:** A time-stamped clean power procurement captures the value of flexibility solutions like energy storage or demand-side management (e.g., electrolyzers), and enables their monetization. The early deployment of these solutions is key to accelerating their learning curves and ensuring the timely decarbonization of power systems at the lowest cost to society. Furthermore, they support a more efficient system with lower RES overproduction.
- **Mitigate the increasing market risks for off-takers:** They provide long-term revenue certainty for PPA providers, while mitigating cost risks for off-takers caused by increased market volatility and reducing hedging costs. Furthermore, they ensure that companies' statements on decarbonization impact are traceable, validating clean, time-matched power consumption claims. Lastly, by giving options that can be implemented today, versions of 24/7 PPAs can help mitigate risk of companies facing future time-matched procurement requirements that are difficult to meet.

Exhibit 4

Assessment of PPA impact on new capacity, price risk, and decarbonization



1. Matching 100% of the load with the supply on an annual basis.
2. Assumes contracts with additionality requirement.
3. Depends on the dispatch strategy and on whether the assets are operated to maximize revenues, load-matching, or carbon impact (see Chapters 3 and 4 for more details).

Other options to increase decarbonization include new market designs, or transmission and distribution (T&D) infrastructure build-out. However, these would likely take longer to implement as they require alignment on the part of a larger stakeholder pool

A wide range of other decarbonization and market risk mitigation levers are also available. Carbon markets and carbon accounting standards, such as the GHG Protocol, are examples of existing solutions to decarbonize economies. T&D expansion and new market designs can also help to decarbonize the power system and smooth out price peaks. For instance, T&D reinforcement reduces grid congestion risks, and technology-specific capacity markets capture the value of new flexibility capacity deployed on the grid, reducing price volatility and the need for fossil-fuel alternatives (e.g., gas peaking plants).

A combination of these instruments will contribute to the full decarbonization of power systems; however, their implementation likely requires the alignment of a larger stakeholder group, which can increase the effort and time required for implementation.

II.

Barriers to 24/7 clean PPAs

Although 24/7 clean PPAs contracts are being increasingly announced, some barriers to their widescale adoption remain. There are five major barriers, perceived as very relevant by industry players (see Appendix B: Survey Responses): the lack of flexibility technologies, the lack of carbon accounting incentives and international certificates, the lack of standardization of 24/7 products, and their cost premium.

The lack of flexibility technologies (e.g., large-scale storage, hydrogen) is discussed extensively in this report and in previous LDES Council publications. How to overcome the lack of carbon accounting incentives (e.g., scope 2 emissions of GHG Protocol) and the lack of international certificate schemes (such as renewable energy certificates or guarantees of origin) with higher temporal resolution is described in Chapter V. This chapter explores the remaining two barriers: the lack of standardization of PPA products and quality as well as the cost premium.

The lack of industry-aligned definitions of 24/7 clean PPAs creates a significant barrier to consistently rewarding players that supply and procure 24/7 clean power

The benefits of 24/7 clean PPAs for the grid are notable, and as such, they are gaining traction in the industry, with a few key players already committing to round-the-clock clean energy procurement. The United Nations' 24/7 Carbon-Free Energy Compact is a noteworthy example of a joint effort by private companies and public organizations to advocate for such systemic change.

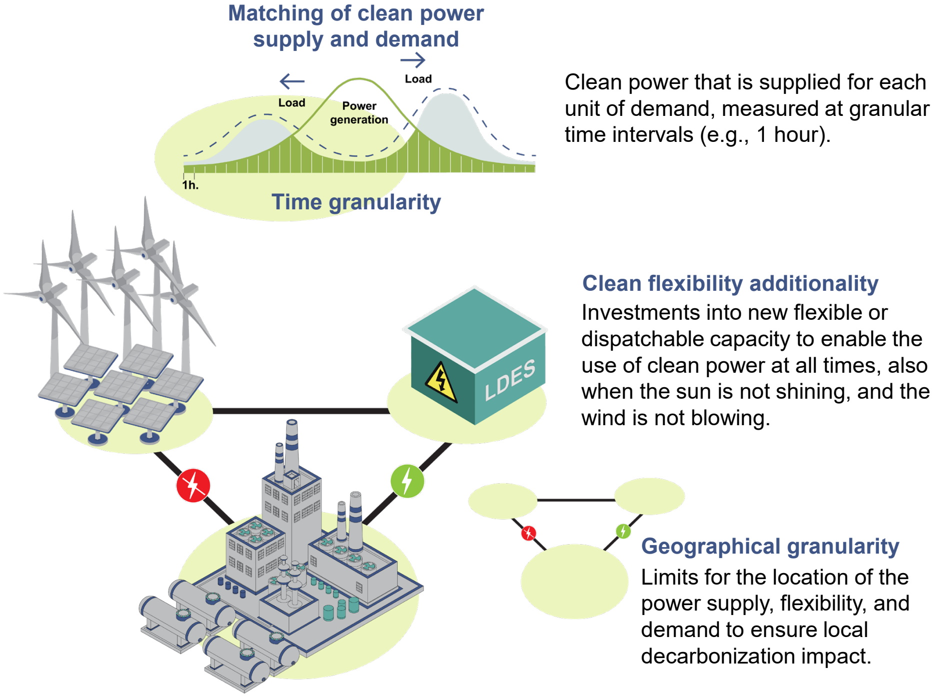
However, the lack of common understanding of these instruments is a significant barrier to their wider adoption. What does "24/7" mean? How about "clean power"? What is "best practice"?

To date, several questions across a set of key dimensions remain, namely:

- **Actual definition of 24/7:** what is the minimum accepted level of clean power that has to be supplied for each unit of actual demand? Considerations around extreme weather events and clean power sourced from the grid should also be discussed.
- **Technology pool:** which clean and dispatchable technologies apart from RES can be considered? The pool includes LDES, hydrogen turbines, geothermal power, small nuclear reactors, demand-side flexibility, and so on.
- **Clean capacity additionality:** what are the requirements on investments into clean generation projects, especially in the case of new loads being connected to the grid?
- **Time granularity:** what is the maximum time window when clean supply must match the load? Hourly time steps are the most standardized across markets, however, some markets have introduced shorter settlement periods (e.g., 5 minutes in Australia).
- **Geographical granularity:** what are the limits for the location of the load and the power supply?
- **Further system impact:** which complementary aspects that further drive grid decarbonization and optimization can be considered (e.g., impact on grid stability and reliability)?

Exhibit 5

Key dimensions of a 24/7 clean PPA



A lack of a common language and agreement on these dimensions has important consequences for suppliers and buyers alike. It limits investors' and capital markets' ability to recognize and reward players that want to go further than carbon offsets to increase their decarbonization impact, and it fails to reward players that go above and beyond the minimum requirements by driving technological innovation and making it easier for society to decarbonize.

Current commercial storage technologies require significant renewables overbuild and price premiums to provide a 24/7 clean power supply Lithium-ion (Li-ion) batteries have a limited ability to provide long-duration flexibility economically. Given that renewables output can be reduced for several hours, sometimes days, solutions based solely on RES and Li-ion are insufficient to cost-effectively cover high levels of time-matched procurement. For example, the levelized cost of electricity (LCOE) in 2025 of a system designed to provide 100% supply-demand matching would be 90-130% higher if the storage was provided only by Li-ion rather than also by LDES (Exhibit 6). As shown, with higher levels of matching, above 80%, LDES becomes key to reducing the overall cost.

Furthermore, there is a need to de-risk potential price variations and supply chain constraints to Li-ion batteries used for stationary applications, since electric vehicles represent the vast majority of battery demand.

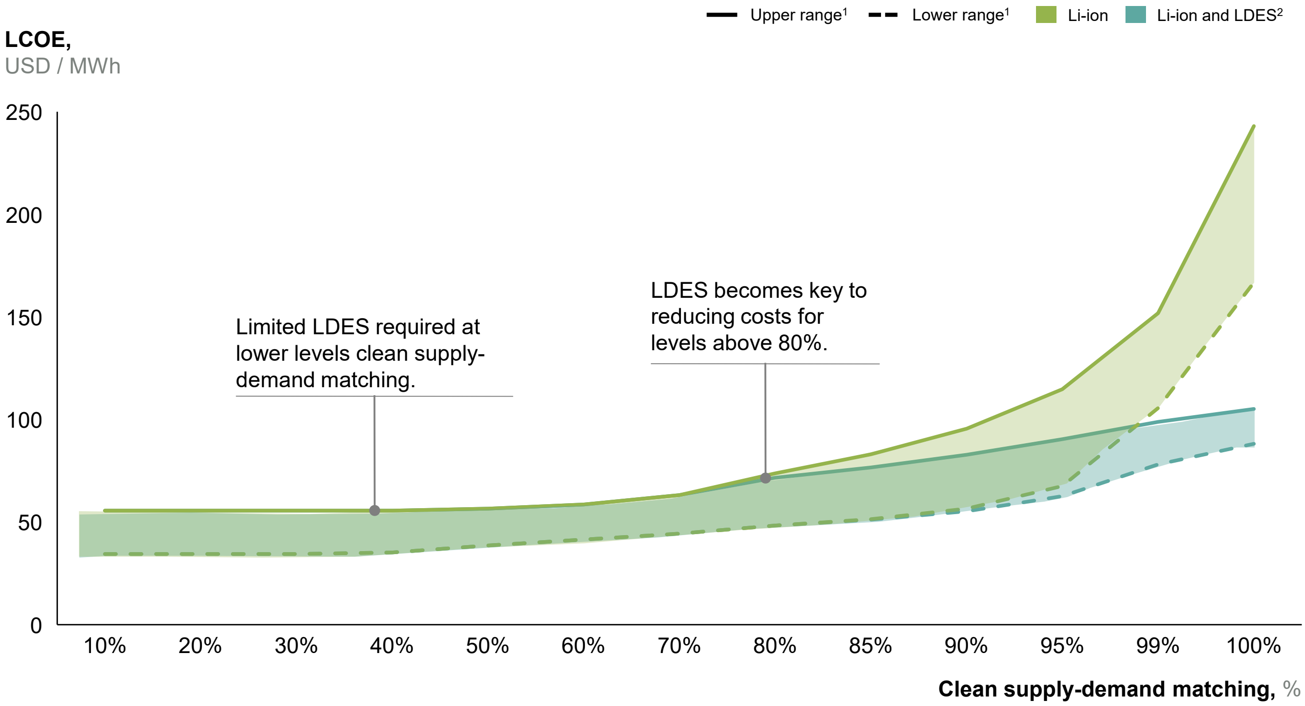
LDES technologies have the potential to enable cost-effective solutions and de-risk investments; however, they are still in the early stages of development and have to be deployed to accelerate learning curves. By 2040, LDES technologies need to have deployed 1.5 — 2.5 terawatts (TW) or power capacity and 85 — 140 terawatt-hours (TWh) of energy capacity[9] to realize their cost-reduction potential.

[9] "Net-zero power; Long duration energy storage for a renewable grid," LDES Council, 2021.

Exhibit 6

LDES is key to reducing the costs at high levels of matching

RES + Storage LCOE for different levels of clean supply-demand matching
2025



1. Based on modelling a baseload in locations with average (UK) and optimal (Australia) LCOE.
2. LDES 8-24h and 24h+ technologies.

Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

III.

Proposed quality assessment framework and implementation

24/7 clean PPAs are expected to play a key role in driving deep decarbonization of the grid. However, to realize their full potential, industry-aligned valuation of these PPAs is required to recognize players that drive systemic change through these contracts and to support adoption. To this end, a quality assessment framework within which the industry can define a set of ratings for 24/7 clean PPAs is proposed. The framework is structured around four quality ratings with growing level of ambition, where the lower bound sets the 'entry level' and the upper bound aims to define today's highest aspiration. Lastly, this section offers an overview of the key technical considerations for their implementation in various countries and with varying technology mixes.

Laying the foundation for a quality assessment of 24/7 clean PPAs

Having a global quality framework in place is the first step to ensure that corporates going beyond pure hedging strategies or annual-based carbon accounting are recognized for their efforts. This framework also provides a pathway to increase decarbonization through higher quality ratings.

A framework is proposed based on four quality ratings and requirements across five key dimensions

This framework aims to provide industry guidance and credit the decarbonization impact of 24/7 clean PPAs.

Given the variety of design options available, the proposed framework includes four levels or ratings — Entry Level , Silver, Gold, and Platinum — each with its own requirements. Both the Entry Level and Silver ratings cover contracts that switch the focus from annual-based to time-matched power procurement leading to greater grid decarbonization. The Entry Level aims at lowering barriers, especially for energy-intensive players, for increased adoption of 24/7 clean PPAs, while the Silver rating is designed for players that seek to further accelerate the transition and support new RES capacity deployment. The Gold and Platinum ratings acknowledge contracts with higher ambitions on load-matching and, consequently, drive further deployment of additional flexibility, including innovative storage technologies like LDES (Exhibit 7).

Exhibit 7

Procurement strategies vary based on corporates' decarbonization and risk appetite; 24/7 clean PPAs are optimal for full grid decarbonization

Corporate power procurement solutions by ambition level		**Conventional approaches**		**24/7 clean PPAs**	
		Optimized procurement, financial products	Conventional renewables PPAs, carbon offsets, unbundled EACs[1]	Entry level	Silver / Gold / Platinum
Decarbonization priorities		Meeting minimum regulatory requirements.	Compliance with recognized decarbonization targets and accounting standards.[2]	Procurement that leads to a 24/7 decarbonized grid.	Procurement that leads to a 24/7 decarbonized grid and goes beyond minimum requirements, supporting decarbonization by driving enabling technology adoption and scale-up.
Risk-management priorities	Power price risks	✓	✓	✓	✓
	Capital market risks		✓	✓	✓
	Carbon price risks			✓	✓
	Reputational risks				✓

1. Energy attribute certificates.
2. For example, the Greenhouse Gas (GHG) Protocol or Science Based Targets Initiative (SBTi).

The quality ratings are delimited by requirements on five key dimensions: the level of clean supply-demand matching, time and geographical granularity, and additionality of renewables and clean dispatchable capacity

The quality ratings look at the big picture, factoring-in all critical elements that work together to create optimal deals from a system perspective. Such elements have been synthesized into five key quality dimensions, each of which include eligibility requirements for the specific ratings (summarized in Exhibit 8).

Minimum level of clean supply-demand matching:

- **Definition:** load-weighted average of hourly clean electricity supply, calculated as:

$$Clean\ supply\text{-}demand\ matching = \frac{\sum_{t=1}^{8760} \min[Clean\ supply(t), Demand(t)]}{\sum_{t=1}^{8760} Demand(t)}$$

  Where 'Clean supply (t)' is the clean electricity delivered from the PPA designated assets (renewables and flexibility capacity).

- **Rationale:** the minimum requirements have been designed by taking into account what level wouldbe economically feasible today (Entry Level and Silver), as well as to set the right level of ambition that would drive the necessary technology deployments and eventually full grid decarbonization (Gold and Platinum). The specific implications of each of the required levels are described in the following report sections.

- **Remarks:** this requirement does not imply that the minimum level of clean supply-demand matching has to be met every hour of the year (i.e., there can be hours when the supply exceeds the minimum requirement and hours when the minimum requirement is not met, as long as the annual average is fulfilled). Furthermore, fulfilling the minimum requirements entails a certain oversizing of the RES supply as the renewables yield can significantly fluctuate across years.

Time granularity:

- **Definition:** measurement interval used to calculate the minimum level of supply-demand matching.

- **Rationale:** the threshold has been set at one hour for all the quality ratings, as this is the most standardized time-step across markets. While lower time steps such as the minimum settlement period could increase 'round-the-clock' decarbonization credibility, they could also disincentivize 24/7 clean PPAs in markets with shorter settlement periods or over-constrain the solution space.[10] The time granularity could evolve towards shorter periods as markets move in this direction.

Geographic granularity:

- **Definition:** limits to the location of the supply, flexibility, and the load.

- **Rationale:** 24/7 clean PPAs should accelerate the decarbonization of the grids where the loads are connected, and truly reflect congestion issues. Therefore, load, flexibility, and supply should at least be connected to the same bidding or balancing zone, whichever is broader.

- **Remarks:** the overarching design principle of this dimension is to encourage deployment of assets in grids where the off-taker is located in optimal locations from a system standpoint without imposing a requirement for physical delivery, which is not possible in all markets. The key factor influencing optimal location is grid constraints, but how this is accounted for varies by market design. For instance, in nodal electricity markets (such as ERCOT in the United States) that reflect congestion in price signals, the geographical granularity could be defined to the settlement point which can ensure sufficient market liquidity and enable buyers and sellers the share the risks of delivering the power. Furthermore, storage should be ideally located in grid locations where it could minimize grid congestions where relevant (e.g., co-located with RES) (although this is not a requirement).

[10] Due to, for instance, limiting the portfolio to technologies with fast ramp-up capabilities.

Renewables additionality:

- **Definition:** requirements on investments into new clean capacity, like variable renewables such as wind and solar.[11]
- **Rationale:**
  - So Silver, Gold, Platinum: the signing of 24/7 clean PPAs should eventually lead to the deployment of new clean capacity on the grid. Therefore, it is required that Silver, Gold, and Platinum PPAs lead to a net clean capacity increase in the system. Repowering assets could also count towards the additionality requirement, provided there is a net clean capacity increase.
  - Entry Level: in recognition of the fact that some renewables would benefit from these PPAs at the end of previous support schemes or offtake contracts, the Entry Level rating allows for existing, subsidy-free RES assets to qualify.
  - To ensure the electricity consumption is actually clean and not based on a certificate-only approach, all ratings require the purchase of bundled EACs with physical power.[12]
- **Remarks:** 24/7 clean PPAs solutions should be technology-agnostic; the RES additionality requirement applies only when renewables are part of the solution.

Clean flexible or dispatchable capacity additionality:

- **Definition:** requirements on investments into new clean flexible capacity, including storage, dispatchable generation (e.g., hydropower, biomass, hydrogen), or demand-side flexibility.
- **Rationale:**
  - Silver, Gold, Platinum: 24/7 clean PPAs with high levels of demand-matching naturally demand flexible capacity to improve the economics of the contract. Given the need for system flexibility, and the need to accelerate the learning curves of many of these solutions, all ratings from Silver and above require all the used flexible capacity to be additional (i.e., leading to a net increase in clean flexible or dispatchable capacity in the system).
  - Entry Level: for Entry-level PPAs, the designated clean flexible / dispatchable capacity should not be older than 10 years. This measure intends to incentivize the deployment of new flexibility on the grid to accommodate the increasing renewables penetration on grids.
  - All ratings: upgrades and retrofits would also qualify to the extent that these result in a clean capacity addition,[13] with the caveat that specific rules need to be designed to truly favor optimal system solutions (and avoid projects carrying out only minor retrofit activities to meet the requirements). Investments in batteries' cells replacements after their degradation would also qualify. On the contrary, standard maintenance work would not meet the minimum conditions, as this would not support the ultimate goal of adding new capacity to the grid.
- **Remarks:** similar to RES additionality, this requirement only applies when flexibility or dispatchable capacity is part of the asset portfolio.

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[11] Also includes non-dispatchable clean capacity like nuclear. Excludes dispatchable assets like hydro, which in this report is classified as flexible capacity.

[12] This requirement could be reconsidered in the future, provided that the certificate markets mature towards higher temporal granularity, establish reasonable geographical / market limits and correctly reflect the needs of the power system.

[13] Including fossil-based power plants retrofitted to generate clean-based electricity (e.g., gas power plants to operate with clean hydrogen) or installation of new generation capacity in legacy / decommissioned hydropower reservoirs.

Exhibit 8

Requirements for each of the quality ratings across the five quality dimensions

Quality dimensions	Entry level	Silver	Gold	Platinum
Minimum level of clean supply-demand matching, MWh / year	80%	80%	90%	>98% (approaching 100% in standard weather years)
Renewables additionality	No requirement (i.e., post-subsidy renewables can qualify)	← If renewables are part of the final system design, 100% of the capacity needs to be additional (including repowering)[1] →		
Flexible / dispatchable capacity additionality[2]	Designated capacity cannot be older than 10 years	← If flexibility / dispatchable capacity required, 100% of the capacity needs to be additional (including upgrades and retrofits)[1] →		
Time granularity	← 1 hour →			
Geographical granularity	← Bidding or balancing zone (whichever is broader) →			

1. To the extent that this results in a net capacity increase in the system, including overhaul of Li-ion storage resulting in an increase in available capacity.
2. Includes dispatchable generation capacity, e.g., hydro power.

Technology deployment, costs, and decarbonization impact of quality ratings

As discussed in Chapter II, a major challenge for 24/7 clean PPA adoption today is the cost premium. The proposed quality ratings help create a transition pathway with incentives to scale-up storage deployment and thus accelerate learning effects for novel flexibility solutions like LDES. This section explores the impact that committing to these quality ratings would have on PPA costs, flexibility capacity deployed, and grid emissions.

Note on the methodology

The following analysis provides indications on expected cost levels for different geographies and customer types. It is based on modeling the least-cost portfolio of renewables and storage to meet the desired level of clean supply-demand matching for a given load profile (i.e., a 100 MW baseload unless otherwise specified). The analysis is based on one average weather year and ignores planned and unplanned maintenance. Thus, the resulting cost levels should be treated as indicative. See Appendix A for details on the methodology and assumptions.

Two key cost metrics for a 24/7 clean PPA are considered (illustrated in Exhibit 9):

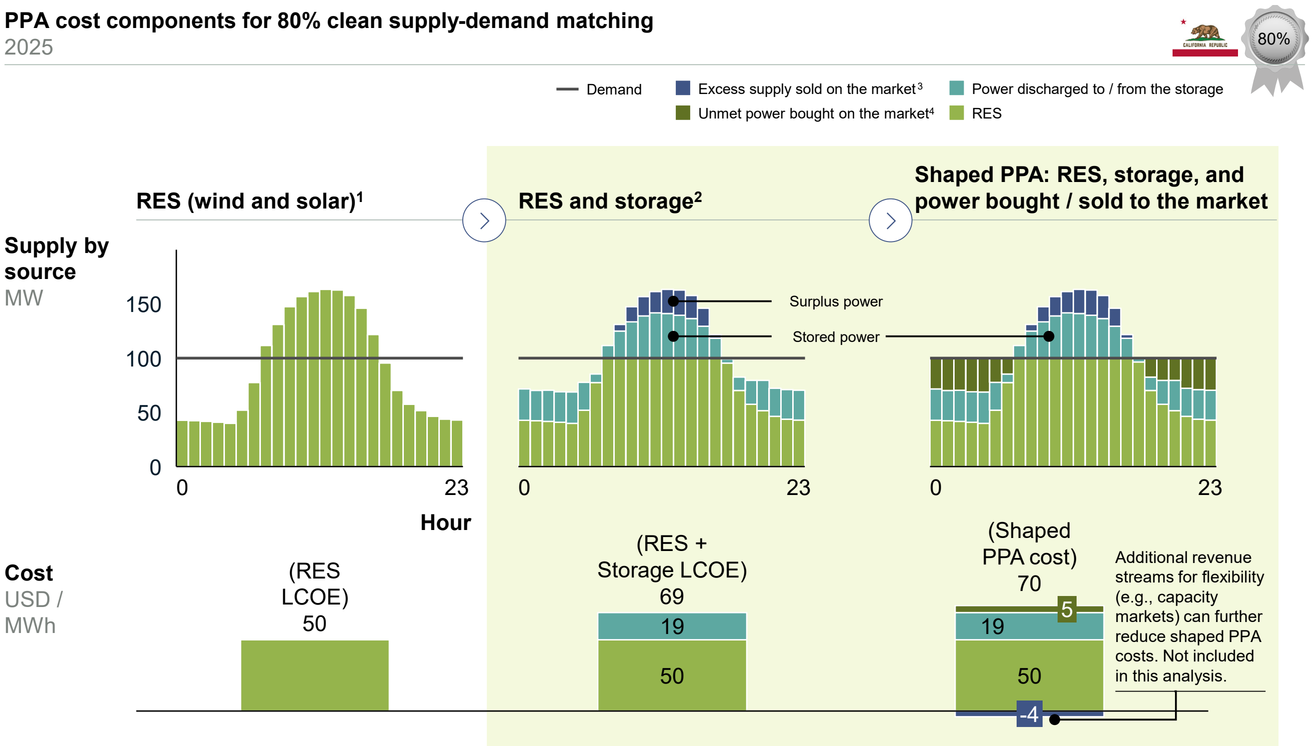
1. **The levelized cost of renewables and storage, herein referred to as "RES + Storage LCOE":** this cost metric reflects the underlying capital expenditures (capex) and operating expenses (opex) of the renewables and storage deployed to meet the clean supply-demand matching requirements.
2. **The final PPA cost, excluding margins, referred to as "Shaped PPA Cost":** this cost metric builds on the RES + Storage LCOE by incorporating additional cost and revenue components that impact the overall PPA economics. Such components include power bought on the market when renewables generation is not sufficient, and revenues from excess generation sold to the grid. In addition, it includes revenues from capacity mechanisms where relevant. Other revenues from optimizing the operation of the flexibility assets based on market signals could be factored-in (see Chapter IV), although they haven't been considered in this chapter.

While the Shaped PPA Cost is a better proxy for the total cost of ownership from an off-taker point of view[14] the LCOE of RES + Storage is the key metric of interest. The former reflects better the final PPA price by taking into account the power bought and sold to the market (excluding the seller margin). The latter represents the cost component that would most greatly benefit from the learning-curves and scale effects of energy storage further enabled by 24/7 clean PPAs.

[14] RES + Storage LCOE or Shaped PPA Cost do not include the margin of the seller.

Exhibit 9

The Shaped PPA Cost consists of renewables and storage LCOE, and cost balance of buying and selling power to the grid



1. Calculated as total costs over energy delivered by solar and wind.
2. Calculated as the total cost of the capacity mix divided by the energy delivered by the renewables and the storage.
3. Surplus power from PPA RES assets sold to the day-ahead market. That excess is assumed to be sold during the average price for cheapest % of hours (where % of hour is equal to the % of time that there is excess generation).
4. Power bought 20% of the hours when supply from low-carbon sources is unable to meet demand. The price at those hours is assumed to be the price of the 20% most expensive hours (as met by peaking assets).

Technology developments are expected to drive significant LCOE improvements

The LCOE of the renewables and storage is expected to decrease over the next years as the maturity of the technologies increases, due to optimized designs and efficiency, learning from volumes, and manufacturing and supply chain improvements. For instance, for LDES technologies the learning rates are expected to be in the 12-18% range, with variations across the different technology categories.[15] Nevertheless, the learning rates across technologies — including Li-ion — are highly sensitive to raw material costs and demand.

For example, the LCOE for PPAs fulfilling different quality ratings in California can decrease around 40% from 2025 to 2040. The decrease in the first years is expected to be more pronounced driven by optimized technology designs. The cost-decrease rate over the next decade would be then mainly driven by volume effects, like optimized supply chains, and continued technological improvements. Similar trends are expected across other geographies, with variations also partly due to different renewables potential (Exhibit 10).

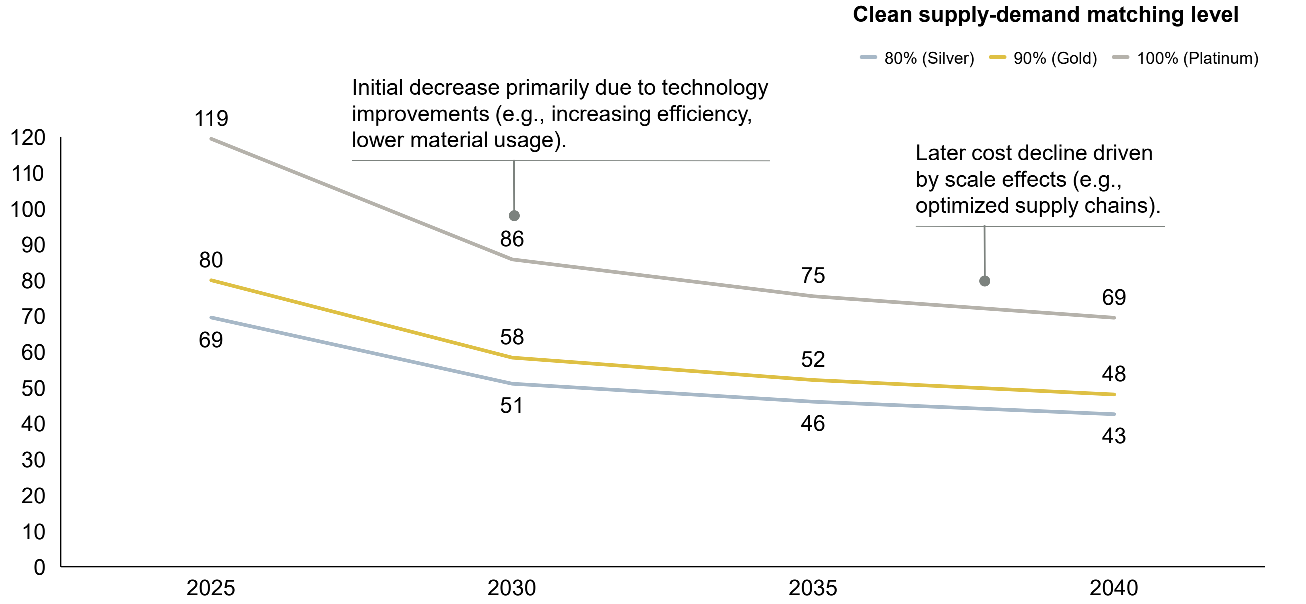
[15] "Net-zero power; Long duration energy storage for a renewable grid," LDES Council, 2021.

Exhibit 10

RES + Storage LCOE to decrease as LDES technologies mature

RES + Storage LCOE[1] for 100 MW baseload 24/7 supply in California over years

USD / MWh



1. RES + Storage LCOE is calculated as: (annualized cost of renewable generation + storage capacity) / clean energy delivered to the off-taker. This excludes additional costs / revenues that would impact final PPA price.

Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

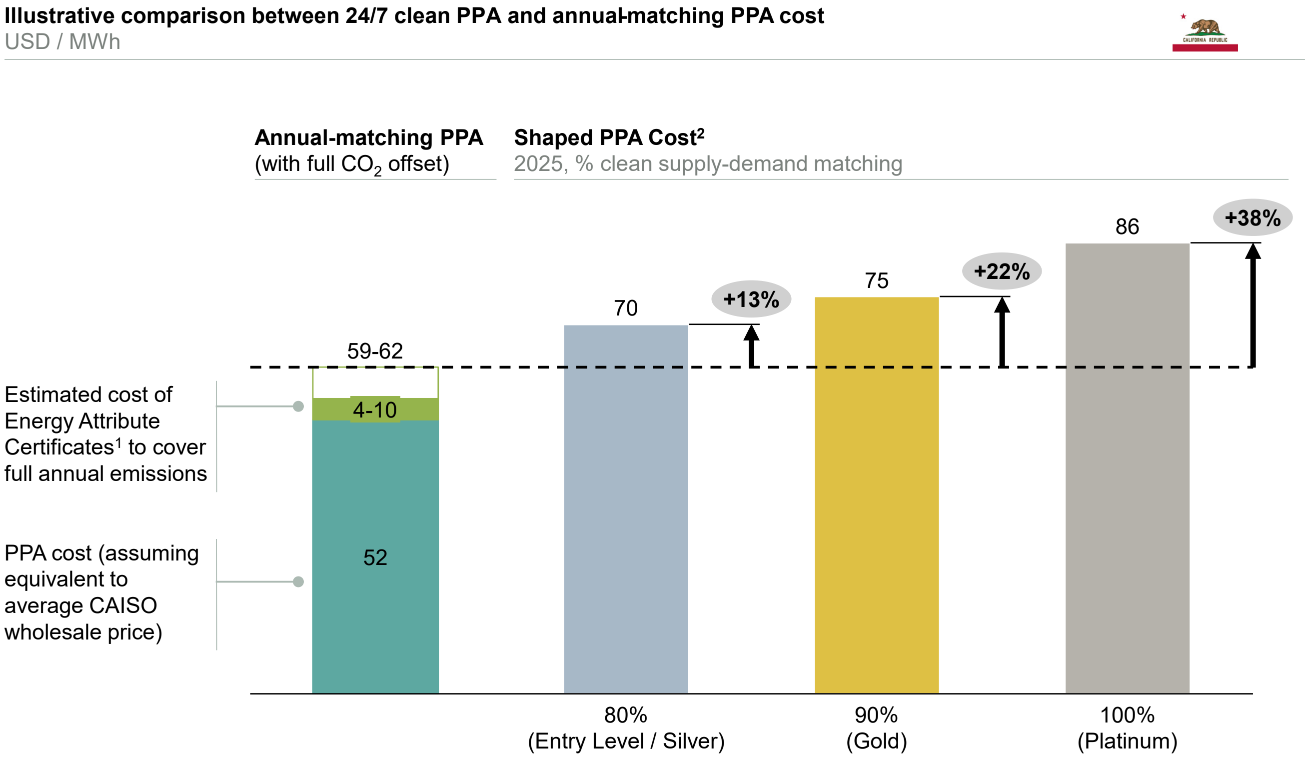
In the near-term, the Shaped PPA Cost premium relative to the average market price and clean power certificates would lie in the range of 10% to 50% for the different PPA quality ratings

When compared to today's average wholesale market and EAC prices in California, a Silver PPA in 2025 can result in a 10 — 15% cost-premium. The premium cost associated with Gold requirements would be lie in the range of 20 — 30%. If the level of supply-demand matching targets Platinum requirements — or is close to 100% — the estimated cost premium would rise to nearly 40 — 50%. LDES is included in the cost-optimal technology mix in all cases (Exhibit 11).

The lower exposure to wholesale market prices — especially in the recent trends of high spot prices — and the higher decarbonization impact that these PPAs deliver, result in these cost levels being attractive. In addition, other revenue streams could further improve the relative 24/7 clean PPA economics. These include the optimal use of surplus generation besides selling power to the market (e.g., in secondary markets). Furthermore, in the mid-to-long term the premium is expected to be lower or even zero due to decreasing technology costs and rising commodity and carbon prices.

Exhibit 11

Cost premium for 24/7 clean PPAs — example CAISO



1. Based on historical 2020-21 REC auctions, California Public Utilities Commission.
2. Excluding revenues from selling surplus Energy Attribute Certificates.

24/7 clean PPAs can offset 80% to 100% of carbon emissions while solar and wind pay-as-produced PPAs meeting 100% of a corporate's consumption would only offset a fraction of that

The reduction in emissions intensity of a corporate's load with an Entry Level / Silver, Gold, or Platinum PPA, would be 80%, 90%, and 100% respectively (compared to the average of the grid to which the load is connected).

This compares to the actual emissions-intensity reduction if the load is supplied by a pay-as-produced PPA meeting the annual power consumption of a load. Exhibit 12 illustrates above example of baseloads in Germany or California, supplied by conventional solar or wind pay-as-produced PPAs. As shown, the average emissions intensity would only be 40% to 50% lower than the grid average for solar contracts, and of 60% to 70% lower for wind.

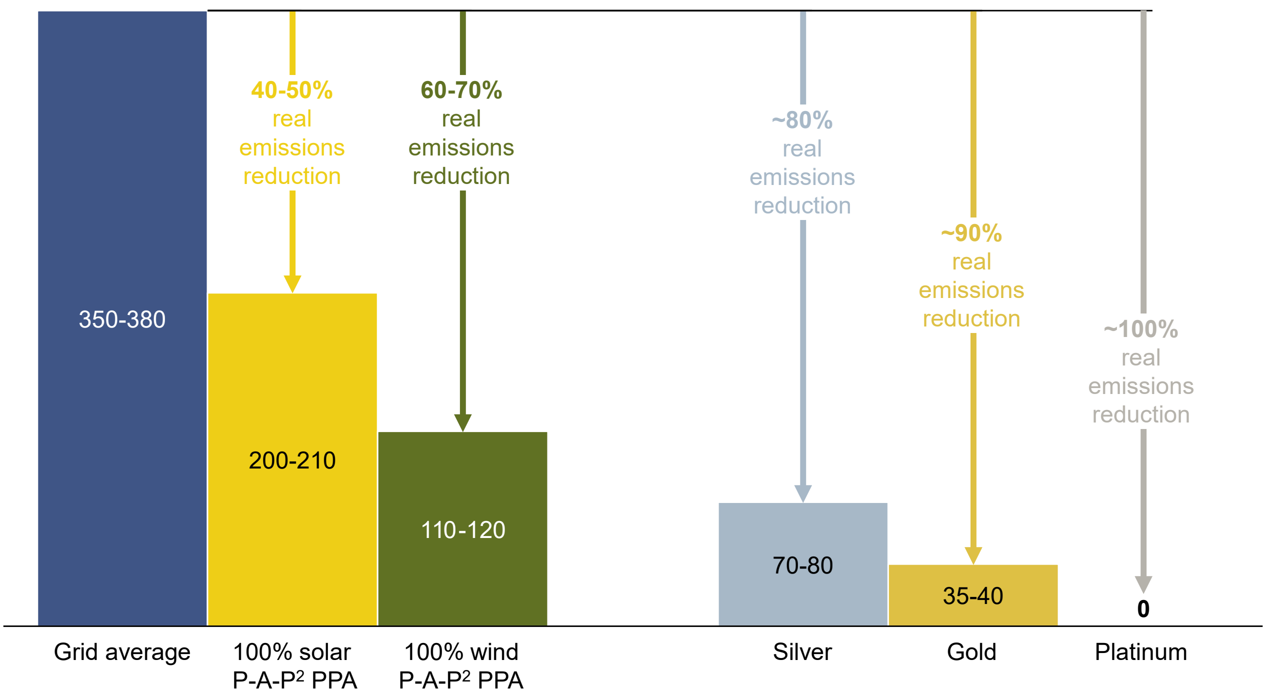
Furthermore, if the 2020 volume of 25 GW of corporate PPAs (see PPAs 101 at the beginning of the report for more details) switches to Platinum rating, this would result in more than 12 million tons of CO_2eq reduced per year (excluding additional system-level benefits, see Chapter IV).

Exhibit 12

Emissions intensity of different power procurement options including 24/7 clean PPAs

Emissions intensity of different power procurement options [1]

gCO$_2$eq / kWh



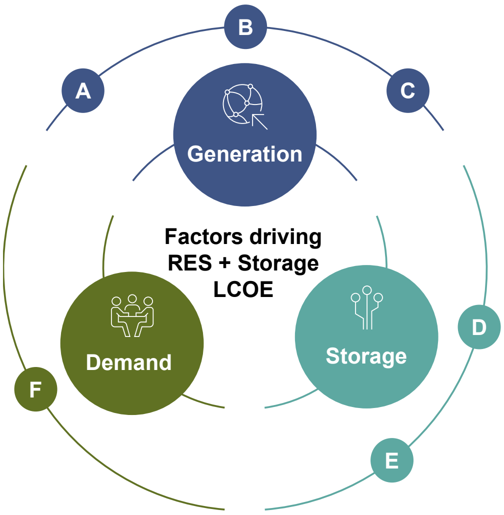
1. Based on 2021 average grid emissions and RES generation data for Germany and California. Emissions intensity of the grid and win PPA: lower range applies to Germany (offshore wind), and upper range to California (onshore wind). Emissions intensity of solar PP/ lower range applies to California, upper range to Germany.
2. Pay-as-produced.

Technical considerations for implementation

The technical implementation and resulting cost of 24/7 clean PPAs depend on several factors linked to generation, storage, and demand. This section presents detailed modeling results and sensitivity analyses across these factors (Exhibit 13).

Exhibit 13

Factors that impact the system LCOE



Generation

A Location of project

Generation profile of RES in the region.

B Weather events deviation

Deviations in power output due to unexpected weather.

C Portfolio aggregation

Aggregated projects across larger geographic areas smoothen the variability of RES supply.

Storage

D Storage mix

Impacts the capex, mainly if only Li-ion or Li-ion and LDES is used.

E Technology-specific cost characteristics

Possibility for asymmetrical charge / discharge capacities (and relative capex required) allows for optimal system configuration.

Demand

F Shape of the demand

Impacts the supply-demand correlation and eventually the need for storage and overall capex.

These are technical drivers. The impact of other drivers (e.g., cost of capital, additional revenues) has not been evaluated.

Generation

There are three major cost drivers linked to the generation side of the PPA: A) the project location, B) the frequency of extreme weather events, and C) the potential for power supply aggregation. These are further described below:

A. Project location: the availability of wind reduces the need for LDES as the generation profile is more stable

The project location determines the availability of renewable resources: factors such as solar irradiance and wind speed are location-dependent, and they in turn influence the amount of storage and the technology required to offset renewables variability. Such variability widely differs by source, with offshore wind having the lowest output fluctuation, up to 20% from hour-to-hour, compared to solar PV where fluctuation can be as much as 40%.[16] Similarly, when looking at the annual capacity factors[17] of the different renewable sources across geographies, significant differences can be found: solar PV ranges from 10% to more than 30% in regions with high irradiation such as California; onshore wind typically oscillates from above 20% up to 45% in regions rich in onshore wind; and lastly, offshore wind varies between 30% to more than 50% across countries (like for example, the UK or Germany). In addition, these factors could be further improved over time following technical developments.

Consequently, the location of the project can have a significant impact on the overall PPA cost. For example, a 100 MW baseload in the UK with a Platinum 24/7 clean PPA supplying 100% of the load with solar PV, would have an LCOE more than 2.5 times higher than a similar

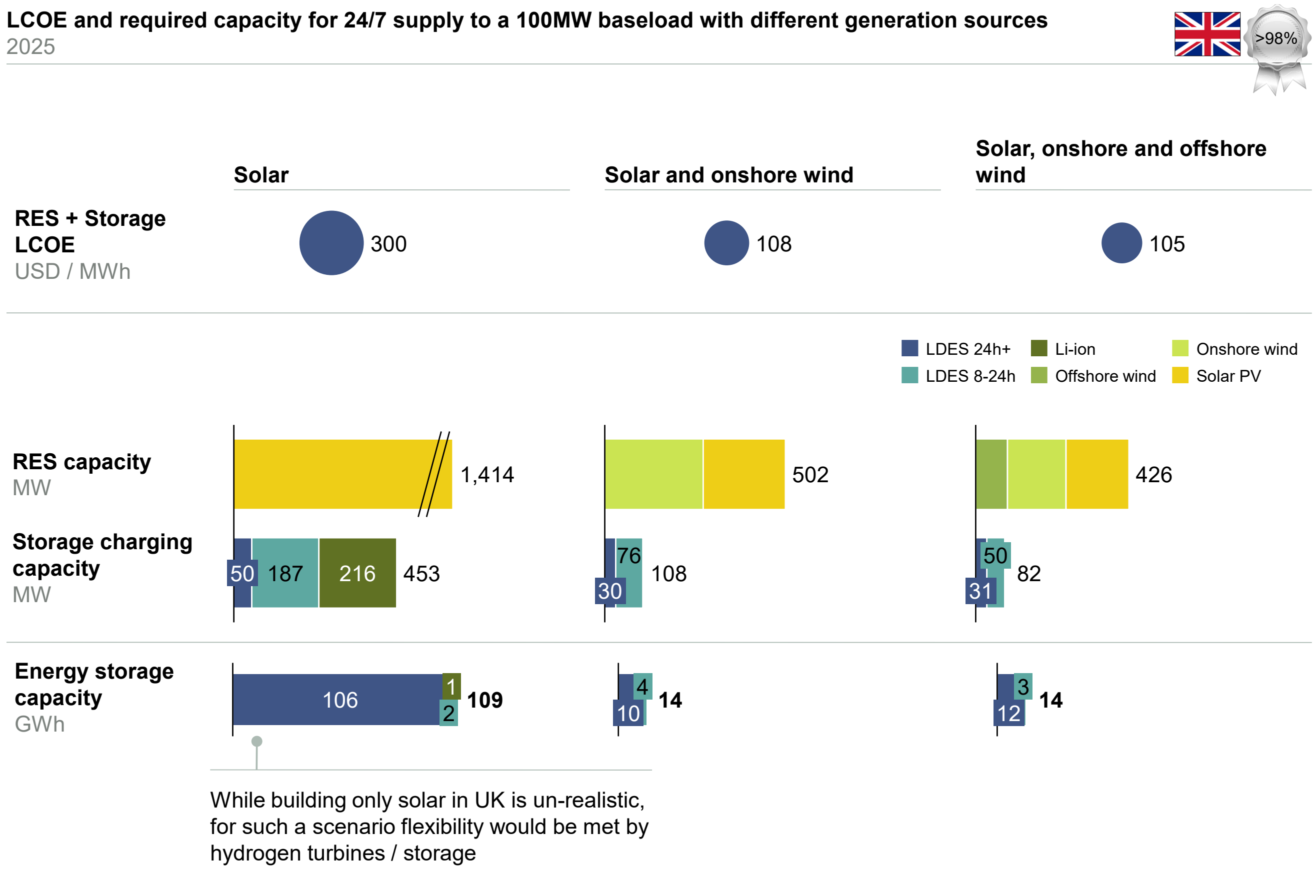
[16] "Offshore Wind Outlook 2019," International Energy Agency (IEA).
[17] A capacity factor measures the fraction of time that the power plant runs during a specific period.

contract that also includes onshore and / or offshore wind in the capacity mix (from more than 270 USD per MWh down to 108 or 105 USD per MWh, respectively). This is the result of higher storage needs to shift the energy from day to night hours (Exhibit 14).

The most economical solutions involve mixing assets with complementary generation patterns like solar PV and wind, and storage. This creates some barriers as suppliers are often not specialized in all required technologies. Nevertheless, this could be addressed by

Exhibit 14

Impact of the supply sources on the LCOE and system capacity mix (including purely hypothetical solar-only setup)



Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

involving intermediators or by suppliers contracting out missing elements (e.g., by pay-as-produced or lease contracts).

B. Weather events: unusual weather events result in reduced renewables output leading to oversizing the storage and to a higher LCOE

Unusual weather events cause deviations in projected RES supply, resulting in the need to adjust the capacity mix to cover such events (oversizing) and to meet the load-matching requirement. Such weather events, which can take the form of tropical and winter storms in California or dark doldrums in Germany, can cause solar and wind generation to be disrupted for days. Furthermore, climate change — in addition to direct impact on human lives and nature — may increase the frequency of such weather events. According to the latest

Assessment Report[18] by the United Nations Intergovernmental Panel on Climate Change (IPCC), extreme precipitation is projected to increase at global warming levels exceeding 1.5° Celsius in nearly all regions.

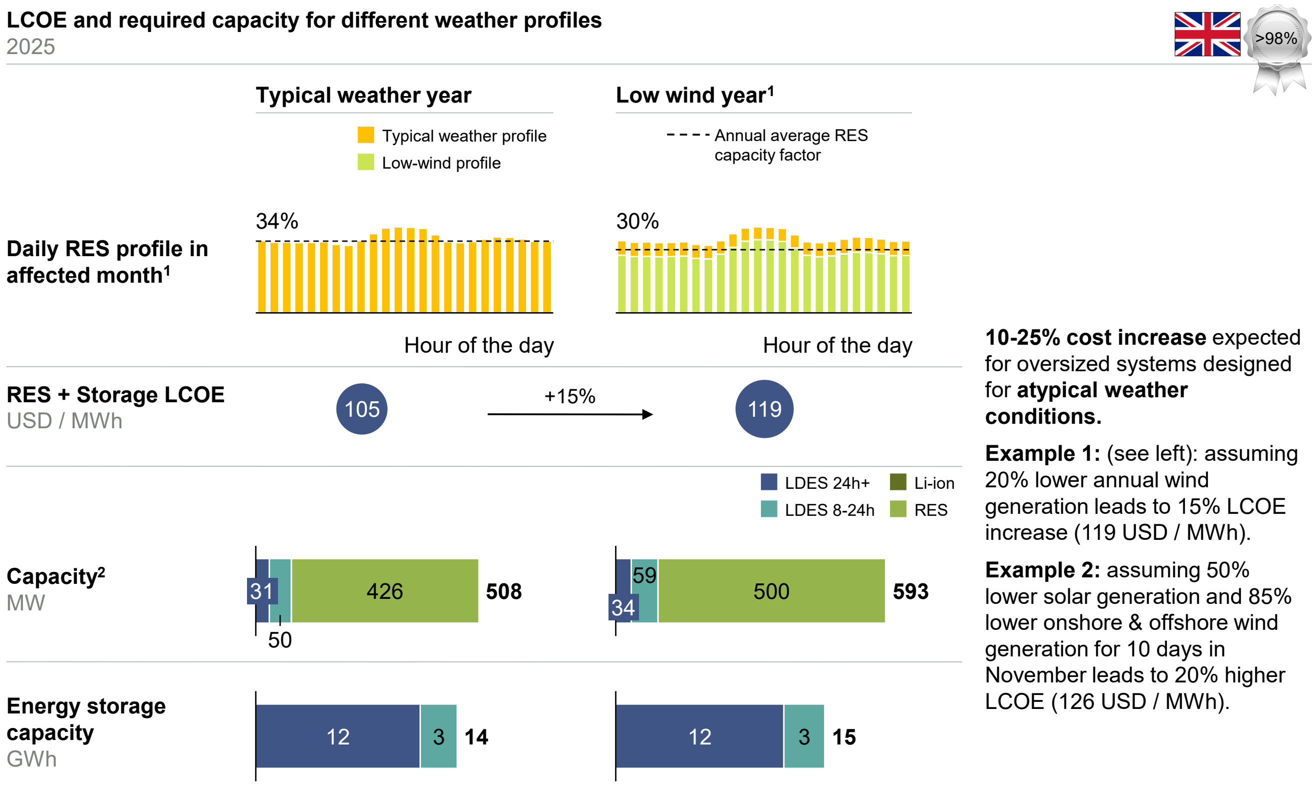
Because the minimum level of clean supply-demand matching must be met throughout the contract's duration, including unusual weather years, the LCOE rises due to the need to oversize the system capacity. The impact of an unusual weather event is depicted in Exhibit 15 below. This example shows the impact of an entire year with 20% less onshore and offshore wind generation in the UK. Such an event would result in increased capacity needs and in 10% increase in the technology-related costs. Furthermore, in preparation for extreme weather years with lower solar and wind generation, higher levels of 24+h LDES storage would be deployed to effectively assure reliable supply.

C. Portfolio aggregation: optimizing the supply portfolio can reduce the LCOE by creating a smoother renewables generation profile and reducing the storage requirement

[18] "Climate change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change," IPCC, 2021.

Exhibit 15

Impact of an unusual weather year on the LCOE and system capacity mix



10-25% cost increase expected for oversized systems designed for **atypical weather conditions.**

Example 1: (see left): assuming 20% lower annual wind generation leads to 15% LCOE increase (119 USD / MWh).

Example 2: assuming 50% lower solar generation and 85% lower onshore & offshore wind generation for 10 days in November leads to 20% higher LCOE (126 USD / MWh).

1. Wind generation (both onshore and offshore) across entire year reduced by 20%.
2. Charge capacity for storage.

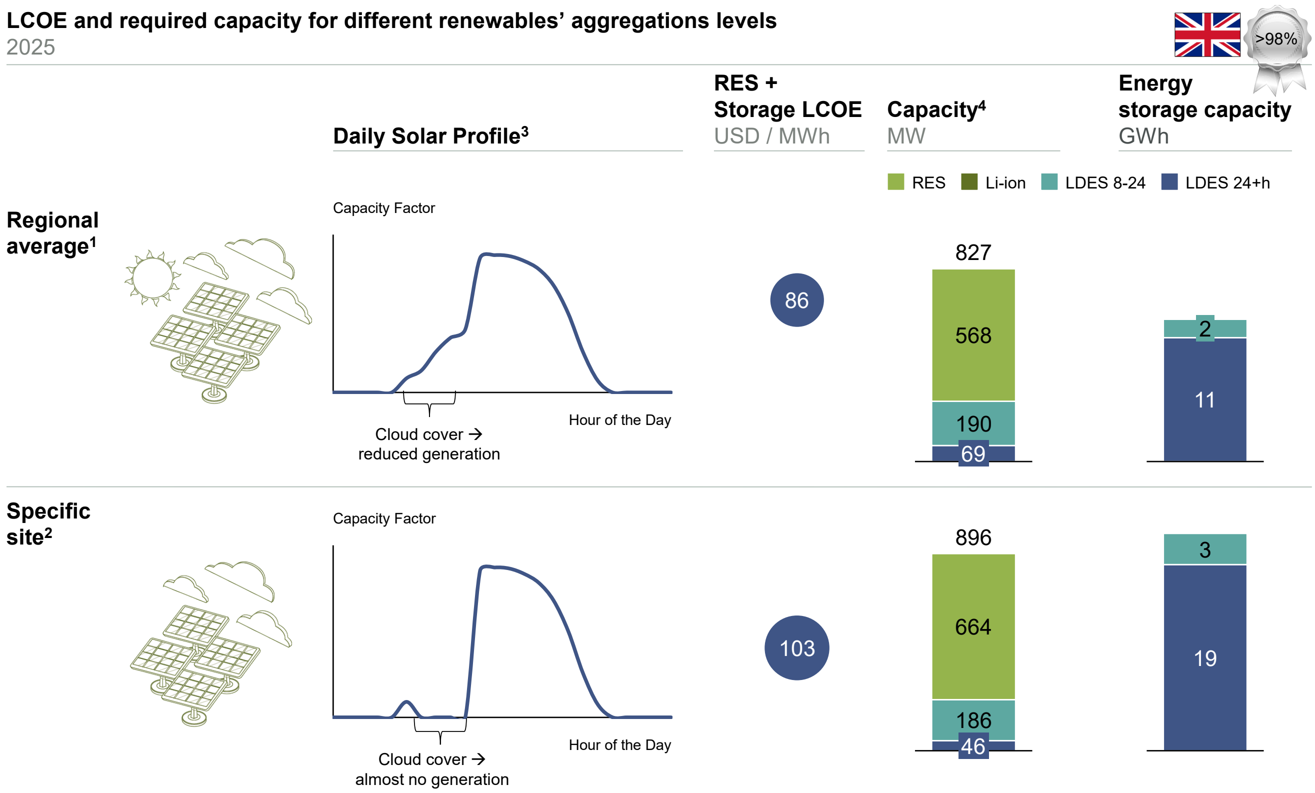
Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

The aggregation of RES supply over a larger geographic area reduces the risks of local events reducing renewables supply to the load and creates a smoother generation profile. This is due to the fact that a scarcity of renewables yield in one region can be compensated for by its availability in another region at the same time, assuming that these are well interconnected.

Because of this, using designated assets from a specific site only is more costly than an optimized portfolio across sites, and requires additional RES and storage capacity to cover times of local 'under-supply'. When modelled using the a specific site rather than a regional aggregation, the LCOE for the California case increases by 20% due to higher generation and storage capacity build-out (Exhibit 16).

Exhibit 16

Aggregation impact on the on the LCOE and system capacity mix



1. Regional average represents an average profile of 5 regions in California.
2. Specific site is modelled with generation profiles of Alta Park Wind farm and Desert Solar farm in California.
3. Profile shown is illustrative.
4. Charging for storage.

Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

Storage

There are two major cost drivers related to storage technologies, classified in: D) the technology mix, and E) the symmetry of storage charge and discharge capacities. These are further described below.

D. The storage mix: LDES is key to reducing costs of 24/7 clean PPAs at high levels of supply-demand matching, especially compared to using only Li-ion batteries

Levels of matching above 80% require assets that can supply clean power reliably for long periods of time. Given the natural intermittency of renewables, 24/7 clean PPAs are only efficiently delivered if flexibility or clean dispatchable capacity is part of the technology mix. Moreover, the different technical and financial characteristics of the technologies impact the optimal asset portfolio to deliver 24/7 clean power. Li-ion batteries have a limited ability to provide long-duration flexibility economically as their energy storage capex increases in a linear relationship to duration. This contrasts with LDES technologies, which generally have higher power capacity capex but can increase energy storage capacity at a low cost, allowing for scalable duration.[19]

In the case of a 100 MW baseload in 2025 in California, the LCOE can decrease from 8% to 12% for a Silver and Gold PPA respectively, if the system adds LDES to the Li-ion and renewables system. If the load holds a PPA with Platinum matching requirements, the LCOE can be more than 15 USD per MWh higher with Li-ion only than if LDES is leveraged. In addition, the 'Li-ion only' solution would be highly inefficient for the system, with excessive RES installed leading to 175%[20] surplus generation (Exhibit 17).

E. Technology-specific cost characteristics: the choice of asymmetrical charging / discharging capacities can drive down the LCOE

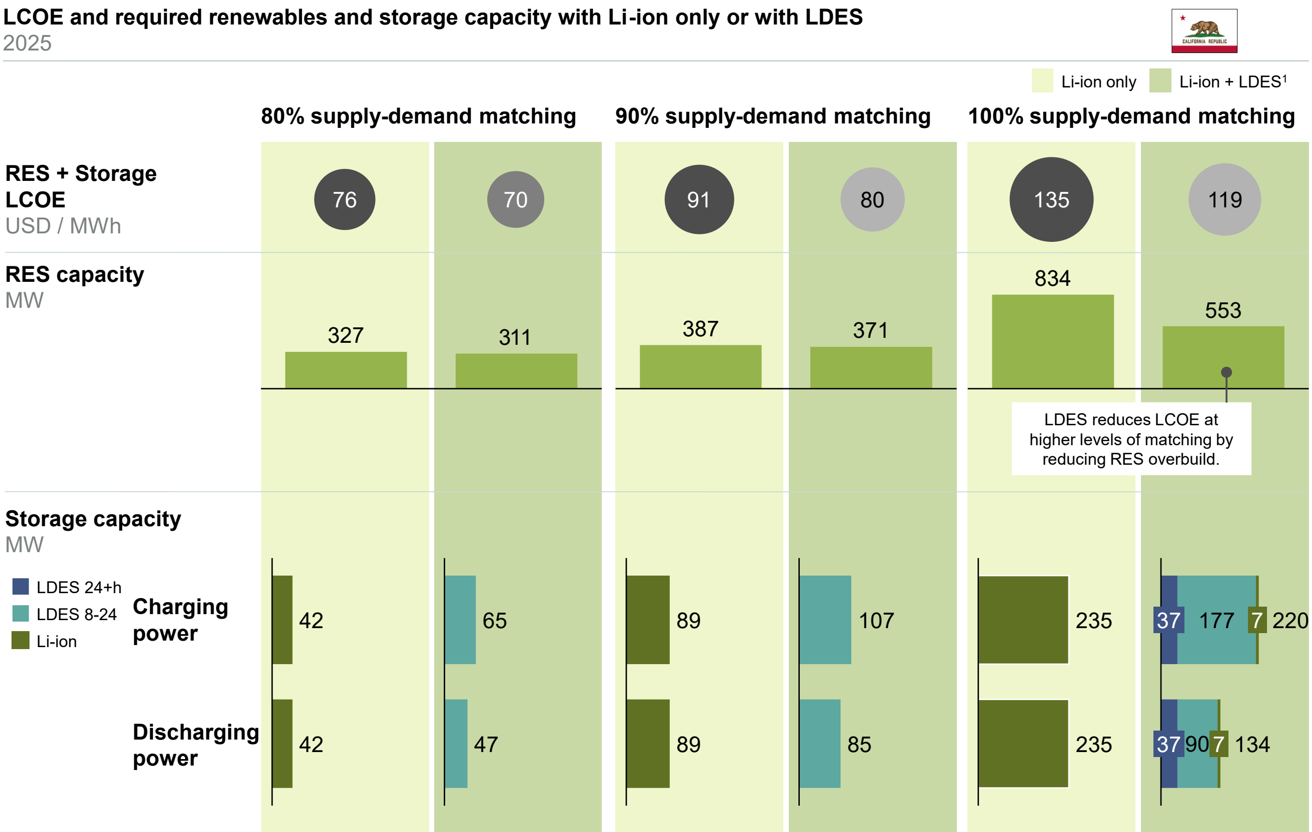
The design of asymmetrical capacities for the charging and discharging equipment also has an impact on the final system design and operation, and consequently on the cost. For example, in a compressed air storage system, the compressor used to charge the storage can have a different capacity than the turbine to discharge the power. Commonly the LDES charging capacity is higher, so the system can capture renewables peak production hours. This characteristic is intrinsic to many LDES technologies, particularly thermal and mechanical and to a lesser extent, electrochemical technologies.

Exhibit 18 depicts the difference in LCOE in 2025 for a 100 MW baseload in California. As shown, an asymmetrical design can lead to lower LCOEs for Gold and Platinum PPAs than if the system is symmetric. In this specific example, the underlying LCOE for a Platinum PPA would be 5 USD per MWh lower. This impact is even more pronounced for those technologies for which the capex (per MW of capacity) of the charging components is lower than the discharging system.

[19] "Net-zero power; Long duration energy storage for a renewable grid," LDES Council, 2021.
[20] Calculated as the amount of excess generation after meeting the load requirements. Excess generation occurs in hours with high solar and wind generation (morning and afternoon). Higher RES capacity buildout is required with Li-ion only due to its reduced capacity to shift bulk generation.

Exhibit 17

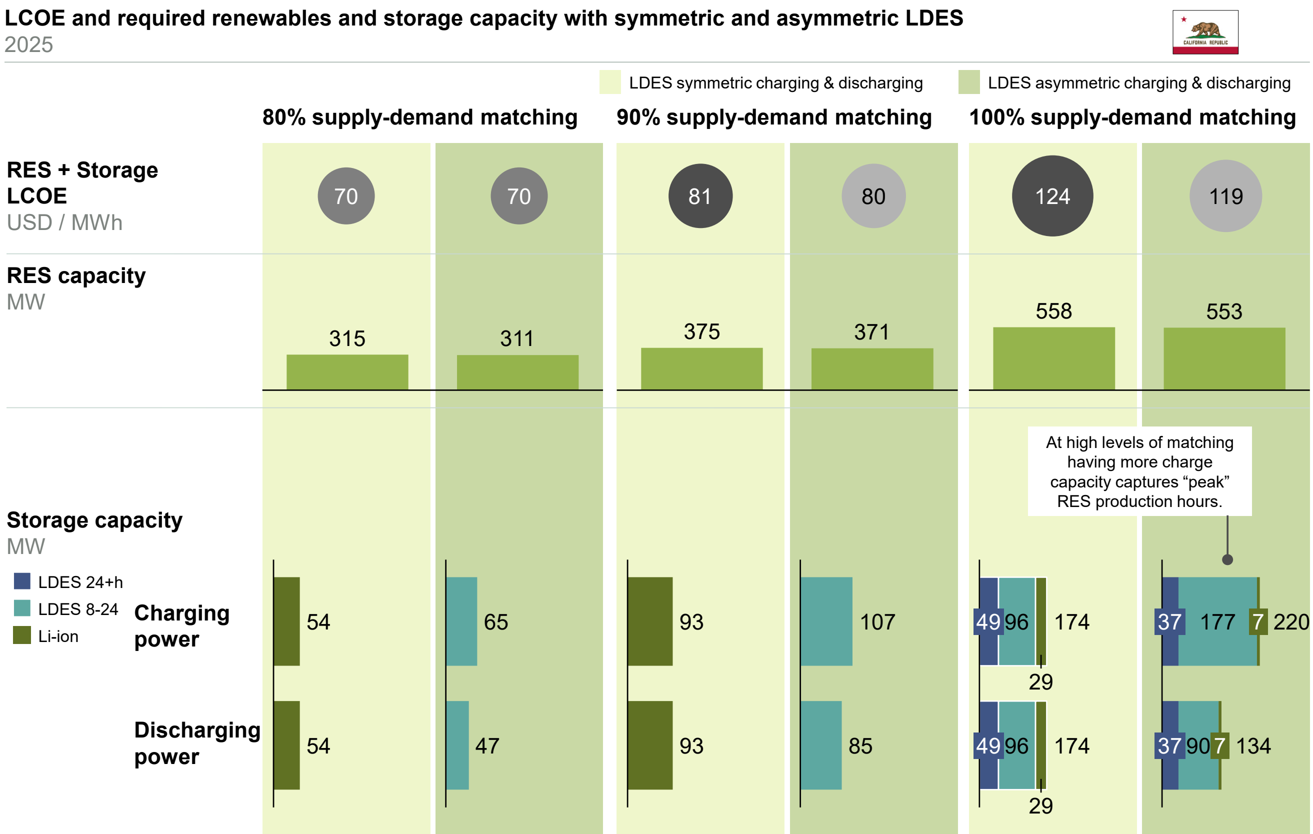
Impact of storage technology on the LCOE and system capacity mix



1. LDES 8-24h and 24+h technologies.

Exhibit 18

Impact of LDES charge/discharge capacity symmetry on the LCOE and system capacity mix



Demand

F. Shape of demand: when the load and the renewables profiles are aligned, less storage is required to shift energy, resulting in a lower LCOE

The amount of energy that has to be shifted in time to meet the PPA requirements is highly dependent on the adequacy of the supply generation profile and the demand profile. As previously stated, the former is dependent on renewable energy resources and project location. Certain areas, such as California or India, are 'solar dominant,' meaning that the solar yield exceeds the wind yield due to geographical and meteorological conditions. This results in a supply profile in which generation is concentrated during daylight hours. In contrast, there are 'wind dominant' regions, such as the UK, where the supply profile is dominated by wind speeds that are more stable throughout the day.

In solar-dominant regions, power generation during the day would be more time-correlated with demand archetypes defined by electricity consumption during the day. This archetype is referred to as a 'load profile'.[21] In the case of wind-based supply, the predominant generation profile would be more correlated with constant consumption, or baseloads (similar to datacenters).

The correlation between the RES generation and the load profile has an impact on the LCOE as

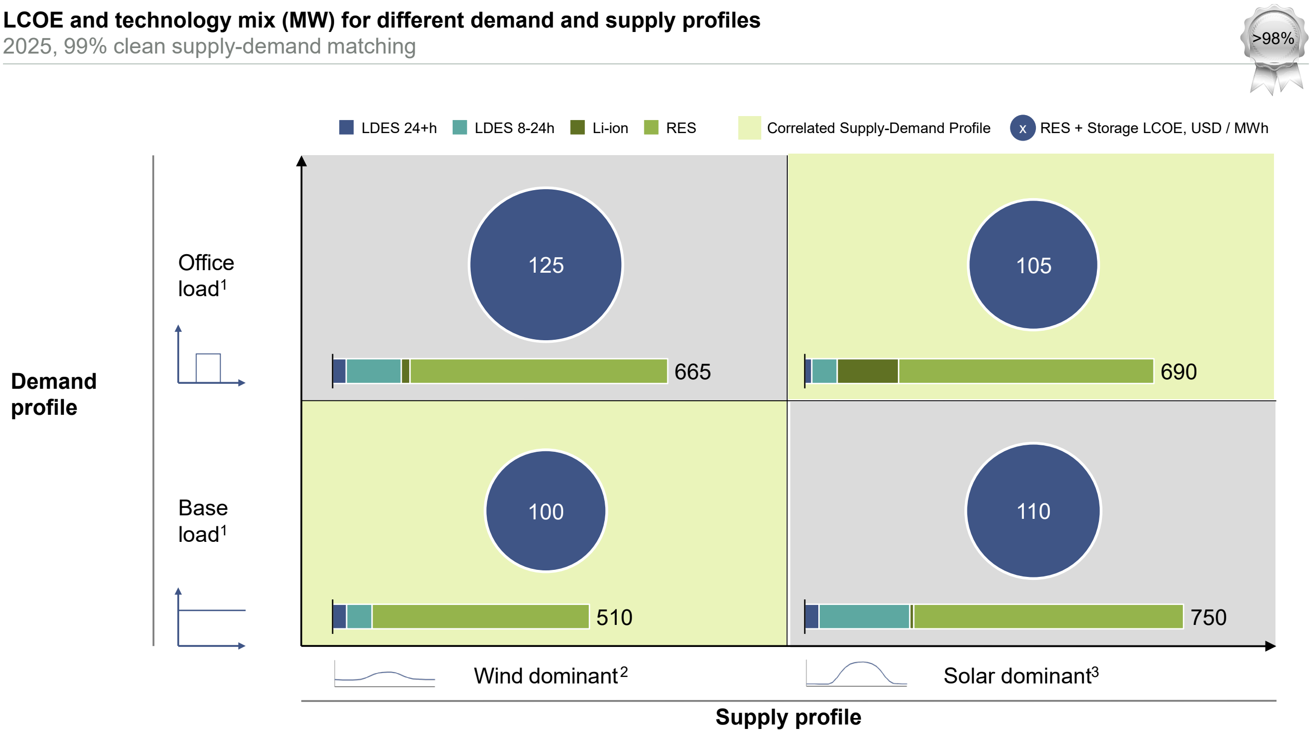
[21] Load profile has a high concentration of electricity consumption at day hours (modeled as 220 MW constant from 9 a.m. to 7 p.m.).

the greater the alignment, the lower the need to shift energy for long durations and the lower the overall system cost. The case example in Exhibit 19 illustrates this trend: the LCOE can range between 100 USD per MWh and 125 USD per MWh depending on the adequacy of the curves.

Exhibit 19

Impact of generation-load profile correlation on the LCOE and system capacity mix

LCOE and technology mix (MW) for different demand and supply profiles
2025, 99% clean supply-demand matching



1. Baseload equals 100 MW. Office load profile considered with same annual consumption as baseload ~ 220MW from 9:00 a.m. to 7:00 p.m.
2. UK example has been shown for markets with wind dominant profile supply or market with supply correlated with baseload.
3. California example has been presented for markets with solar dominant profile or market with supply correlated with office load.

Source: LDES Council 2021 technology benchmark and report, McKinsey Power Model.

IV.

Ensuring impact is captured

This chapter highlights key considerations for a certification of 24/7 clean PPAs for official announcement. In addition, it discusses options for continuous measurement during PPA lifetime. As context for this, the the different impacts of optimizing off-taker or system-level decarbonization is also discussed.

There is a tradeoff between corporate and system-level decarbonization

Deviations from 100% clean supply-demand matching can improve cost and minimize system emissions

24/7 clean PPAs today are driven by demand from off-takers that seek to fully decarbonize their actual emissions from power procurement. However, there are also system level implications and they are strongly influenced by the dispatch approach of the designated clean flexible capacity.

On the one hand, the operation of the assets could maximize the decarbonization of a off-taker's load by ensuring 100% load-matching. On the other hand, it could look beyond a single load and maximize the impact on the grid, e.g., by discharging power to the grid at times of peak emissions intensity. This may happen to a certain extent also when there is a strict 100% clean supply-load matching requirement (by using the flexible capacity for system-level optimization when it's not needed for load-matching). The system-level impact can be further enhanced by lowering the load-matching constraint. Exhibit 20 shows a comparison of these different approaches and the resulting impact on the Shaped PPA Cost and system-level emissions abatement. The example analysis for Germany shows that:

- 24/7 clean PPAs designed for 100% load-matching achieve full decarbonization of the off-taker's power consumption, but in addition, feed-in of surplus generation leads to system-level decarbonization (Scenario 1);
- Allowing for market arbitrage (with unutilized storage capacity) at 100% load-matching already slightly reduces Shaped PPA Cost and increases system-level decarbonization impact by around 40% (Scenario 2); thus 24/7 clean PPA contracts would benefit from being designed in a way that the operator can at least use the surplus capacity for market arbitrage;
- By weakening the load-matching constraint from nearly 100% to 80%, cost and system-level CO_2 impact can be further improved: around 25% lower Shaped PPA Cost and around 50% higher decarbonization impact compared to 100% load-matching (Scenario 3).[22] Thus, there is a tradeoff between off-taker and system-level decarbonization.

[22] The impact numbers will differ by market and change over time.

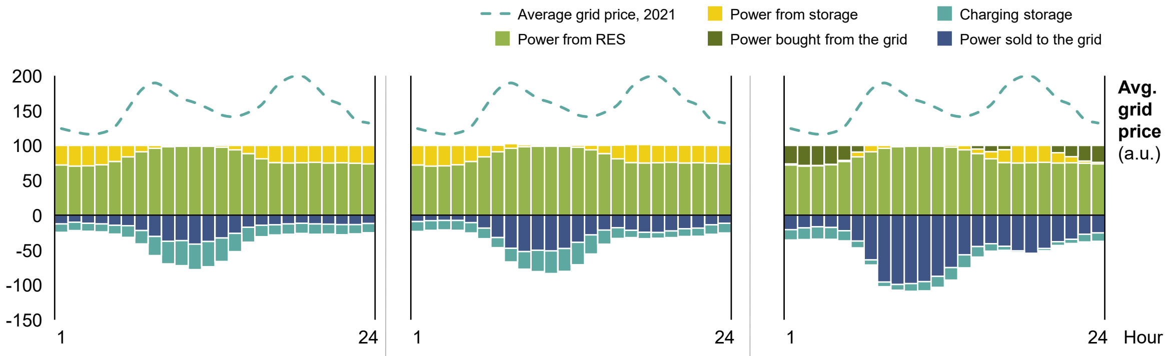
Exhibit 20

Changes in hourly dispatch for different optimization objectives and load-matching constraints

Average daily generation for different dispatch approaches

2025[1]

Dispatch scenario (same system)	**Scenario 1: dispatch objective is 100% load-matching**	**Scenario 2: dispatch objective is 100% load-matching and market arbitrage** (with remaining capacity)	**Scenario 3: dispatch objective is 80% load-matching and market arbitrage** (with remaining capacity)
Hourly generation mix MW			
Impact	**100% clean power to off-taker.** **54 000 t additional system-level CO_2 abatement[2]** (from surplus generation). **89 USD / MWh shaped PPA cost[3].**	**100% clean power to off-taker.** **75 000 t additional system-level CO_2 abatement** (from surplus generation + arbitrage). **86 USD / MWh shaped PPA cost.**	**80% clean power to off-taker.** **104 000 t additional system-level CO_2 abatement** (from surplus generation + arbitrage). **64 USD / MWh shaped PPA cost.**



1. The generation shown is annual average, hence in a given hour there is both grid buying and selling. Based on 2021 power market prices.
2. In addition to decarbonization of the off-taker's power demand.
3. This includes RES + Storage LCOE and costs of grid balancing (with hourly grid prices driving grid buying and selling costs).

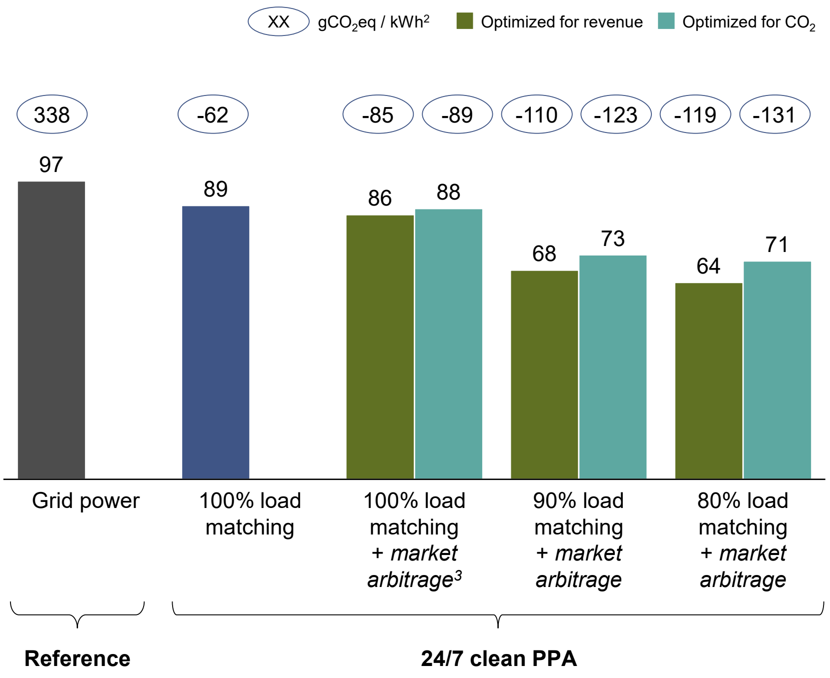
These results are based on pure economic optimization of the dispatch. An additional analysis has been performed to assess the maximum carbon abatement impact when optimizing the dispatch purely based on grid-level emissions intensity. Exhibit 21 shows the Shaped PPA Cost and implied net emissions intensity for the off-taker in a direct comparison for both optimization approaches. The analysis shows that dispatch optimization based on revenue also achieves strong decarbonization impact (due to the correlation between grid price and emissions intensity); optimizing purely for CO_2 impact can improve decarbonization further (around 10%).

The analysis also shows that in markets with a strong correlation between carbon and market price signals, 80 — 90% minimum load-matching is a sweet spot of both high off-taker decarbonization and system-level decarbonization impact. On the other hand, there would be an emissions-cost tradeoff in markets that continue to rely on low-cost coal power.

Exhibit 21

Impact of different dispatch optimization approaches on Shaped PPA Cost and CO_2 emissions

Shaped PPA cost for different dispatch-optimization approaches and decreasing load-matching constraints
2025[1], USD / MWh



Remarks:

All results are based on a fixed hardware configuration (solar, wind, storage) that has been defined based on a 100% load-matching requirement.

Actual costs and emissions abatement potential highly dependent on market and year as market prices and CO_2 emissions intensity differ significantly by region and over time.

Lowering the load-matching constraint below 80% does not substantially change the resulting shaped PPA cost and emissions impact.

1. Shaped PPA Cost calculated from 2025 LCOE, but based on actual 2021 power market price data in Germany, emissions estimates also based on actual data for 2021, results to be treated as estimates since the model has perfect foresight.
2. Emissions per kWh consumed by off-taker, estimated based on hourly average grid emissions, values for 24/7 clean PPAs negative due to feed-in of surplus generation and impact of arbitrage.
3. "Market arbitrage": charging from and discharging to grid enabled, storage dispatch adjusted to leverage free capacity for either maximizing market arbitrage revenues or maximizing grid emissions abatement (by shifting electricity from hours with low emissions intensity to hours with high emissions intensity).

Ensuring the PPAs adhere to the minimum requirements would benefit from a certification system.

The quality rating would need to be approved prior to execution by an independent party, based on a standardized approach

To ensure rigor and consistency, awarding an Entry Level, Silver, Gold, or Platinum rating to a specific PPA contract would need to be doneby an independent certification body. This entity would be responsible for validating that the contract terms and designated assets meet the pre-requisites across all quality dimensions outlined above.

To ensure the minimum level of clean supply-demand matching, it is recommended that the certification approach is based on either of the following two options, or ideally both combined:

1. **Contractual obligations:**
   The third party would validate the contract terms of the PPA, which need to be sufficiently robust to ensure that the execution of the contract adheres to the clean supply-demand requirements. This requires tight contractual obligations such that it is clear how the provider would deliver clean power consistently with the certified quality level and what provisions would be made in the event of non-delivery.

2. **Pre-measurement:**
   Given the current lack of standard protocols for auditing the actual hourly delivery of clean power, transitional measures are required to ensure that the designated assets[23] are sized appropriately to be able to meet the desired clean supply-demand requirements. A pre-measurement simulating the projected power supply using a significant number of historical weather years is proposed as core part of the certification of a 24/7 clean PPA.[24] This simulation would optimally be done by by the independent certification body (using consistent weather data across all locations, which emphasizes the importance of repositories with location-specific representative weather data sets).

After initial certification of the PPA, continued monitoring of the actual power delivery would be beneficial to ensure impact

The PPA provider and buyer have different options to ensure contractual obligations are being met. Continued monitoring of the actual power delivery allows the involved parties to communicate the decarbonization impact of the PPA and ensures that the contractual obligations are fulfilled.

24/7 clean PPAs typically are signed by off-takers that have the ambition to fully decarbonize their power consumption (24/7 load-matching). However, the designated flexible clean capacity may have an even stronger system decarbonization impact when dispatch is optimized based on the hourly grid emissions intensity (see previous section). Thus, PPA provider and off-taker should align the objectives of the dispatch optimization.

In the following, two archetypes for continuous monitoring approaches that can be linked to different dispatch objectives are introduced. Either strategy would affect the actual power supplied to the demand, and consequently the level of supply-demand matching. The two archetypes are defined below, by increasing implementation complexity (Exhibit 22):

A. Monitoring of 24/7 load-matching
This approach would be based on tracking the hourly clean supply, flexibility, and demand, to confirm that the desired minimum level of clean supply-load-matching is met. This may be implemented in two versions:

- A1. The power supply could be restricted to the designated assets, or
- A2. The share of clean power from the grid could also be factored in. In this case, specific measures and data transparency on the hourly residual grid mix would be required to avoid double counting.

This method would enable businesses with clean electricity targets to demonstrate and communicate their efforts on clean energy consumption.

B. Monitoring of decarbonization impact:
In addition to purely assessing clean supply-demand matching, this approach would measure the hourly decarbonization impact of dispatching the designated capacity. This measurement is more complex and would require high data transparency on actual marginal grid emissions intensity.

This approach would fit those players looking to maximize their overall decarbonization impact on the grid, rather than only maximizing the decarbonization of their own load.

[23] Designated assets do not need to be owned by the PPA provider, and assets may be shared across multiple PPAs as long as there is sufficient capacity designated to each PPA to ensure delivery.
[24] Clean power from the grid delivered to the load would be excluded from such a test. Surplus power from RES could be sold to another load (e.g., with higher demand-side flexibility like hydrogen production).

The two archetypes outlined above demonstrate that there are different ways to continuously measure the impact of 24/7 clean PPAs. Third-party solutions for such continued tracking / measurement are expected to emerge, including blockchain-based tracking of delivered power.

Continuous tracking during the PPA lifetime would be beneficial to ensure fulfillment of the contract. Players may choose not to follow any of the aforementioned approaches given the complexity they entail today, in the absence of mature tracking solutions. Nevertheless, it is expected that players with high decarbonization ambitions would benefit from communicating load-matching and carbon impact during execution; such players are expected to adopt commonly accepted and reliable tracking approaches.

Exhibit 22

Approaches to certify the 24/7 clean PPA for announcement and options for continued measurement during PPA lifetime

Mandatory certification by third party

PPA announcement

The quality rating needs to be independently certified – ideally using both approaches below:

Assessment of contract terms

Definition of contractual obligations for the provider to deliver clean power consistently with the certified quality level, and clear provisions in the event of non-delivery.

Pre-measurement of designated assets

Modeling designated PPA assets against historical weather years to ensure system design can meet the requirements.

PPA lifetime

It is recommended that the power supply is continuously monitored to ensure contractual obligations are being met

No tracking

No standardized tracking of clean power delivery.

A Tracking of load-matching

Continued measurement of actual hourly supply and demand.

Clean supply-demand matching can be achieved via:

- A1 Designated PPA assets only
- A2 Designated PPA assets and clean grid power

B Tracking of carbon impact

Continued measurement of supply, demand, and displaced carbon emissions in the grid.

As a result, flexibility assets can be operated to maximize load-matching, while minimizing grid emissions.

Lowest complexity → Highest complexity

Each of the continuous measurement approaches has a set of advantages and disadvantages that should be taken into account

The various measurement approaches (and implied objectives) have implications for contract economics, system decarbonization impact, ability to prove round-the-clock clean power consumption, and reputational risks that should be evaluated (Table 1).

Table 1

Advantages, disadvantages and considerations for different measurement approaches

Measurement approach	Pros	Cons	Considerations for implementation
No tracking of clean power delivery	**Easy to implement.** **Lower PPA cost** due to option to optimize dispatch for maximum market revenues**.**	Inability to **prove round-the-clock clean power consumption.** Higher risk of **green-washing allegations** **No transparency on actual performance** of assets (incl. degradation).	**Requires certification based on pre-measurement** of designated assets to ensure designated assets are sized appropriately. **Option to implement annual audits** to ensure full capacity is still online.
A1 **Tracking of load-matching** from designated assets	Ability to **prove round-the-clock clean power consumption.** **Full transparency for off-taker,** also to identify hardware failures leading to non-delivery of power.	**Potentially lower system decarbonization impact** as in option B. **Higher cost** (higher effort to meet matching requirements).	Requires advanced **data infrastructure** to track hourly supply and demand.
A2 **Tracking of load-matching** from designated assets and clean power from grid	Ability to **prove round-the-clock clean power consumption.** **Easier to meet** matching requirements (due to option to use clean power from the grid). Emphasizes the need to add **clean power resources complementary to the grid** (i.e., at the grid's dirtiest hours).	**Potentially lower system decarbonization impact** as in option B. **Lowers incentives** to deploy clean **flexibility .** Risk of **double-counting clean power** (e.g., clean power from grid already sold as GOs) due to the lack of data for hourly residual grid mix.	Requires advanced **data infrastructure** to track hourly supply, demand, and clean power from the grid. Requires **clear rules on grid emissions accounting** (e.g., average, marginal) and definition of "clean power".
B **Tracking of carbon impact**	**Allows for maximization of system decarbonization impact.** **Potentially lower PPA cost** than option A due to correlation of CO_2 emissions and market prices (esp. in markets with strong CO_2 price signal).	**High implementation complexity** due to need to demonstrate carbon impact. Risk of **double-counting avoided emissions** due to simultaneity with other players' marginal impacts.	Requires advanced **data infrastructure** to track hourly supply, demand, and grid emissions. Requires the **definition of clear rules for the calculation of avoided marginal grid emissions**.

The ambition of the quality ratings could increase over time, and an approach hierarchy could be developed as the system's decarbonization needs evolve

Power system needs are rapidly evolving. A growing number of countries are recognizing the importance to decarbonize electricity grids as an essential lever in their path to net-zero. This trend is also reflected in the amount of RES capacity additions, which in 2020 reached an all-time high with almost 280 GW added to the system.[25]

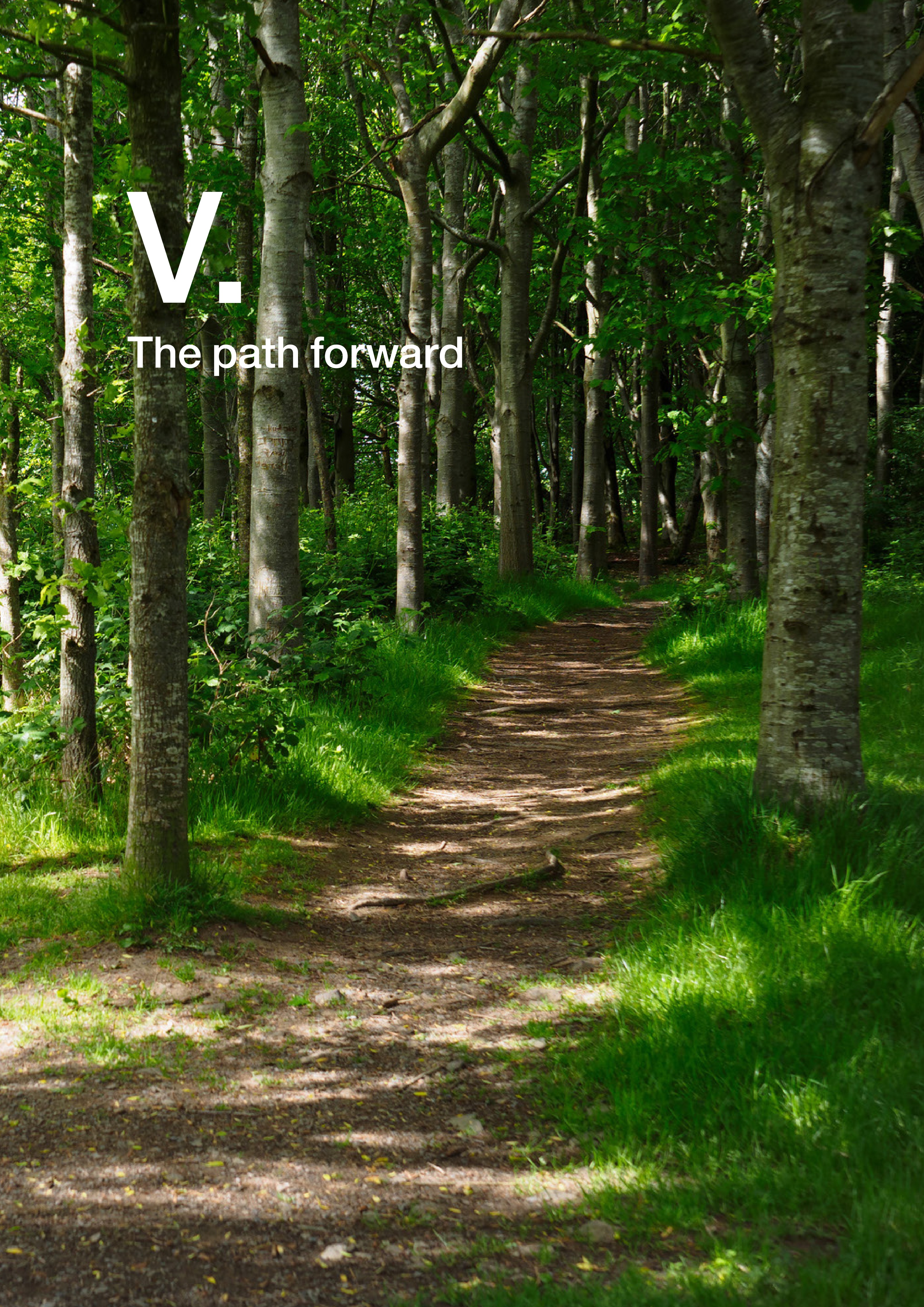
As a result, it is acknowledged that the quality ratings and minimum requirements should be revisited and the ambition increased, as new technology developments take place and the grid accelerates towards 100% decarbonization. Alternatively, new quality ratings could be introduced to indicate emerging needs (for instance, a new 'diamond' rating with lower time granularity that is closer to the settlement period, or with obligations towards grid optimization or ancillary services). This would ensure the framework remains dynamic and drives greater technological improvements.

Similarly, while each of the above dispatch optimization approaches has a different impact on the ultimate goal of grid decarbonization, they also require varying levels of sophistication (approach B being the most impactful but complex to implement). As a result, while all approaches might be valid in the short term, a hierarchy could be introduced based on the learnings and noting that a carbon-optimization approach would be the most beneficial solution for the system.

25 "Renewable Energy Market Update, Outlook for 2021 and 2022," IEA, 2021

V.

The path forward



There are a few elements that could be considered to support the widespread implementation of 24/7 clean PPAs.

Launch of a globally-relevant 24/7 clean PPA certification process by an independent governance body

The 24/7 clean PPA market would benefit from the definition of standards and a detailed assessment framework by an independent body. This governance body would need to ensure a reliable certification process that can be applied globally to avoid multiple conflicting interpretations of 24/7 clean PPAs. Potential governance bodies include key energy certification entities such as the Association of Issuing Bodies in Europe, M-RETS in North America and the International REC Standard Foundation, which works in other parts of the world.

Examples of already emerging time-bound energy procurement standards include e.g., TÜV Süd's power product certification EE02 "Certification of electricity products from renewable energies with simultaneous production", or the LF Energy Carbon Data Specification Consortium and the Granular Certificate Scheme Standard from energytag.org. Organizations like United Nations' 24/7 Carbon-Free Energy Compact, energytag.org and energy web are already pushing to educate the public, gaining real work knowledge through pilots and are advocating for standardization.

Key to these efforts will be the tech providers who can furnish the optimal means of validating the underlying power flow for the customer.

Accurate real-time carbon accounting standards and commitments from a broader customer base to increase demand for 24/7 PPAs

Today, consumers with ambitious sustainability targets, as well as academic experts, are driving the momentum on 24/7 clean PPAs. But a large energy consumer base will be required to scale this to be the next industry standard. This demand can be accelerated through increased industry awareness and supportive carbon accounting standards.

Carbon accounting standards currently give only limited guidance on evaluating power purchase emissions on an hourly basis

The location-based method reflects fossil generation as it is "based on statistical emissions information and electricity output aggregated and averaged within a defined geographic boundary and during a defined time period". More and more companies are starting to report in the market-based method which is "associated with the choices a consumer makes regarding its electricity supplier or product." But this is typically done on an annual basis, which results in a systematic underestimation of the true carbon footprint of purchased power. Standards like the GHG Protocol would need to evolve to be based on hourly resolution to improve accuracy of accounting and an advanced "real-time" or "24/7" market-based method. This would create the necessary market demand for emerging technologies like LDES and granular products (24/7 clean power certificates) that drive deep decarbonization.

Increased industry awareness: beyond reporting standards, company activities incorporating the 24/7 concept would create a pull effect on broader industries

Today RE100 only requires matching annual energy purchase volumes to 100% by 2050 latest. A new 24/7 label would be beneficial to enable the differentiation and reward of more ambitious players.

Furthermore, organizations that set globally-accepted carbon emissions reporting standards and targets -- like the Carbon Disclosure Project (CDP) and the Science-Based Target Initiative (SBTi)-- could consider including hourly 24/7 matching as a requirement to boost additional clean dispatchable capacity.

Transparent and standardized data ecosystem to set the technical foundation

To enable measurement and enforcement of 24/7 PPAs, data transparency and a robust data ecosystem are required.

Smart meters are the technical foundation and key enabler for real-time hourly matching of clean energy. Data can also inform project design and capacity sizing, and improve flexibility in operation of assets and dispatch to tap into additional revenue streams. Further transparency and coordination between traditional EAC and 24/7 EAC registries will be crucial to avoid double counting and double claiming of clean energy produced, as the hourly and traditional certificates probably will be traded simultaneously for quite some time.

Universal standards for protocols, application programming interfaces (API), blockchain technology, and so on, are a prerequisite to ensure the veracity, trade-ability and acceptance of 24/7 Energy Attribute Certificates (24/7 EACs) in the market.

Open-source software collaborations like Energy Web democratize this movement, reducing the barriers for small players to measure and manage the matching of clean energy production and demand. It is important to note that 24/7 EACs and the underlying tech solutions are key enablers for proving the actual power flow to the customer — but properly defined PPA contract terms remain important (e.g., for aspects like additionality of the designated clean capacity).

A supportive local regulator to eliminate barriers and catalyze deployment

First, ensuring markets and regulations are supportive of a range of storage and clean flexibility options would enable optimal system solutions. Second, supporting regulation or subsidies could accelerate the 24/7 build-out and mobilize corporate and private investments into this field.

Additionally, governments can also play a catalyst role in being a lead customer purchasing 24/7 PPAs for their own energy consumption. An example is President Biden's December executive order that calls for 50% of federal power to be emissions-free on a 24/7 basis by 2030 and "produced within the same regional grid where the energy is consumed."

Expanding PPAs to new customer groups in the next wave to scale beyond large corporate buyers

- Increased role for intermediaries to combine and broker portfolios to meet 24/7 clean PPA requirements
- New business models enabling shared asset ownership
- Digital platforms enabling players to aggregate load and supply
- Additional marketplaces for bundled or unbundled hourly EACs will be needed to create a tradeable 24/7 product to fill generation gaps or compensate for higher-than-expected loads of bilateral 24/7 PPAs. This would require further core elements: hourly certificate issuers, traders, registries, aggregators, and matchmakers.

Conclusion

In a world where rapid decarbonization of the power grid is an increasingly important priority, there is an urgent need to manage the fluctuations of supply and demand and price risks associated with renewable power generation. 24/7 clean PPAs can increase the effectiveness of emission reduction efforts by creating a closer match between renewables supply and demand. A combination of renewables and storage creates dispatchable clean power, a highly desirable commodity for corporates looking to reduce their Scope 2 greenhouse gas emissions.

This report has explored some of the key economic and technical issues that need to be resolved in order for 24/7 clean PPAs to see wider adoption. Key elements include a standardized quality assessment framework with different grades of ambition, official certification by an independent organization based on transparent criteria, optimization of the technology mix, and —equally crucially— a lowering of barriers to entry for corporates that will drive economies of scale.

While there are many obstacles to overcome, the key message of this report is that this is an entirely feasible task, that LDES is a key enabler, and that the prize of effective power decarbonization is well worth the effort.

Appendix A: Modelling Methodology

The modelling throughout this report is based on an optimization determining the capacity mix (and subsequently dispatch) of a set of renewables and storage assets required to meet the proportion of hourly demand-matching from the PPA designated assets at the lowest cost. This results in an approximation of the technology costs component of a PPA (RES + Storage LCOE).

Additional analysis to incorporate cost and revenue components that impact the overall PPA economics are then factored in to estimate the "Shaped PPA Cost," which serves as a proxy for the total PPA price paid by an off-taker.

An additional set of analysis has also been conducted to understand the implication of dispatching the storage assets to meet the load versus optimizing to minimize system-level emissions or market prices.

Optimal renewables and storage capacity mix and resulting RES + Storage LCOE

The LCOE from the model is referred to as the "RES + Storage LCOE". LCOE is the ratio between the annualized cost of capacity and the total energy delivered by the capacity. This excludes costs such as power bought from the grid, excess generation sold to the grid, and capacity revenues from the storage assets. The LCOE has been calculated as shown in Exhibit 23.

Exhibit 23

LCOE methodology

✓ Already in the model ✗ Not in the model

$$\text{CAPEX x } \frac{\text{WACC x (1+WACC) ^ (project lifetime)}}{\text{(1+WACC) ^ (project lifetime) - 1}}$$

$$\left[\sum_{\substack{RES\ sources \\ Storage\ sources}} \left(Annualized \frac{CAPEX}{MW} + \frac{OPEX}{MW} - Yearly\ capacity\ revenue\right) * MW + \sum_{Storage\ sources} \left(Annualized \frac{CAPEX}{MWh} + \frac{OPEX}{MWh}\right) * MWh \right] \div Energy\ delivered$$

Level of matched clean supply-demand x demand x hours

Assumptions

Project lifetime	✓	15 years Li-ion , 30-35 years LDES.
WACC	✓	6%
OPEX variation	✓	1% increase for batteries. 0% for other capacity / storage sources.
Capacity revenues	✓	0 USD / MW / yr
Asset asymmetry	✓	Li-ion has symmetric power for charging and discharging. LDES can decouple charging and discharging capacities.
Power sold to the grid	✗	0 USD / MWh.
Power bought from the grid	✗	(Not in optimisation but analysed separately) to compute total "Shaped PPA" cost.

Constraints

Level of supply-demand matching	✓
SOC[1] initial < SOC final	✓

1. State of charge.

With the objective function and constraints, the optimization solves for the LCOE (USD per MWh), the renewables capacity (MW), the storage charging and discharging capacities (MW), and the energy storage (MWh).

Shaped PPA Cost

To estimate the total cost of ownership for a 24/7 clean PPA, the "Shaped PPA Cost" was calculated after the LCOE optimization. This involved computing the costs for buying unmet demand from the market as well as re-selling excess renewables generation production.

In the reference scenario, the cost of buying power for unmet demand from the grid is taken as the price of top (x%) expensive hours for historical wholesale prices in the market of interest, where x = (1 - % of clean supply-demand matching). The cost of selling excess renewables generation was taken as the MWh of excess renewables supply that could neither be consumed by the load or used to charge the storage assets multiplied by the average price of the lowest y% hours for historical wholesale prices, where y = (MWh excess generation produced / total MWh produced by asset).

In addition to grid buying and grid selling costs, a fixed capacity revenue has been added (per MW) for the storage asset. 10,000 USD / MW for Li-ion, 20,000 USD / MW for LDES 8-24h and 30,000 USD / MW for LDES 24+h.

Analysis on varying storage operation to optimize for system emissions or market

Throughout the report, the storage is dispatched to optimize for meeting the load. However, as discussed in Chapter IV, optimizing for individual load can be sub-optimal for the overall system. Two additional variations on the storage dispatch were run to understand the implications. In both scenarios the model was first run using the base case assumptions above (the renewables and flexibility capacity are sized to meet the minimum supply-demand matching):

- Carbon-optimized dispatch: the storage dispatch minimizes grid emissions based on hourly average grid emissions intensity factor.
- Market-optimized dispatch: the storage dispatch maximizes revenues from selling power to the market based on hourly wholesale price signals.

The major caveat is that both of these optimizations are deterministic — the system assumes perfect foresight of future carbon or market prices potentially overestimating the impact.

Modelling inputs and assumptions

The geographies modeled include: California (US), UK, Germany, and Australia. These were selected as geographies that represent typical archetypes where we see the most LDES deployment due to high renewables penetration and limited low-carbon dispatchable capacity.

Several financial, operations, and technical assumptions were held constant across all geographies. The renewables technology modeled included onshore wind, offshore wind, and solar PV. The key inputs for each geography were a representative production profile (accounting for a typical weather year and the capacity factor for the technology) and technology capex and opex projections based on combinations of sources agreed upon by LDES Council members.

Key simplification and caveats

Several simplications have been run for the model: while there are other sources of low-carbon dispatchable power (nuclear, biomass, hydropower), these are not available across all geographies and cannot be quickly developed should an off-taker want to include these in their designated PPA assets. Furthermore, in regions with high penetration of zero-carbon dispatchable technologies - we see a smaller market opportunity for LDES technology.

Demand-response, while a source of flexibility, is not considered as this would likely be both a risk internalized by the off-taker and thus not part of the solution offered by a PPA provider, and an alternative to short-duration storage assets (Li-Ion) and not displace LDES technologies.[26]

[26] "Net-zero power; Long duration energy storage for a renewable grid," LDES Council, 2021.

Further work

Currently, the model is based on a single "typical" weather year, due to limited consistent data availability across regions. However, to be more representative, the model should run across a distribution of several weather years, to properly size a system that would be able to perform under varying conditions.

Two sensitivities of extreme weather events were carried out: one by reducing the output of solar PV by 50% and onshore wind by 85% for 10 consecutive days in November, and the other by reducing onshore and offshore wind generation in each hour of the year by 20%. With climate change, the likelihood of extreme weather events is expected to increase. Further modelling of various extreme weather scenarios would enhance this work.

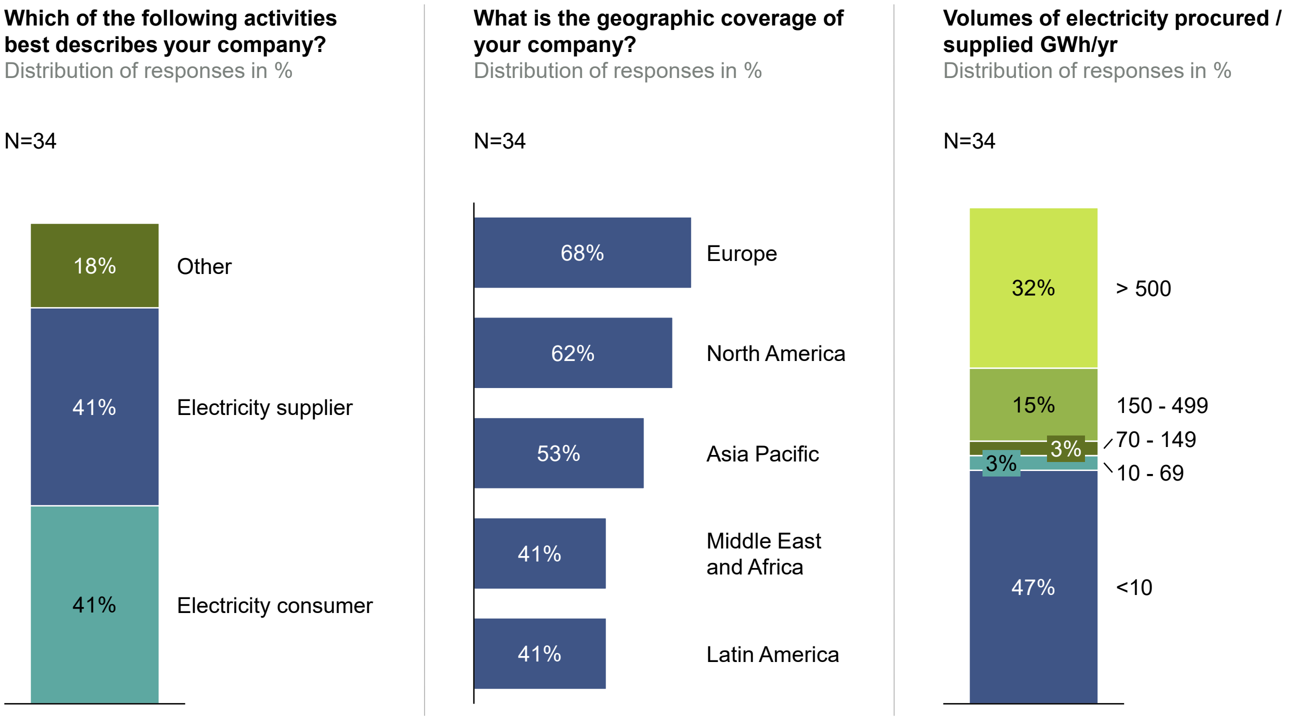
Currently, the model uses cost assumptions for a pool of LDES technologies and not one specific technology. Further, the model uses LDES technology which is asymmetric charging and discharing capacities (MW) but assumes the same capex for both equipments. Research shows the charging and discharging costs can significantly differ based on the sophistication of underlying technology, hence potentially impacting the LCOE and capacity mix. Further modelling for different LDES technologies can lead to higher accuracy in the analysis.

Appendix B: Survey responses

In order to identify key barriers for widespread adoption of 24/7 clean PPAs, a short survey has been conducted across power sellers and off-takers. The results are summarized below.

Exhibit 24

Survey demographics (1/2): respondents have a diversified geographic coverage and around half have small electricity consumption/supply



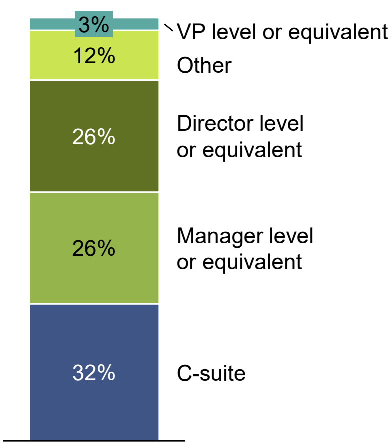
Source: LDES 24/7 PPAs survey, results as of 14/02/2022 N = 14.

Exhibit 25

Survey demographics (2/2): >30% of respondents are C-suite level, and all the consumer respondents influence the procurement decisions

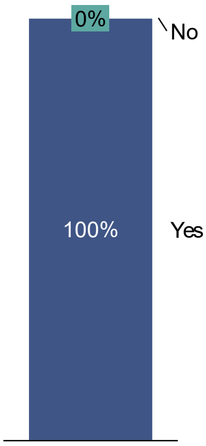
Which of the following best indicates your level of seniority?,
Distribution of responses in %

N=34



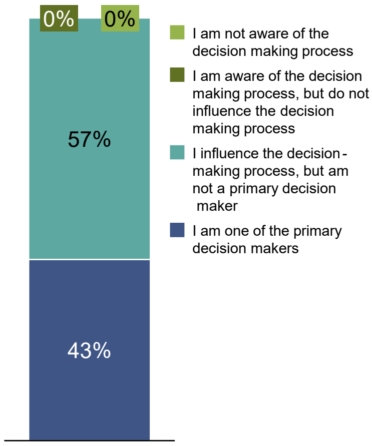
[Consumers] Are you familiar with current and/or future purchasing criteria for (zero-carbon) electricity in your organization?,
Distribution of responses in %

N=14



Are you involved in the current and/or future decision-making process to set-up guidelines/criteria for the purchase of (zero-carbon) electricity strategically or operationally in your organization?,
Distribution of responses in %

N=14



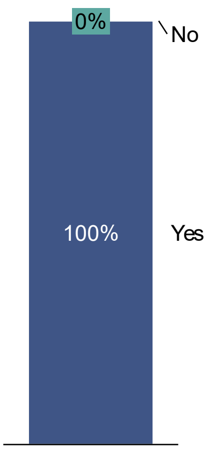
Source: LDES 24/7 PPAs survey, results as of 14/02/2022 N = 14.

Exhibit 26

Company ambitions (1/3): the companies of all consumer respondents have sustainability targets in place and procure clean power

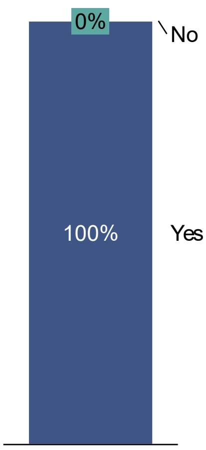
[Consumers] Does your company have any sustainability targets in place (e.g., greenhouse gas emission reduction targets, renewable energy procurement)?,
Distribution of responses in %

N=14



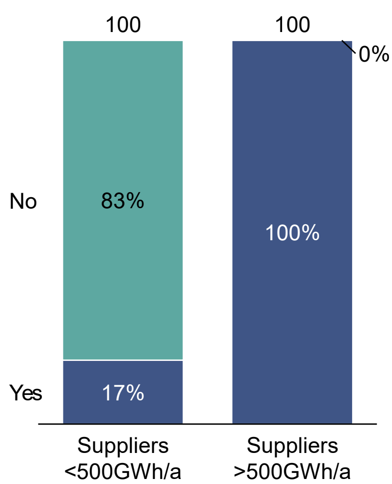
[Consumers] Is your company currently procuring zero-carbon electricity?,
Distribution of responses in %

N=14



[Suppliers] Is your company currently supplying zero-carbon electricity?,
Distribution of responses in %

N=12 N=2

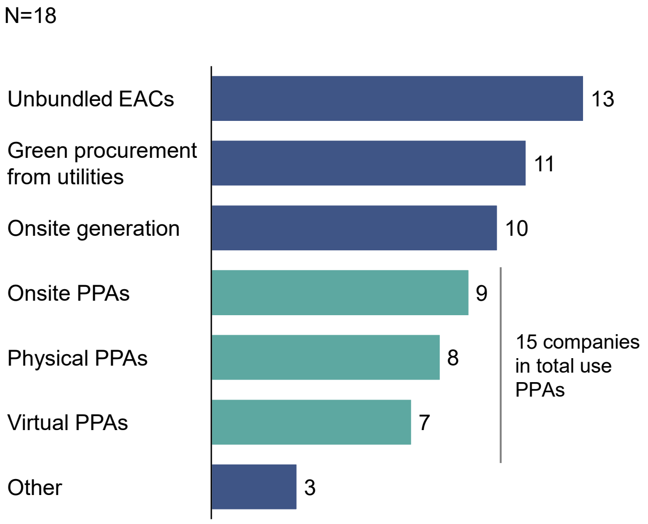


Source: LDES 24/7 PPAs survey, results as of 14/02/2022 N = 14.

Exhibit 27

Company ambitions (2/3): 15 respondents currently supply / procure clean power using PPAs, the majority using pay-as-produced or — consumed

[Consumers and suppliers with zero-carbon electricity] How does your company procure / supply zero-carbon electricity?,
Number of responses



[Consumers and suppliers with PPAs] What type of PPA does your company procure / supply?,
Number of responses

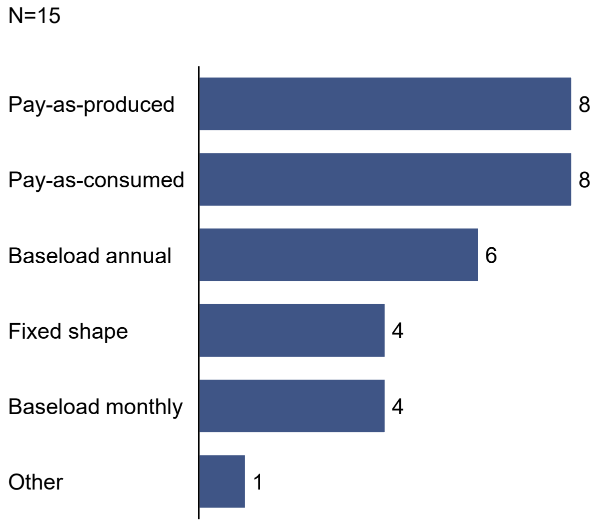
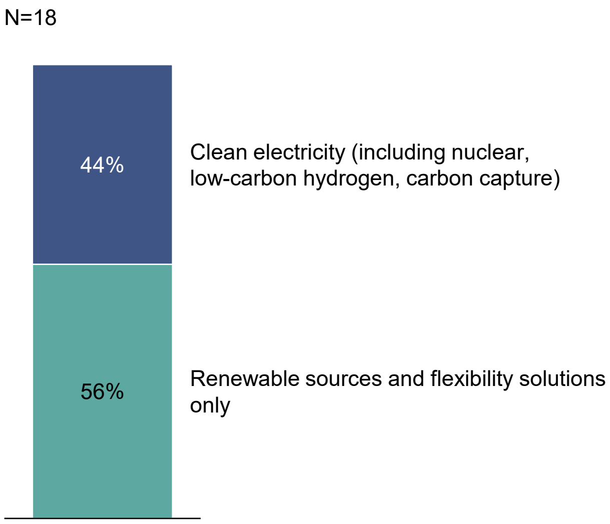


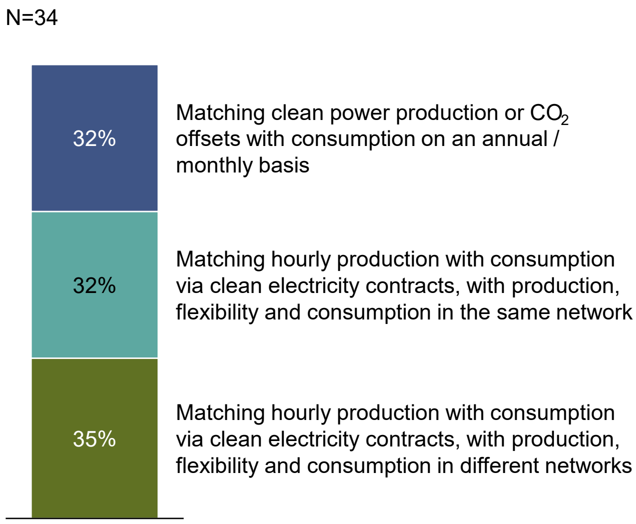
Exhibit 28

Company ambitions (3/3): Respondents do not have a clear preference for RES over more general clean power or decarbonization standard

[Consumers and suppliers with zero-carbon electricity] What is the overall preference of your company regarding zero-carbon electricity procurement / supply?
Distribution of responses in %



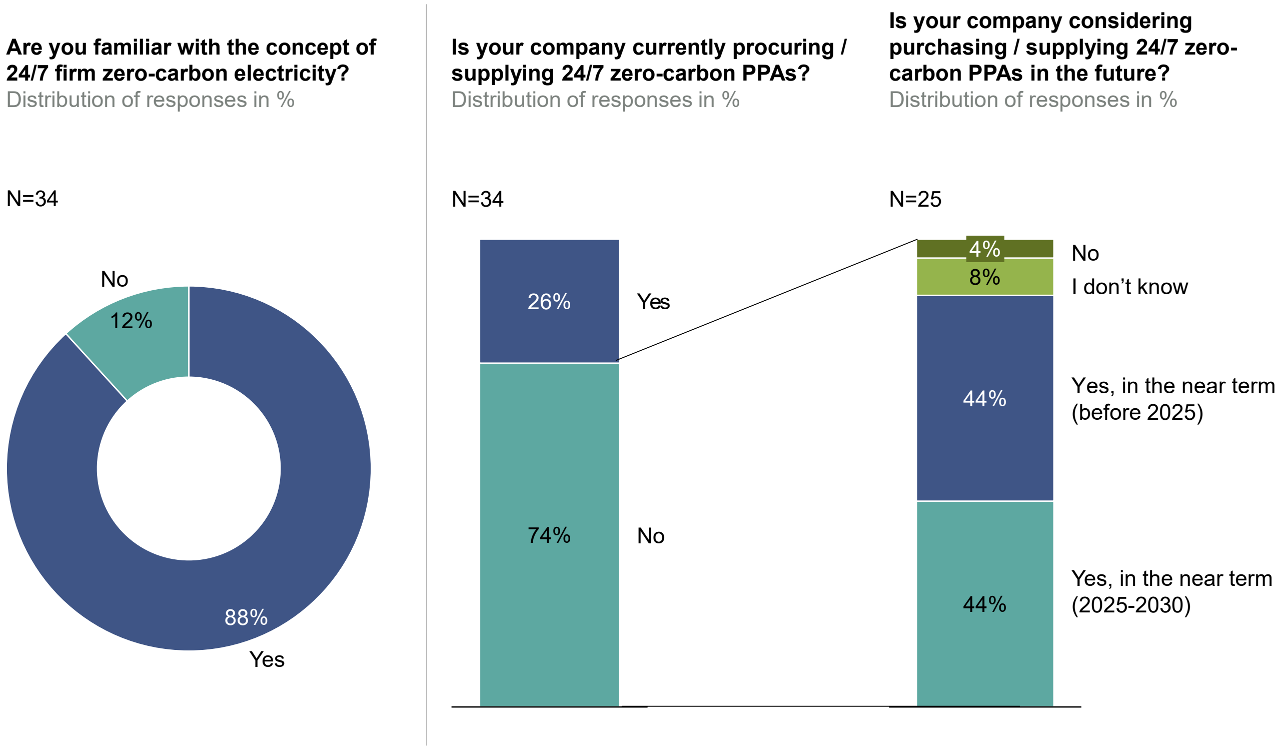
What do you think should be the decarbonization standard for power in 2030?
Distribution of responses in %



Source: LDES 24/7 PPAs survey.

Exhibit 29

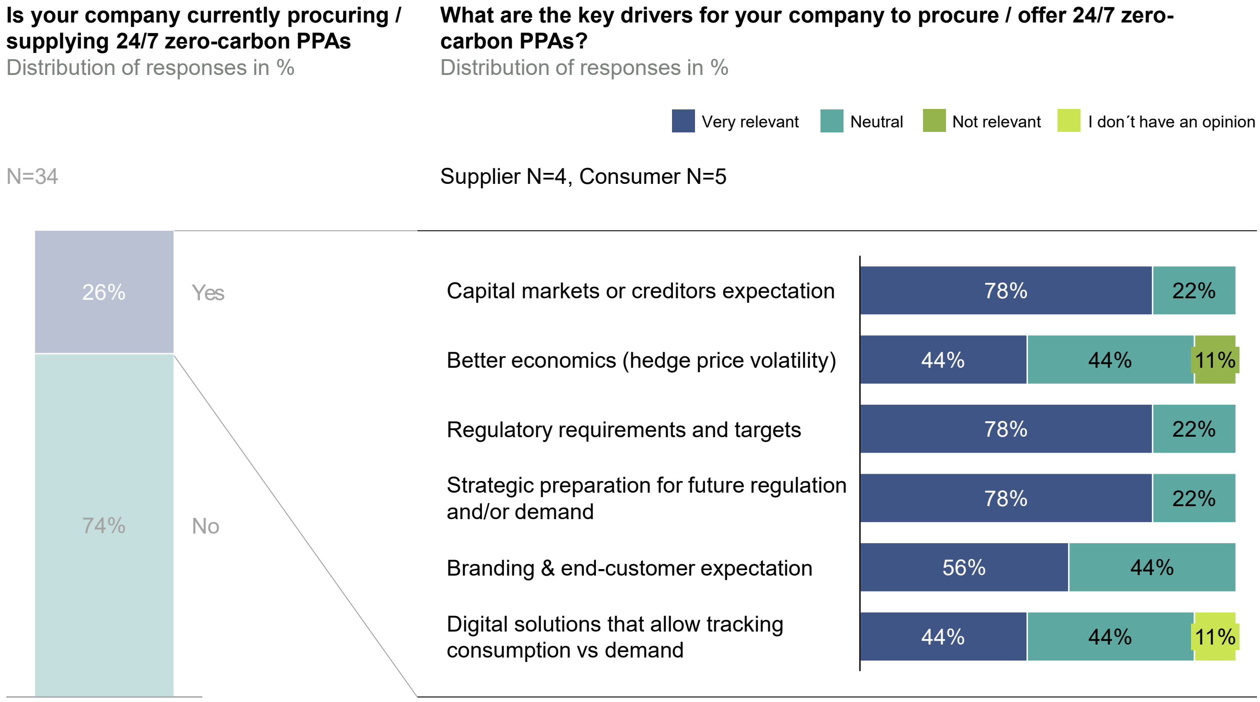
Drivers and barriers (1/5): >25% is currently procuring/supplying 24/7 clean and nearly 90% is considering doing it in the future



Source: LDES 24/7 PPAs survey.

Exhibit 30

Drivers and barriers (2/5): the major drivers of companies currently procuring 24/7 clean PPAs are capital markets, regulatory targets and strategic preparation for the future



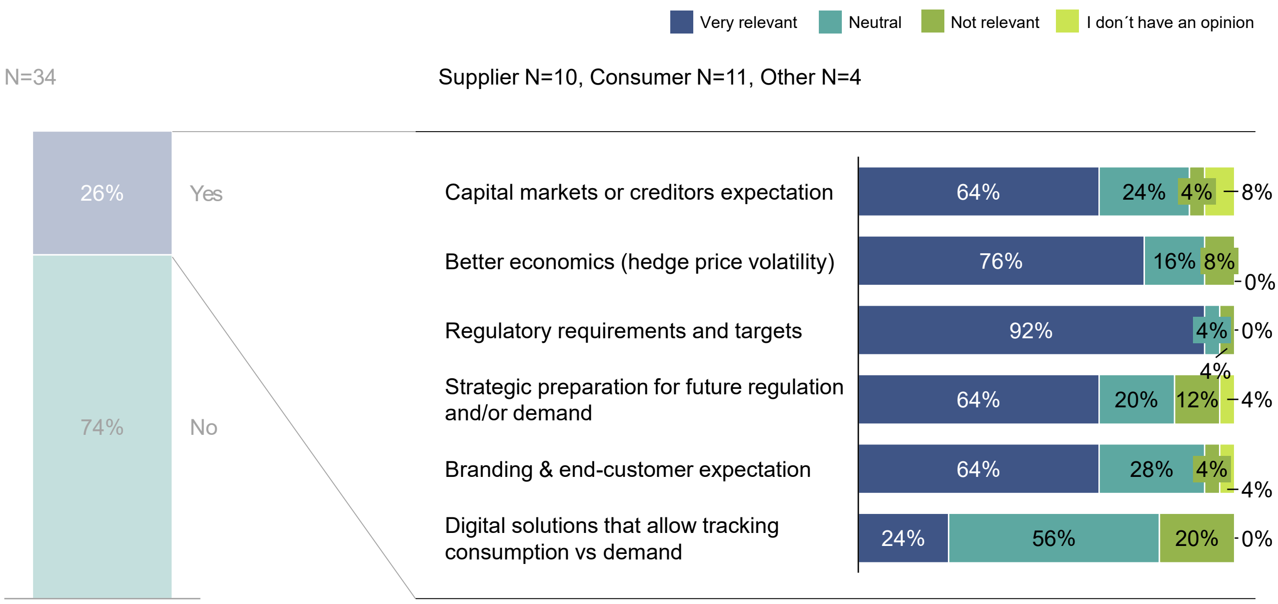
Source: LDES 24/7 PPAs survey.

Exhibit 31

Drivers and barriers (3/5): Regulation targets and the ability to hedge price volatility could increase the willingness to procure 24/7 PPAs

Is your company currently procuring / supplying 24/7 zero-carbon PPAs?
Distribution of responses in %

Which of the following would increase the willingness of your company to procure / supply 24/7 zero-carbon PPAs?
Distribution of responses in %



Source: LDES 24/7 PPAs survey

Exhibit 32

Drivers and barriers (4/5): The cost premium, the lack of carbon accounting incentives, and the lack of flexibility technologies are seen as the highest barriers

What is preventing your company from procuring / supplying (more) 24/7 zero-carbon PPAs in the near term?
Distribution of responses in %

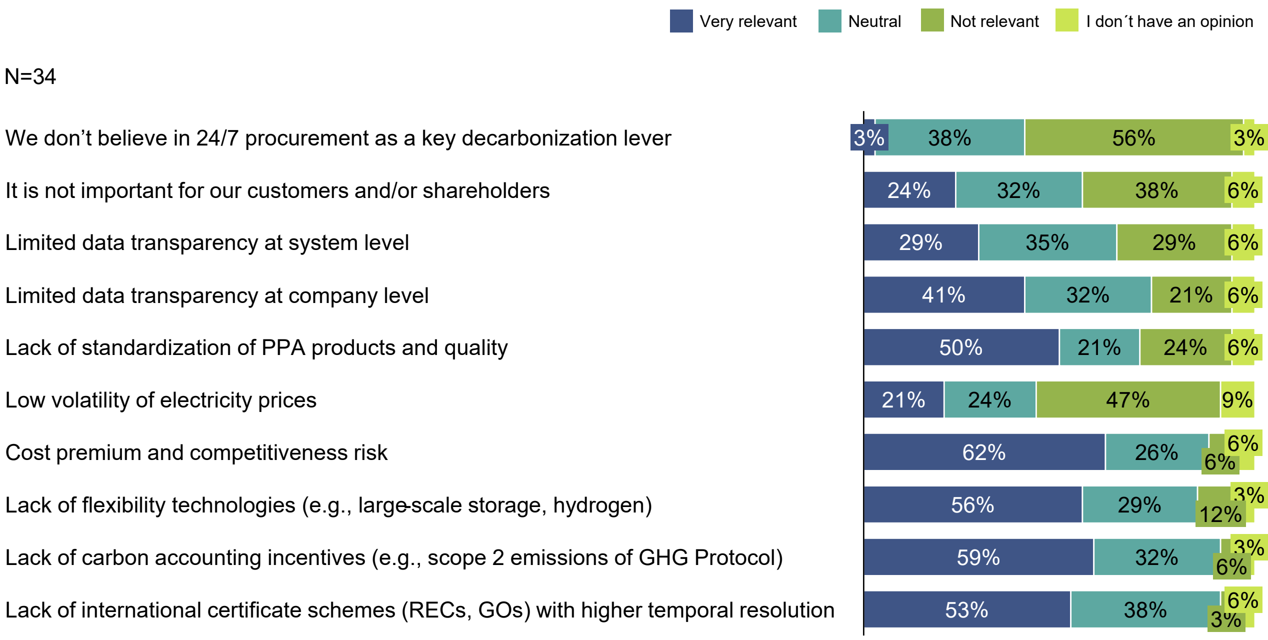
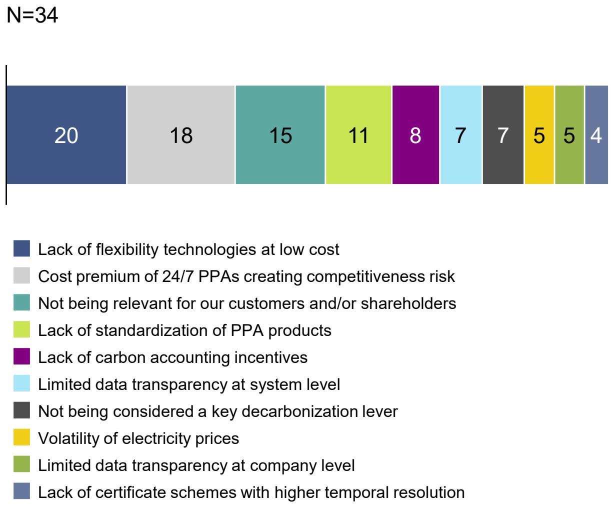


Exhibit 33

Drivers and barriers (5/5): the majority of respondents expect 24/7 PPAs will become more relevant in the future

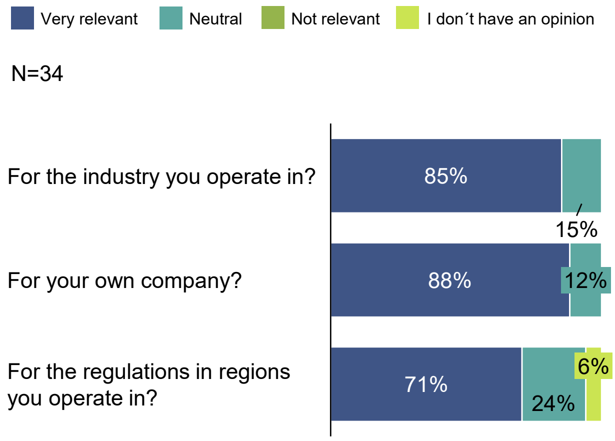
Please select up to 3 barriers that you think will decrease (and therefore increase 24/7 PPAs relevance) over the next 5-10 years

Number of responses



Do you think 24/7 zero-carbon PPAs procurement / offering is something that WILL BE relevant in the future (2025 to 2035)?

Distribution of responses in %



Source: LDES 24/7 PPAs survey.

Under embargo until 11 May 08:00 CET