Financing assets converting Power-2-X

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Project: Financing assets converting Power-2-X

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In collaboration with: Eurus Energy Europe
Battolyser Systems
Ocean Grazer
Elestor
Carbyon

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Summary and key learnings

Power-2-X refers to electricity conversion, energy storage, and reconversion pathways that use electric power. Such technologies are capable of consuming surplus power during periods where fluctuating renewable energy generation exceeds load, and as such are an enabler of the transition to clean energy.

To reach the Paris Agreement target of limiting global warming to 1,5 °C, large amounts of renewable electricity will have to added to the energy system. For example, The Netherlands aims to increase the amount of electricity generated by renewable sources from some 30% of load today to 70% in 2030, almost entirely from solar and wind.[1] It is a challenge for electricity grids to integrate the amounts of renewable electricity envisaged safely, while continuing to provide a high level of reliability. Storage and conversion technologies can help by enabling the energy system to absorb electricity at times of high production, releasing energy at another time or in another form.

In this report we consider the earning potential of certain technologies when operated flexibly with respect to their electricity use – switching on or off in near-real-time according to the price of electricity. The technologies were selected to provide a broad range across the spectrum of power-2-X technologies. This report is intended for project developers, lenders, and energy suppliers, traders, and consumers, as background information and input for evaluating investment cases. It is also intended as input for the participating ventures and other technology developers to understand better the value of their technologies.

Our work focusses on 5 technologies which are currently being developed by entrepreneurs in the Netherlands (two electricity storage technologies, two electricity to molecules conversion technologies and one hybrid with both conversion and storage). The earning potential of possible storage or conversion installations is calculated based on scenarios of the future energy system, with hourly price granularity.

We use two scenarios based on widely accepted IEA inputs: Announced Pledges Scenario (APS); and Net Zero Emissions (NZE). In the Announced Pledges Scenario, fossil fuels are still in use to some extent in 2040, consistent with 2 °C global warming in 2100. Net Zero Emissions describes a faster-decarbonizing world, with higher renewables penetration, and no fossil fuels use for electricity by 2040, consistent with 1,5 °C global warming in 2100.

[1] Rijksoverheid (2019) Klimaatakkoord (link)

Alongside this quantitative analysis, we present a qualitative assessment of the potential to deploy the technologies in different countries around the world. And we discuss what elements technology providers and project developers need to consider in contractual arrangements.

Key learnings:

Power-2-X assets can be used flexibly. All technologies considered have technical potential to be switched on and off, or modulate capacity, rapidly and with negligible losses, recovery time, or equipment degradation.

Flexible operation adds value. The earning potential of power-2-X assets is higher for an asset that responds to market prices than for one that follows a pre-set dispatch pattern. This holds for storage assets and conversion assets. The asset can be seen as an option: it can be switched on or off at will. Choosing when to use the asset and when not to, in response to events (such as changes in commodity prices), means the operator can avoid running at times which would be loss-making and only run at times which are profitable.

Value can come from different places:
- Trading: peak shifting and peak shaving
- Capex optimisation: overplanting, reduced curtailment losses
- Portfolio effects: reduced shaping & imbalance costs (at portfolio level and/or grid connection level)
- Potentially, offering fast-response services to the electricity grid, such as Frequency Containment Reserve and Frequency Response Reserve

Storage tends to earn more in the APS scenario. This is especially true for longer storage durations and is a consequence of the marginal price of electricity still being set by fossil fuels in some hours in this scenario.

Conversion tends to earn more in the NZE scenario. This is a consequence of the higher penetration of renewables leading to lower electricity prices and therefore more profitable conversion.

Sharing a grid connection with a wind park can bring value, especially in a situation where curtailment can be reduced. We estimate that a 20% undersized grid connection will lead to curtailment of some 8.5% by volume, costing some 105 €/kW of curtailed capacity/year in the APS scenario (71 €/kW in the NZE). This cost can be offset by flexible use of a power-2-X plant.

Ancillary services could be a way to generate a separate income stream, unrelated to the primary business of the power-2-X asset. However, returns over the long-term are unlikely to be significantly higher than they are in the general business of the asset. Therefore, the ancillary services market should not be a priority for power-2-X developers.

Arriving at a fair value estimate for a project requires the value of flexible operation to be taken into account. The earning potential from a flexible asset can be considered as consisting of two components: intrinsic and extrinsic value. Intrinsic value represents the earning potential of the asset, given a specific view of the future. The extrinsic part represents the value of being able to operate flexibly, reflecting that in practice we cannot know the future, and have an asset which we can switch on or off according to circumstances. In the use cases and scenarios investigated, extrinsic value can be significant (up to multiples of intrinsic value). This requires special attention when valuing the business case for a development project. Traditional valuation methods may not give a complete picture of the earning potential.

Project finance structures should be developed which reflect the value of flexible operation. This aspect has received little attention and is growing in importance with the increasing need for flexible assets to enable integration of new renewable generation. Being able to finance the extrinsic value component of projects could reduce the costs of the energy transition and accelerate projects.

Contractual agreements should envisage flexible operation. Wherever there is an obligation to take and use electricity (for example, an agreement to take power from a specific wind park) or an obligation to supply (for example, a daily minimum production of hydrogen), earning potential of the power-2-X asset is reduced. This needs to be compensated through monetary or other contractual conditions. Where a power-2-X asset shares a grid connection with another grid user (for example, a wind park), attention must be paid to priority rights at the grid connection.

Internationally, many countries will need new sources of flexibility in their electricity system, including The Netherlands, Germany, UK, Texas, California, Australia, and Japan. These markets all score high in this regard and show openness to accommodate new solutions. For storage technologies, regions with high penetration of renewables, little hydropower, and weak electricity grids, are the best targets. For conversion technologies, existence of a local buyer for hydrogen (as feedstock or as fuel) or carbon dioxide (for agriculture. as feedstock, or for sequestration) is critical.

1. Introduction

The transition to clean energy is changing energy markets. New technologies are being developed and deployed to help the energy system absorb large volumes of renewable electricity from variable sources such as wind and solar. Pressure to adapt our energy system is increasing. For the world to reach the Paris target of containing global warming to 1.5°C will require CO_2 emissions to halve in the next 8 years. According to the IEA, as much new renewable generation will be added in the next 5 years as was added in the last 20.[2]

A critical element in this new electricity landscape is flexibility: the ability to modulate supply or demand. Traditionally provided by flexible generation (typically natural gas-fired and hydro) flexibility is now increasingly supplied by batteries. Upcoming technologies (new storage technologies, as well as power-to-gas technologies) also have the potential to be viable sources of flexibility.

As is often the case with new technologies, financing projects is a challenge. Lenders seek certainty, and new technologies, by definition, have little track record. Invest-NL aims to help accelerate adoption of new technologies by making financing "easier": by investing ourselves and by conducting research into financing structures. Lower financing costs lead to lower levelized cost of energy (LCOE), levelized cost of storage (LCOS) or other total cost of ownership (TCO) measures. As a result, technologies which enable CO_2 emission reduction will be scaled more rapidly.

The present project combines expertise in energy markets, law, and valuation, and considers five emerging technologies as case studies. We consider probable use cases where the technologies will be dispatched flexibly and propose market-entry and contract structures. We focus on The Netherlands for siting the new technologies and also include a qualitative assessment of a number of countries around the world. This work is of interest generally to anyone engaged in new technologies in our changing energy landscape.

The purpose of this analysis is to enable better financing by bringing into focus the value of flexible operation in the energy system of the future.

[2] IEA (2022) Renewable power's growth is being turbocharged as countries seek to strengthen energy security (link)

2. Goal and scope

This study investigates the potential value created by flexible operation of certain emerging technologies relevant in the transition to clean energy. By providing insights into the potential value creation, this paper aims to contribute to available knowledge and thereby enhance opportunities within the investment landscape. The technologies included have been chosen to present a broad range of emerging power-2-X technologies:

- Electricity storage: flow battery (Elestor), hydromechanical (Ocean Grazer)
- Electricity conversion: hydrogen production (Eurus), direct air capture of CO_2 (Carbyon)
- Combined: battery combined with electrolyser (Battolyser)

The five ventures in question have actively participated in this study, providing input on technical parameters and likely use cases for their technologies.

The output includes:

1. A quantitative component: valuation of the gross margin that can be earned by the technologies in a variety of different use cases.

   Our calculations are forward-looking and for The Netherlands. We estimate only the gross commodity margin that can be earned ('earning potential'): for example, in the case of an electrolyser producing hydrogen from electricity, the output of our calculations is the predicted income from selling the hydrogen produced minus the cost of electricity needed to produce it. The capital costs of the plant and running costs (other than the cost of electricity) are not taken into account. Our calculations aim to:

   - show which use cases are likely to be more valuable;
   - serve as one of the inputs when estimating the overall economics of a project.

2. Discussion of factors to be taken into account in contractual agreements.

   We discuss typical legal structures and focus on what the implications are of flexible operation.

3. Assessment of the fit of the technologies in selected countries.

   We review the energy system and prospects in 11 energy markets and score each technology within each market, taking into account the specific market characteristics and specific technology.

4. Conclusions and recommendations per technology and more generally.

This report is intended for the participating ventures and for project developers, lenders, and energy suppliers, traders, and consumers. The results of this study have been documented by means of a confidential report per venture, and a public report.

3. Participating ventures

The ventures participating to this study are summarized in section 3.1. The subsequent sections provide a brief description of each venture.

3.1. Summary table

	Elestor	Ocean Grazer	Carbyon	Eurus	Battolyser
venture type	technology developer	technology developer	technology developer	project developer	technology developer
function	storage	storage	conversion	conversion	combined storage and conversion
type of technology	flow battery	hydromechanical	direct air capture (DAC)	electrolyser	hybrid
energy commodities	electricity to electricity	electricity to electricity	electricity to CO_2	electricity to hydrogen	electricity to hydrogen or to electricity

Table 1 - Summary of participating ventures

3.2. Elestor

Elestor is developing a hydrogen-bromine flow battery technology. Elestor started commercialization of its technology in 2021, with Vopak as launching customer. Elestor's platform launches with a configuration of 1MW power and 15MWh energy (15 hours of storage) as its basic system.

A key characteristic of flow batteries is the possibility to create a relatively large storage volume (energy) for a given capacity (power in or out). Increasing the energy volume is relatively cheap, as this can be realized by increasing the size of storage tanks for the chemicals involved (in this case hydrogen and bromine). Elestor technology is therefore suitable for longer duration storage than is normally considered for batteries.

3.3. Ocean Grazer

Ocean Grazer is developing a pumped hydro storage technology which is installed on the seabed and makes use of hydrostatic pressure. The design is modular, consisting of a machine room element for pump and turbine, connected to one or more storage units. The objective is to add value to offshore wind farms.

3.4. Carbyon

Carbyon is developing a direct-air-capture (DAC) technology, to remove CO_2 from the atmosphere. The technology has been proven at a laboratory scale and is currently being scaled up to a pilot plant. Carbyon expects to make its first commercial deliveries in 2025.

The device's value is in net CO_2 removal – so if there is CO_2 emission related to the electricity used to power the device, the value is reduced. Carbyon intends that its devices will be powered exclusively by green energy, of which the first generation exclusively by green electricity.

3.5. Eurus Energy

Eurus is a renewable energy project developer. Eurus is planning to build and operate an electrolyser for the production of hydrogen in The Netherlands, sharing a grid connection with an existing wind farm. The site aims to build a local hydrogen pipeline connecting it to the major offtaker.

3.6. Battolyser

Battolyser is developing a battery technology that is designed to also produce hydrogen. At low fill level, the stack acts as a pure storage device. At higher fill level, hydrogen and oxygen are produced. The installation can be run as a pure electrolyser. The unit has a modular design, in ‘stacks’. Each stack can be steered independently.

4. Gross margin calculation

4.1. Methodology

Background

The aim of the quantitative analysis is to estimate the earning potential of hypothetical power-2-X assets based on the various technologies included. The earning potential is expressed in €/MW/year and is the gross margin the asset can earn. Gross margin refers here to the margin that can be earned on the commodities—electricity, hydrogen, CO_2—without taking into account amortization of capex costs, nor fixed operational costs. In other words, we estimate the earning potential of an asset without considering its capital cost. This method was chosen so that calculation results stand independent of the technology roadmap, as emerging technologies can have a steep learning curve with year-on-year reductions in capital costs.

The gross margin calculation is based on a list of use cases for valuation. These use cases were chosen to address the most likely situations an asset will be operating in. We aim to estimate the gross margin that can be earned for each use case, including the value of flexible operation.

In calculating the value of a use case, three types of input assumption are necessary:

- Assumptions about the energy system, and the resulting electricity price level and price volatility in future (Energy Market Scenarios)
- Assumptions about the technical parameters specific to the facility, such as cycle efficiency, start-up time, etc.
- Assumptions about the contractual conditions applicable around the use case - for example, whether electricity may be bought from the spot market or whether it must be bought exclusively from a specific wind park

To estimate the gross margin, we first generate price forecasts based on Energy Market Scenarios. We then use these as input in for a model which simulates the daily or hourly decisions the facility's operator will make. The process is described in detail below.

Energy market scenarios

This analysis is based on scenarios describing future development of the energy system. The scenarios describe realistic versions of the future: energy demand can be met by supply, and there is sufficient flexibility to keep the system in balance. Each scenario is used to generate an hourly electricity price forecast based on input prices, electricity demand forecasts, and the electricity generation stack. The scenarios consider the future generation mix and future demand patterns and model hourly demand and hourly supply (including from variable sources such as wind a solar).

We model each scenario for the years 2025, 2030, 2035 and 2040 separately.

We focus on prices in The Netherlands. To create consistent scenarios, we include neighbouring countries in our modelling (UK, France, Belgium, Germany, Norway), as these countries' electricity systems influence The Netherlands (and vice versa).

We define two basic scenarios:

- Announced Pledges: based on policy measures announced to date, which would result in 2 °C global warming in 2100; and
- Net Zero Emissions: based on a path leading to a zero-carbon energy system in 2050, which would result in 1.5 °C global warming in 2100

Both these scenarios are founded on previous widely published and accepted International Energy Agency (IEA) work, supplemented by local sources for details in the countries considered. For the year 2025 we use as inputs commodity prices (gas, oil, coal, ...) offered in the futures market (at the time of performing this study, mid-2022). For 2030, 2035, and 2040 these input assumptions are taken from the IEA scenarios.[3]

As well as differing gas, coal and CO_2 price input assumptions, the scenarios have different power generation mixes (with faster growth of renewable generation in the NZE scenario) and different power consumption (with greater uptake of electric vehicles and electric heating, as well as more electricity used to make hydrogen, in the NZE scenario).

The scenarios are each run for four future years: 2025, 2030, 2035, and 2040. For each scenario and each of these years, we obtain an hourly electricity spot price forecast which we then use as input for asset gross margin calculations. The results are characterized in Figure 1 for the year 2040, for the APS and NZE 'base case' scenarios, using inputs as described above. The results for the years 2025, 2030 and 2035 are listed in Appendix B.

[3] The full overview of input parameters (market prices, installed capacity, demand) is available on request. Please find contact information in the colophon.

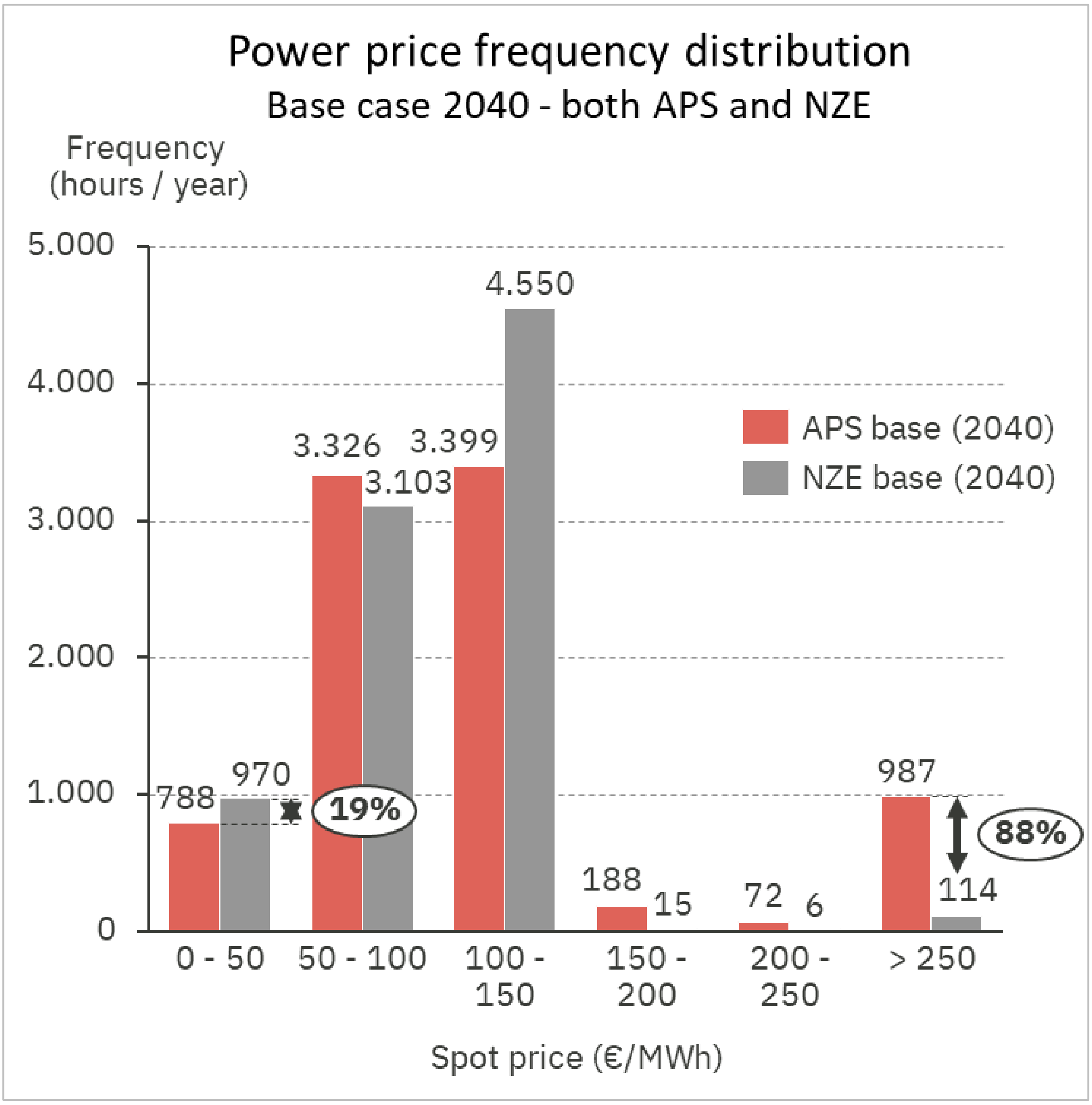

Figure 1 - Power price frequency distribution in base case 2040. Average prices are 143 €/MWh for the APS scnenario and 102 €/MWh for te NZE.

Alongside the 'base case' APS and NZE scenarios a number of variant scenarios were modelled, to investigate how sensitive results are to certain input assumptions:

- In Annouced Pledges Scenario:
  - Higher natural gas price: the IEA APS scenario was created before the current energy crisis. We run a variant with higher gas price.
  - Larger amount of battery capacity in the energy system: this is a way to check the robustness of the value of flexible operation.
- In Net Zero Emissions scenario:
  - Higher natural gas price: the IEA NZE scenario was created before the current energy crisis We run a variant with higher gas price.
  - North Sea Grid: construction of a well-interconnected electricity grid in the North Sea, connecting Great Britain, Norway, The Netherlands, Belgium, and Germany, after 2030. Such a development is not present in the base case scenario but seems probable if Europe proceeds on the Net Zero Emissions pathway.
  - Higher and lower hydrogen prices: in the NZE scenario, hydrogen becomes the marginal fuel. In the NZE base case hydrogen price is based on the LCOE of wind energy+electrolysers. This variant checks the effect of lower hydrogen prices (which could occur with large-scale development of blue hydrogen+CCS) and higher hydrogen prices (which could occur if the hydrogen market does not function efficiently).

The above variants were selected as being the most likely to affect the results and therefore are most critical to take into account when putting the outcomes into practice.

The effect of variant scenario 'North Sea Grid' is shown in Figure 2.[4] Adding electricity grid interconnection in the North Sea (total 100GW capacity) shifts many hours from price range 100-150 €/MWh to a lower price range 0-100 €/MWh (for the year 2040). This can be explained by a more economically efficient distribution of renewable power generation over the countries surrounding the North Sea, a result of the additional interconnector capacity which removes bottlenecks in power transmission between countries.

[4] The full set of power price results, including all variant scenarios, is available on request. Please find contact information in the colophon.

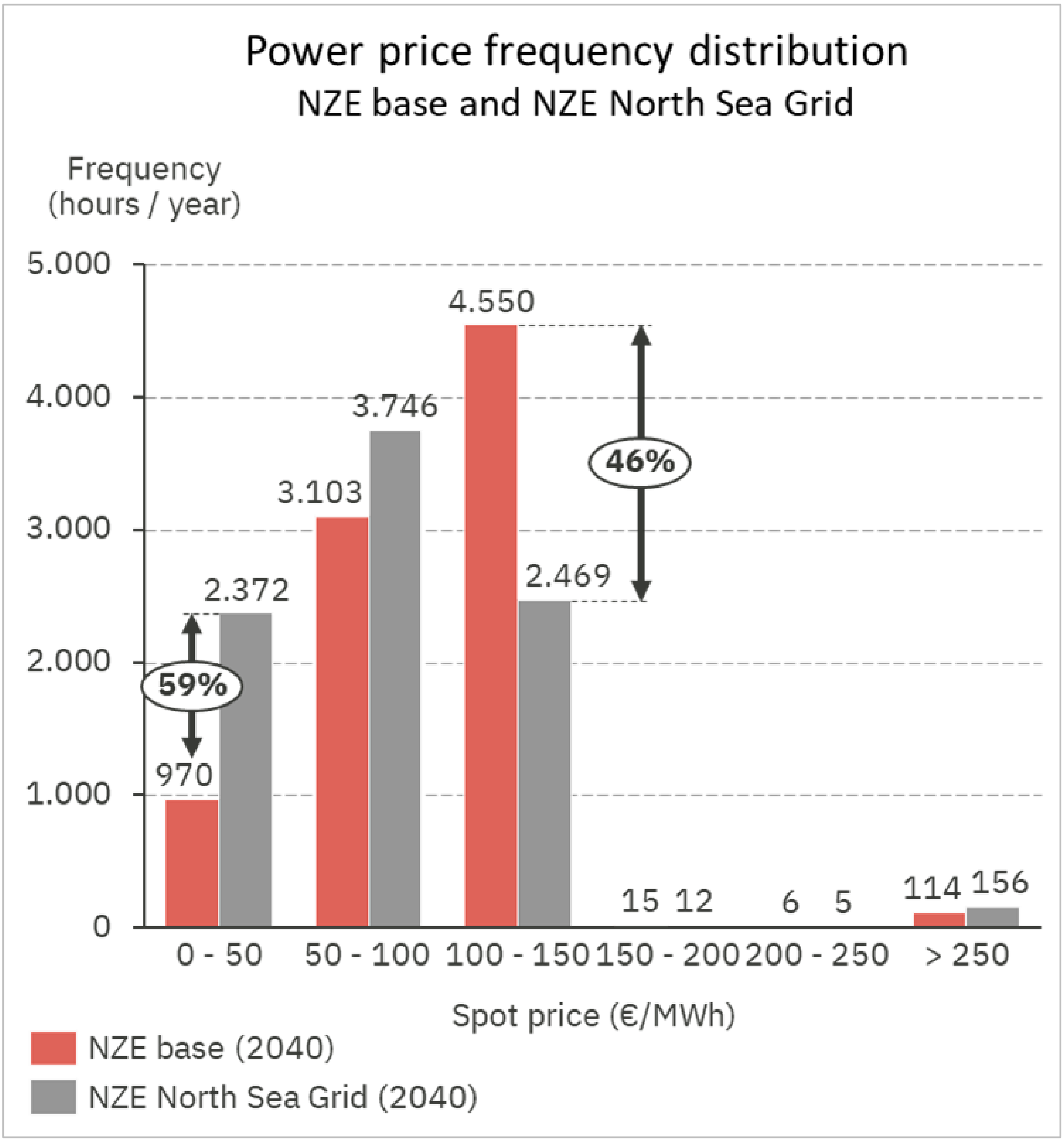

Figure 2 - Power price frequency distribution in NZE base and variant scenario NZE North Sea Grid, both in 2040. Average prices are 102 €/MWh for NZE base and 86 €/MWh for NZE North Sea Grid.

Weather (wind and sunshine) will have an increasing impact on the energy system in the future as more renewable energy is generated. We chose 2015 as our reference weather year, using hourly wind and sunshine data from 2015 as input to the scenario calculations. To understand the impact of weather variations, we ran our scenarios based on 3 other sample years with widely differing weather patterns, creating separate hourly price forecasts for each.

Calculation process

Once the price forecasts have been generated for each scenario and variant, the calculation process to estimate the gross margin earned by an asset is summarized in the diagrams below.

We take three types of inputs:

- price forecasts for electricity, hydrogen, and CO_2 (taken from forecasts from our energy system model scenarios, described above) – these inputs are different for the different scenarios and variants;
- technical parameters of the respective asset, such as cycle efficiency (for a storage technology), conversion efficiency (for a conversion technology), or plant capacity – these inputs are different for the different technologies;
- parameters specific to the use case being analyzed, such as constraints on grid connection, or supply or delivery obligations – these inputs are different for the different use cases.

These inputs are fed into a dispatch model, which simulates the actions of the plant operator over time, to calculate the gross margin. The asset is seen as a price-taker, i.e., the addition of the asset in the scenario is taken to have no influence on prices.

For use cases where a power-2-Xx asset is combined with a wind park or solar field, the power-2-X asset pays spot price for electricity.

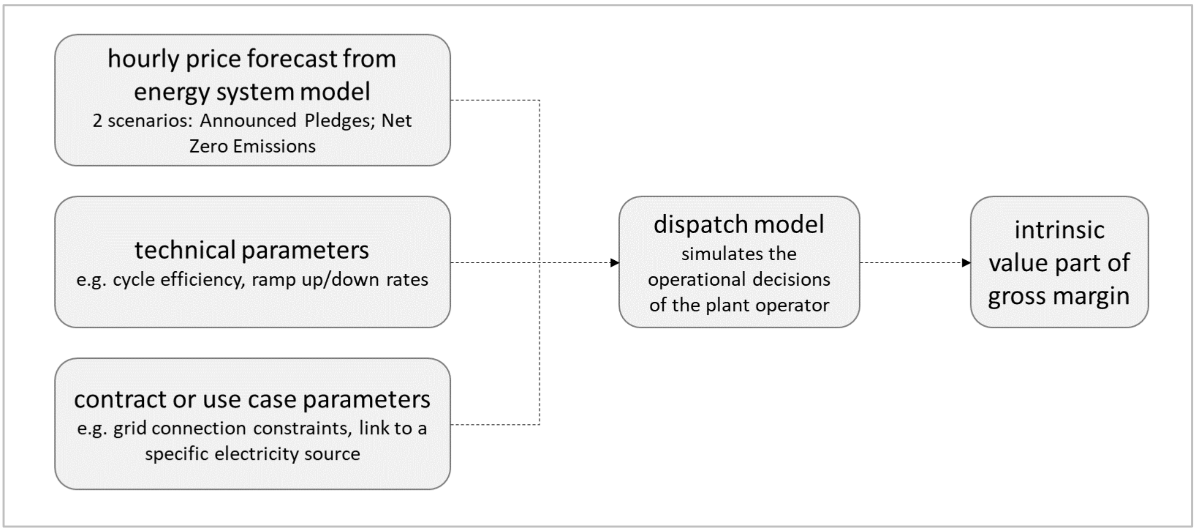

Figure 3 - Process for calculating the intrinsic value part of the gross margin for a use case

Intrinsic, extrinsic and full value

We consider the flexible operation of an asset as an option: in any hour, the operator has a choice to use the asset or not, depending on market prices (and, in certain use cases, other considerations). Like any option, the asset has:

- intrinsic value: the value that can be secured today in the traded market
- extrinsic value (also called time value): the value of being able to make a choice whether to operate the asset or not at any given time
- full value: defined as the total of intrinsic plus extrinsic value

'Intrinsic value' valuation of use cases

Because we are estimating value over a long time horizon in this study (for which no wholesale market energy products exist), in this study we use a proxy for the intrinsic value.

For each use case in each scenario, we take the hourly price path and use it to run a dispatch simulation, which simulates the actions of the plant operator – for example, turning an electrolyser on or off depending on the price of electricity in that hour; or deciding to charge or discharge a battery in that hour. In sum these actions result in a margin (in money) between outputs and inputs. This is the *intrinsic* part of the gross margin.

Where the use case includes some constraint – for example, an obligation to supply product or to consume electricity in certain hours – this is built into the dispatch simulation.

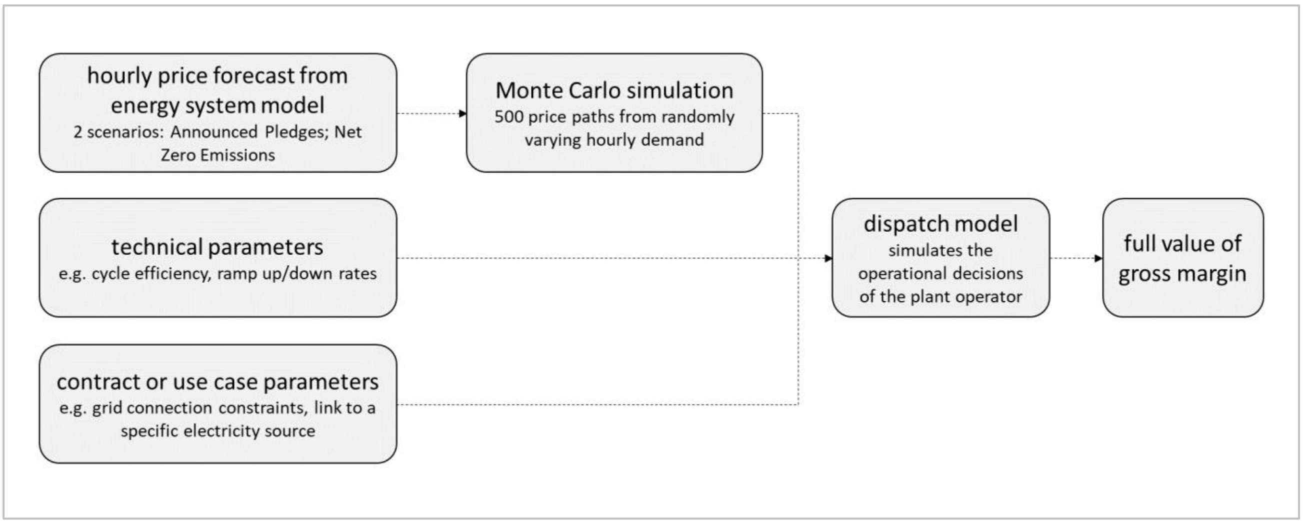

Figure 4 - Process for calculating the full value of the gross margin for a use case (intrinsic plus extrinsic value)

'Full value' valuation of use cases

To estimate the *full value* of the gross margin, we re-run the scenario 500 times, introducing a small random variation in the hourly electricity demand. This results in 500 slightly differing price paths for that scenario. These price paths are used to run a dispatch simulation. The average outcome of the 500 runs is typically a bit higher than the intrinsic value since the simulation will only dispatch the asset when profitable; the effect is not symmetrical. This average of the 500 runs is the *full value* of the gross margin and reflects both the intrinsic value and the time value of the option to run the asset.

Regarding equipment lifetime

The dispatch simulation takes into account the cycle efficiency (for storage) or conversion efficiency (for conversion) of the asset. The technologies studied have negligible losses, hysteresis, recovery time, or equipment degradation, in use. The design lifetime of the equipment is not part of the simulation as this study analyses earning potential only. A full business case analysis, including capex requirements, financing costs, fixed operating costs, and replacement or decommissioning costs at end of technical life, is out of scope for this study.

Allowing for non-perfect foresight

One of the characteristics of such valuation calculations is that inputs assume a complete view of the future – 'perfect foresight' – which in practice we do not have. In a real situation, at the time an asset operator has to make a decision how to dispatch their asset, they may know for certain what prices will be in the next few hours but with less certainty for tomorrow and next week. To incorporate this effect, we added random 'noise' to hourly prices between the dispatch decision and the outturn calculation. This random component has a normal distribution, and is capped at a percentage of the hourly price level.

Regarding use cases with long-duration storage

In the use cases that involve electricity storage, the dispatch model makes a 'decision' once per week, deciding for all hours in the coming week when to fill and empty the storage. A fresh 'decision' is made the following week for the whole week. This will yield an underestimate of the true value, since in practice there will be scope to revise dispatch decisions at any time, not just once a week. The underestimate is larger for long duration storage (some of the use cases have 150 hour storage depth) since these use cases have enough flexibility to take advantage of changes in price that affect upcoming days and weeks. For small storage depths the underestimate is negligible since the entire storage depth is generally used within each 24-hour cycle.

Regarding use cases where capacity is reserved for the imbalance or system services markets (ancillary services)

It is problematic to estimate future imbalance and system services prices ('near-real-time products'). Such markets are heavily regulated and may change radically over the long term. They are extremely affected by the availability of flexibility in the system as a whole, and also (for some products) at local level. If growth of renewables generation outpaces growth in flexibility sources, prices for system services will increase; but once flexibility sources catch up, prices could collapse. In this study, we use a simple proxy for system services price in use cases that include offering capacity to these markets. We take the historical ratio between imbalance prices and spot prices and apply this ratio to our scenario hourly price forecasts. We take the resulting price as a proxy for all near-real-time products, whether frequency containment reserve, frequency restoration reserve, or imbalance trading. The calculation results are to be taken as illustrative; they are not based on detailed modelling the behavior of these markets.

Possible uses of output data, and further analysis

The results of this study can be used to inform investment cases for power-2-X assets. The hourly granularity of the simulations makes it possible to perform further analysis per use case beyond what is presented in this report. For each use case and each scenario, it is possible for example to show the hourly dispatch pattern of the asset.

Financial discount factor

Our calculations were made separately for each of the years 2025, 2030, 2035, and 2040. In order to derive comparable figures for earning potential over the lifetime of a project in each use case and each scenario, we applied a discount factor of 5% per year to the calculation results (discounting back to 2022), and then averaged the results of the four calculation years. This discount factor was applied consistently to ensure results are comparable. No significance is intended regarding the size of the discount factor.

4.2. Use cases

The following use cases were selected for calculation of gross margin of the asset, modelled in the context of a full energy system:

Storage use cases – these use cases were analyzed for both Elestor and Ocean Grazer

- Merchant operation
- Sharing a grid connection with a wind farm
- Sharing a grid connection with a wind farm, where the grid connection is constrained
- Sharing a grid connection with industrial electric load and solar generation

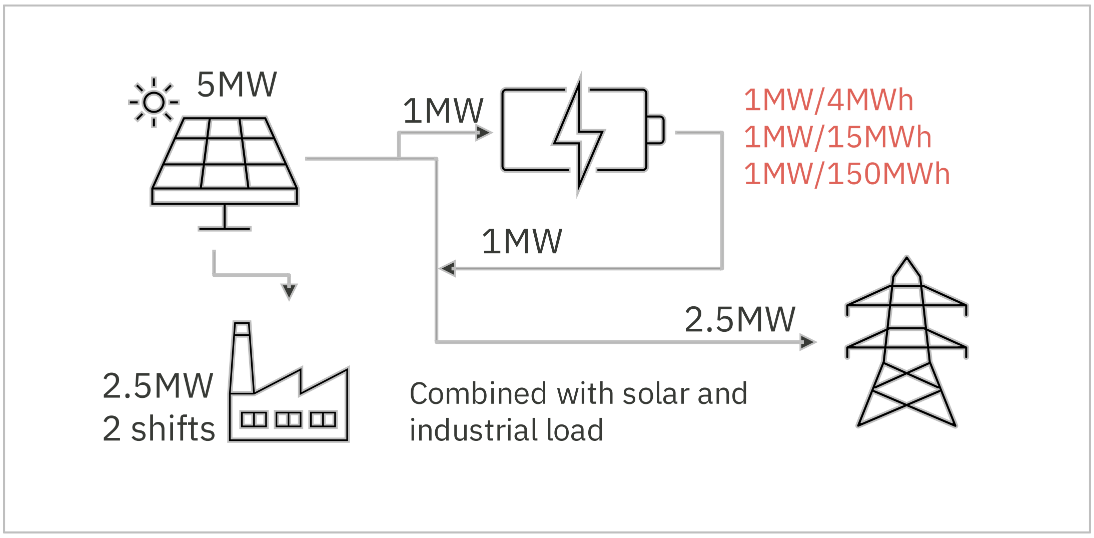

Figure 5 - Schematic overview of configuration with shared grid connection between industrial electric load and solar generation

Conversion use cases – these cases were analyzed for Carbyon, Eurus and Battolyser. Electricity is converted into CO_2 or hydrogen. In the case of Battolyser the conversion to hydrogen is combined with storage of electricity, inherent in the technology used.

- Merchant operation – hydrogen or CO_2 production
- Merchant operation - hydrogen or CO_2 production - with some capacity held back to offer system services to the grid
- Daily delivery obligation
- Operation during wind hours only (2 separate situations)
- Combined hydrogen production and electricity storage – merchant operation
- Battolyser in 'island operation' as pure electrolyser with dedicated electricity source

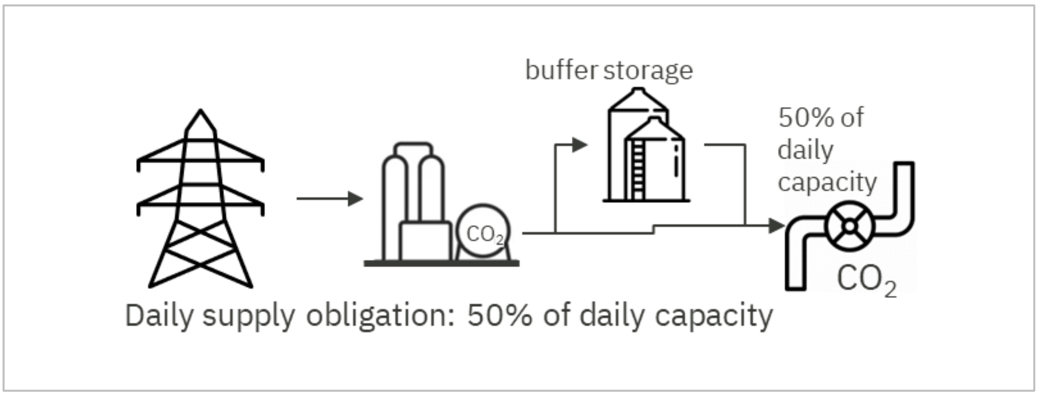

Figure 6 – Schematic overview of configuration with merchant operation CO_2 production and daily delivery obligation

Note that for the purposes of this calculation, in the cases where a power-2-X asset is combined with a generation asset, we assumed the power-2-X asset pays spot price for the power it uses. In practice we expect room to negotiate different terms, and these will affect the rate of return of an investment case.

4.3. Results

Flexible operation adds value. The earning potential of power-2-X assets is higher for an asset that responds to market prices than for one that follows a pre-set dispatch pattern. This holds for storage assets and conversion assets. We demonstrate this by showing in our calculation of earning potential the extrinsic value (value from flexible operation) separately from the intrinsic value (value from fixed operation).

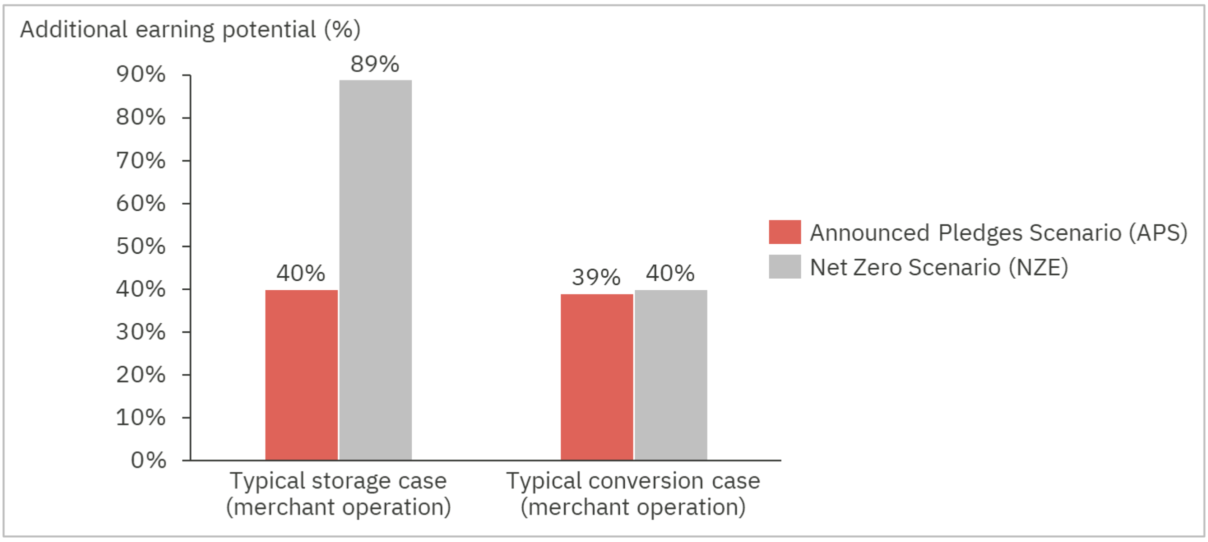

Figure 7 - Earning potential from flexible operation as addition to earning potential from fixed operation

Value can come from different places:

- Trading: peak shifting and peak shaving. At any moment in time, the decision when to switch on and off is taken in relation to spot market prices, based on a forecast of prices available at the time. The decision moment can be up to an hour or so before delivery under current market rules. A storage asset will essentially take electricity at cheaper times, to release it at expensive times ('peak shifting'). A conversion asset will try to use electricity in the cheapest hours, switching off at expensive times ('peak shaving').
- Capex optimisation: overplanting, reduced curtailment losses. Here the power-2-X plant is seen in combination with a generation asset (for example, a wind park), and they share a grid connection. To save capex costs, the grid connection may be undersized; or conversely the wind park

can be oversized ('overplanting'). The flexible use of the power-2-X asset can help minimise curtailment losses. An analogous case exists if sharing a grid connection with an industrial electricity user. Full evaluation of the investment case requires modelling the earning potential of the assets, and also the capex and other fixed costs associated with different combinations of power-2-X capacity, generation (or load) capacity, and grid connection capacity.

- Portfolio effects: reduced shaping & imbalance costs (at portfolio level and/or grid connection level). Here the context is a larger electricity portfolio (for example, that of an energy supplier with many customers, or that of an energy generator with many wind parks). The portfolio manager suffers shaping costs: since the power they purchased does not have the same profile from hour to hour as the power they supply to customers, they need to trade electricity in the market to be able to supply their customers at reasonable cost. Further, they suffer imbalance costs at any time when they have not exactly matched the power they purchased to the load they supply. For the portfolio manager, the ability to steer the power-2-X asset in response to the needs of the portfolio can save costs.
- Potentially, offering fast-response services to the electricity grid, such as Frequency Containment Reserve and Frequency Response Reserve (ancillary services). The Transmission System Operator buys certain products from the market, which enable it to maintain the smooth functioning of the grid. To be able to offer such products, capacity must be available at all times (for many products the capacity must be symmetrical, i.e. at any time the plant must be able to either take more or less electricity. Such products can be a lucrative way to sell flexibility. There are strict operational requirements. Potentially, a power-2-X plant would reserve a part of its capacity to offer such products, as a way of securing an additional income stream.

Storage tends to earn more in the APS scenario and conversion tends to earn more in the NZE scenario. With storage this is especially true for longer storage durations and is a consequence of the marginal price of electricity still being set by fossil fuels in some hours in this scenario. The higher earning potential in the NZE scenario for conversion cases is a consequence of the higher penetration of renewables leading to lower electricity prices and therefore more profitable conversion.

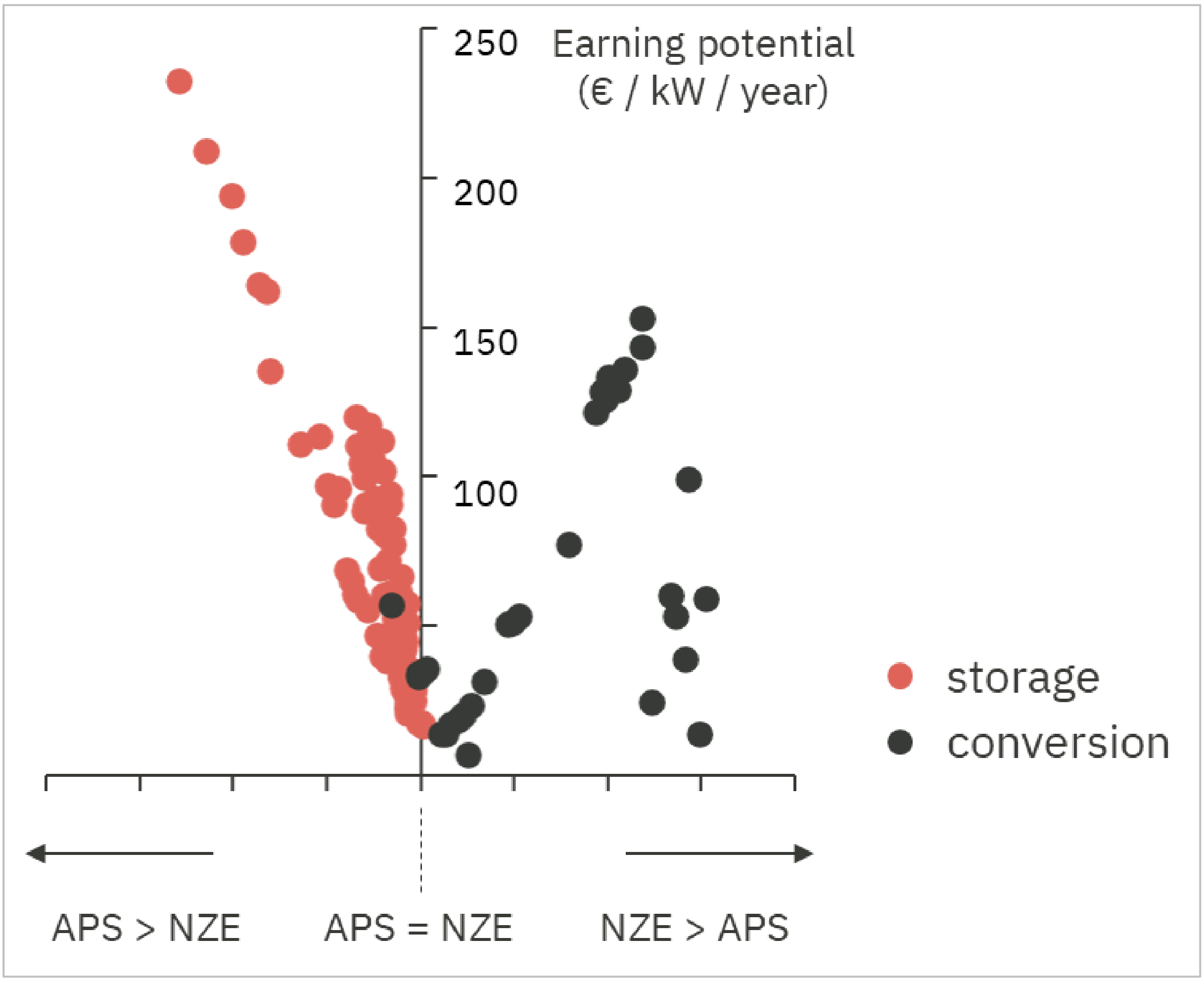

Figure 8 - Earning potential in for each configuration only showing the datapoint of the scenario with the highest earning potential, being either Announced Pledges Scenario (APS) or Net Zero Emissions (NZE). The graph shows storage cases typically have more earning potential in APS and conversion cases have more earning potential in NZE.

Sharing a grid connection with a wind park can bring value, especially in a situation where curtailment can be reduced. We estimate that a 20% undersized grid connection will lead to curtailment of some 8.5% by volume, costing some 105 €/kW of curtailed capacity/year in APS scenario (71 €/kW in NZE). This cost can be offset by flexible use of a power-2-X plant.

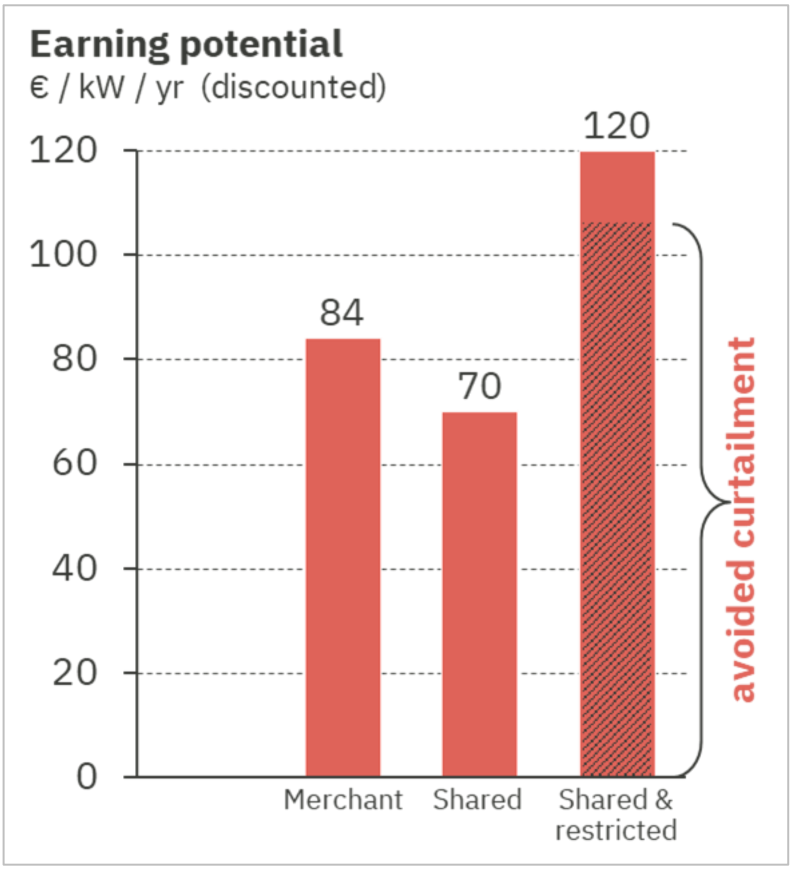

Figure 9 - Example of earning potential with storage asset in three configurations: merchant (direct connection to grid), shared grid connection with a wind park, and shared grid connection with a wind park with undersized (restricted) grid connection.

Figure 9 shows the effect of sharing and sharing & restricting grid connection. In the 'shared' case, the grid connection is sized for the wind park's maximum output. In the 'shared & restricted' case, the grid connection is sized for 80% of the wind park's maximum output. In both, the storage asset does not have priority at the grid connection.

In the ‘shared’ case, earning potential is lower than for a merchant asset, since the asset does not have priority for use of the grid connection and there are times when it cannot dispatch optimally with respect to market prices. In the ‘shared & restricted’ case, which has an undersized grid connection, dispatch is even less optimal when compared to a merchant asset; but the value enabling the wind park to continue producing at times when the grid connection capacity is not sufficient, more than makes up for this (‘avoided curtailment’).

Ancillary services could be a way to generate a separate income stream, unrelated to the primary business of the power-2-X asset. However, returns are unlikely to be significantly higher than the core business over the long-term, and therefore the ancillary services market should not be a priority for power-2-X developers.

Ancillary services are services which the electricity grid operator contracts from market parties to help keep the system running. These are typically fast-response services. In our use cases, we modelled 20% of the power-2-X asset’s capacity reserved for this purpose. There is an opportunity cost to doing this: that capacity is not available for normal power-2-X production. After taking this opportunity cost into account, offering ancillary services added a modest 10-14 €/kW/year to the earning potential of the asset. This conclusion should be taken as illustrative only (as explained in section 5.1), given the inherent difficulty of estimating the price of such services.

Arriving at a fair value estimate for a project requires the value of flexible operation to be taken into account. The earning potential from a flexible asset can be considered as consisting of two components: intrinsic and extrinsic value. Intrinsic value represents the earning potential of the asset, given a specific view of the future. The extrinsic part represents the value of being able to operate flexibly, reflecting that in practice we cannot know the future, and have an asset which we can switch on or off according to circumstances. In the use cases and scenarios investigated, extrinsic value can be significant (up to multiples of intrinsic value). This requires special attention when valuing the business case for a development project. Traditional valuation methods may not give a complete picture of the earning potential.

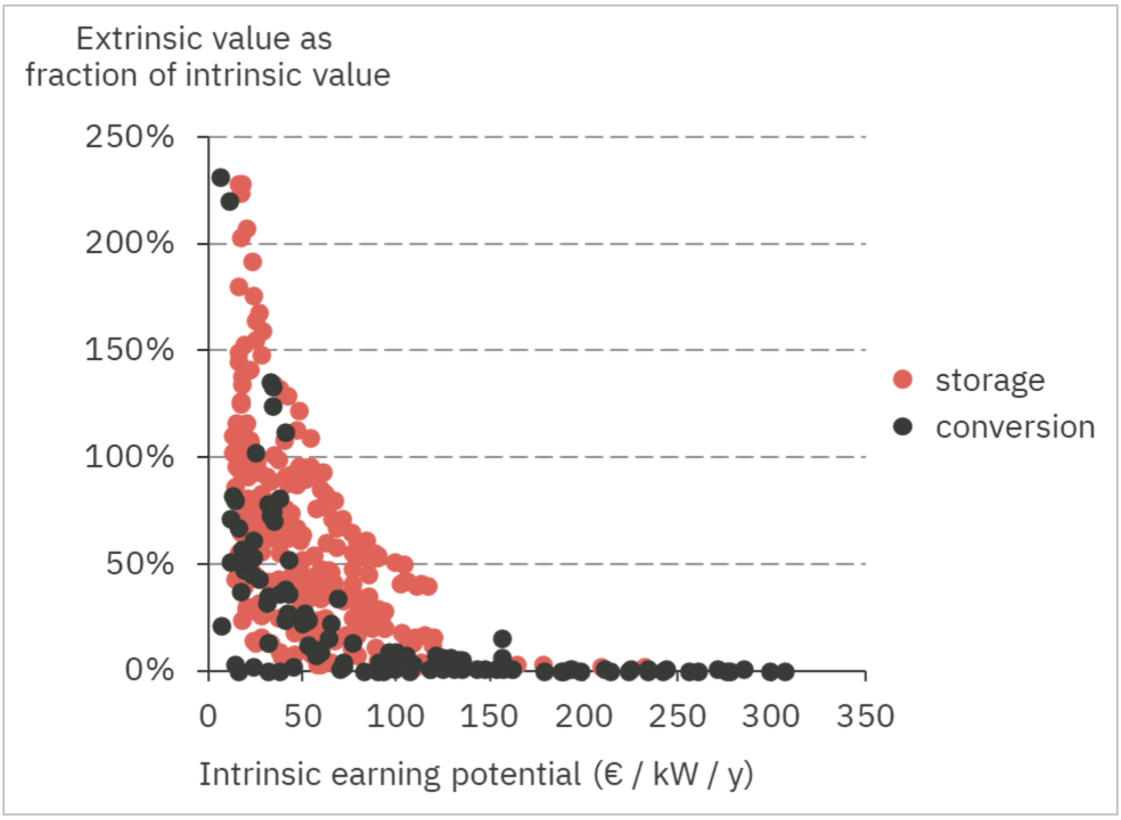

Figure 10 - Extrinsic earning potential as fraction of intrinsic earning potential (in percentage) plotted to the intrinsic earning potential

4.4. Discussion

As a general result, we observe that storage technologies have higher earning potential in the APS scenario than the NZE scenario, while conversion technologies have higher earning potential in the NZE scenario than the APS scenario. This is a consequence of generally lower electricity prices in the NZE scenario.

For both storage and conversion technologies, merchant operation gives the asset operator the most freedom to dispatch commercially, and results in high earning potential. Any contractual condition which entails an electricity offtake obligation (for example from a wind park) or supply obligation (for example a commitment to supply a certain daily volume) will need to be priced appropriately to compensate the asset for the resulting loss of freedom. In this study the asset is assumed always to pay the spot market price for electricity.

Combination with a wind farm at a restricted grid connection could yield high value considering the avoided costs of curtailment. Value results from the scarcity of grid connection capacity.

Emerging technologies seeking to de-risk their project should seek out suitable partners with the opposite exposure:

- A storage asset can likely add value to a wind park development where there is constrained grid connection capacity. But both wind farm and storage asset have higher earning potential in the APS scenario than the NZE. A potential partner for risk-sharing could be industrial load, which has higher earning potential in the NZE scenario with its lower electricity prices.

- Conversion technologies have higher earning potential in the NZE scenario than in the APS. Where there is unconstrained grid connection capacity, the power-2-x asset has higher earning potential in merchant operation than when combined with renewable electricity production. Merchant operation gives the freedom to use the asset only in the hours that it is profitable to do so. Nevertheless, for a conversion technology, renewable electricity production could be a good partner for risk-sharing purposes, generation has higher earning potential in the APS scenario than in the NZE.

Extrinsic value is an important component of the earning potential. For storage cases, it ranges from 20% to multiples of the intrinsic value, depending on the use case and scenario. For conversion cases it can reach well over 50% of the intrinsic value. Traditional valuation methods may not include this value component.

5. Legal perspective

5.1. Introduction

This section has been written to provide certain insights to the technology ventures in relation to the legal structuring and requirements that lenders generally and on a high level expect to see for project financed assets.[5]

The aim of this section is to allow entrepreneurs developing new technologies (also referred to as 'technology ventures') to anticipate such requirements in their dealings with project companies and to support the entrepreneurs in respect of their go-to-market strategy.

The project finance community is accustomed to renewable generation developments, where flexible operation doesn't arise. In the case of power-2-X assets, including the value of flexible operation in the financing structure would help reduce overall costs. Key to the success of a power-2-X project in this context will be how to incorporate the intrinsic and extrinsic value into the contract structure.

5.2. Typical project structure

Figure 11 provides an overview of the typical setup of a project financed project and the roles that the technology venture and the project company will have.

The green and blue shading indicates capital or operational expenditure. The purple shading indicates sources of income of the project company.

The project company is at the heart of the structure. It will enter into all relevant contracts that allow it to develop, operate and finance the asset.

Such contracts include the construction of the asset and the purchase of equipment from the technology venture (which may be combined in an Engineering Procurement and Construction Contract), other construction contracts, the purchase or long term use rights of the land as well as any contracts for operation & maintenance services, purchase of feedstock, offtake and sales of product or services, grid connections and utilities.

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[5] Please note that this section does <u>not</u> provide a comprehensive list of all legal matters that need to be taken into account when developing and financing a project. Expert advice may be required, including in relation to any regulatory matters.

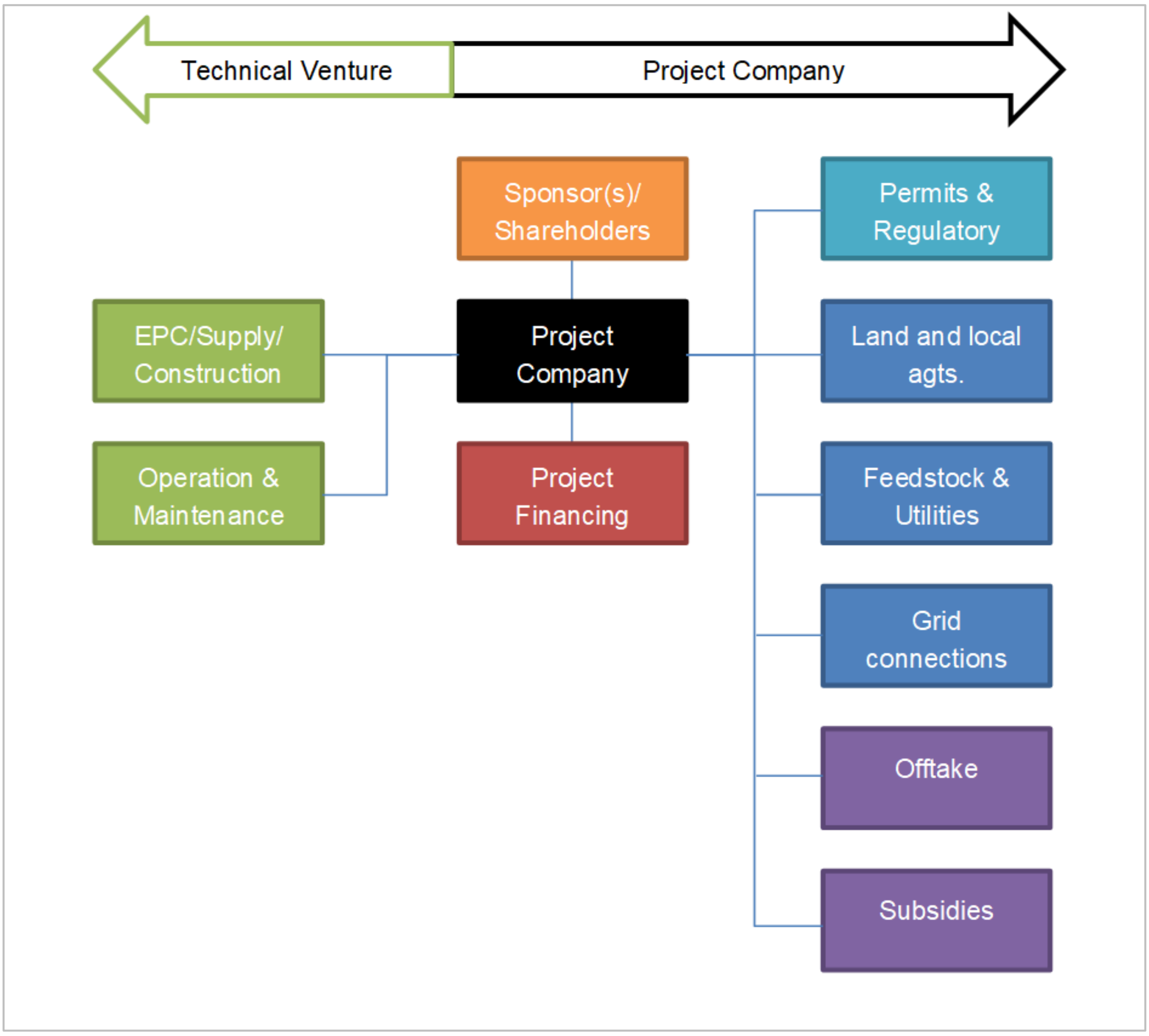

Figure 11 - Overview of the typical setup of a project financed project

5.3. Bankability

According to the Cambridge dictionary[6] '*bankable'* means '*likely to make money*' and '*acceptable to banks*'.

The assessment by the lenders whether a project is bankable will depend on the business case of the project company and more in particular whether it is sufficiently secured that the capital and operational expenditure of the project company and the repayment and interest obligations to the lender are ascertained by the project company's offtake, subsidy and other income after completion of the asset. The lenders will involve technical, legal, insurance and other experts in such a due diligence assessment.

A project finance is structured as a non-recourse or limited recourse financing. This means that the lenders can only take recourse on the project company and its assets and cannot rely on any other security (non-recourse) or only to a very limited degree (limited recourse). This aspect will obviously increase the lender's scrutiny when assessing the bankability of a project.

It is noted that in addition to the financing provided by the lenders, the shareholder(s) of the project company will also be required to provide funding for a certain portion of the investment costs to be made, for example by means of equity or shareholder loans.

5.4. Project company requirements

When taking the above bankability requirements into account, the project company will focus on generating a reliable, steady and sufficiently high cash flow in order to meet its obligations towards the banks and have a successful and profitable project.

The income generated by the project company from selling its products and services to its customers (i.e. the intrinsic value) will be the starting point for the underlying business case of the project company and the assessment of the banks.

In addition, the project company would aim to capitalise on the extrinsic value, for example by offering capacity congestion services[7] or saving costs when producing the products and services when electricity costs are low and stopping production

[6] Cambridge Dictionary – 'bankable' (link)

[7] In the use case that a project company is connected to the same grid connection as for example a producing asset, the project company would against payment curtail its operations or undertake to supply electricity to the grid in order to comply with the available grid connection capacity. Adding such elements may allow the producing asset to optimise its position for example by overplanting or avoiding grid congestion issues.

and sourcing alternative product in the market when electricity costs are high. If possible, such flexibility/extrinsic value is to be secured in the underlying contracts that the project company enters into[8]. This would allow the project company to reduce merchant risk in the project and strengthen its business case.

In respect of the supply, construction and/or operating and maintenance contract with the technology venture, the project company will therefore look for:

(a) certainty of performance of the asset in order to meet the requirements of its customers. Such requirements are often translated into:

   i. performance warranties[9]; and
   ii. liquidated damages to compensate the project company in case such performance warranties are not met;

(b) certainty of the amounts payable to the technology venture, which usually translates itself into a request for a lump sum price and limited circumstances under which the price can be adjusted;

(c) certainty of the moment of delivery of the product or completion of the construction works and, if not met, delay liquidated damages to compensate the project company for the consequences of the delay; and

(d) certainty about the transfer of ownership in view of the payment schedule, meaning that if the technology venture requires advance payments (before transferring products or adding value on site), bonds or other means of credit support will be requested.

5.5. Interests of the technology venture

When entering into a contract with a project company, the technology venture will have other areas of interest. These include:

(a) proving its technology in practice and gather data and information to further develop its technology;

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[8] Adding such flexible elements may impact the normal 'sales' contracts by including lower guaranteed amounts of product or availability of services and adding flexible pricing elements. The intrinsic and extrinsic contracts will need to be assessed jointly in order to arrive at the full value.

[9] Performance is used as a generic term and may include output, energy efficiency, availability, but also flexibility (by means of quick response times, etc.) and other aspects relevant for the specific project.

(b) safeguarding its intellectual property rights;

(c) generating income from selling or constructing the asset and providing operation and maintenance services. Such income will often also be used to recover its technology development costs;

(d) ensuring a cash neutral payment schedule to avoid that the technology venture must pre-finance any payments to its suppliers and contractors;

(e) avoiding responsibility for matters outside of its control;

(f) limiting its risk and exposure in case of issues in the performance of the contract, including by defining clear scope limits, time bars and pre-defined consequences (including by means of capped liquidated damages).

5.6. Step-in rights of the lenders

A project company will request the technology venture to cooperate with the step-in rights of the lenders. Usually these are in the form of a direct agreement, but these may also be included as a third-party stipulation in the contract. Such step in rights would allow, but not oblige, the lenders to:

(a) remedy any default of the project company (e.g. non-payment);

(b) have the agreement with the project company assigned to the lender (or another company designated by it); or

(c) require the technology venture to terminate the contract with the project company and enter into a new contract with the lender (or another company designated by it) on similar terms.

The technology venture will be asked to grant a grace period to the lender during which the lender can decide whether or not it will make use of its rights and the technology venture is prevented from making use of its contractual remedies (e.g. suspension and termination of the contract with the project company).

6. International perspective

To help guide the ventures' (future) commercial efforts, we researched the electricity market situation in selected countries: The Netherlands, Germany, Norway, Portugal, UK, USA (3 separate market areas), Australia (2 separate market areas) and Japan – a total of 11 markets. These countries were selected for having contrasting energy systems and also having:

- advanced economies;
- a generally positive attitude towards the transition to clean energy; and
- open electricity markets.

Each market's energy system was characterised according to 20 separate criteria. Of these, selected criteria were used for scoring. Each market was given:

- An overall flex score based on 5 key criteria. This score reflects the expected future need for flex and the openness of the market.
- Specific scores reflecting the prospects for each of carbon offtake, hydrogen offtake, long duration storage, and offshore wind power.

These scores were combined to generate an overall view of the relative attractiveness of each market to each technology in this study. The higher the score, the more attractive the market. The scores are shown in Figure 12, Figure 13, and Figure 14. A detailed rationale behind the scores is given in Appendix C.

6.1. Summary comments by technology:

Electricity Storage

Scores well in markets that need to integrate a lot of renewable energy, that have no hydroelectricity resources, or that have bottlenecks in their power grid. Further, niche applications exist in island situations.

Power to Hydrogen

Scores well where governments are giving clear support to develop a hydrogen economy, and where there is plentiful supply of renewable electricity. Further, niche applications exist in the production of circular synthetic fuels, plastics and builing materials.

Power to CO_2

Scores well where governments are giving clear support to develop CO_2 sequestration, and where there is plentiful supply of renewable electricity. Further, niche applications exist in hi-tech agriculture, and in the production of circular synthetic fuels, plastics and building materials.

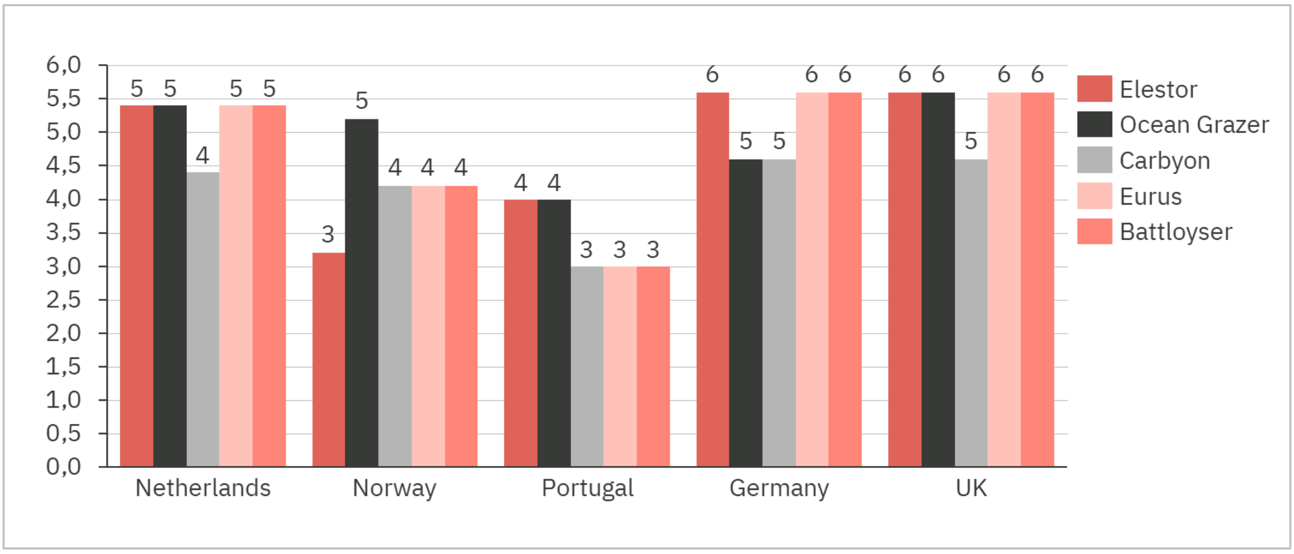

Figure 12 - Market attractiveness score the five technologies (part 1: EU regions)

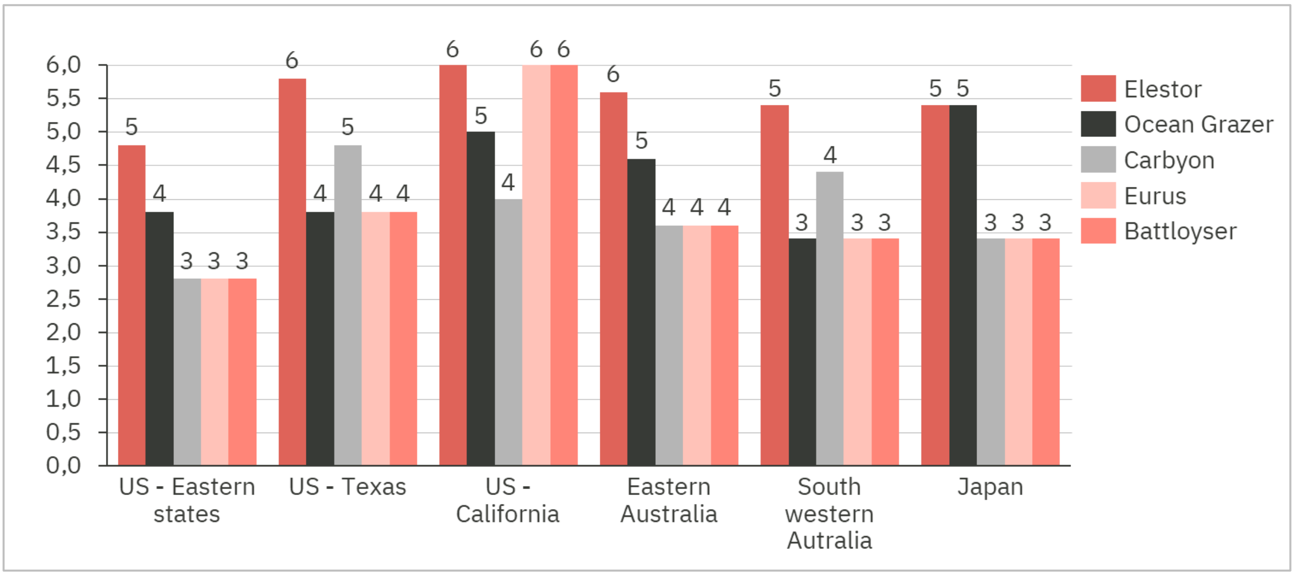

Figure 13 - Market attractiveness score the five technologies (part 2: non-EU regions)

6.2. Summary description per market:

Netherlands

Open market, high ambitions in renewables (onshore and offshore wind, hydrogen, CO_2 sequestration), high need for new sources of flexibility. A high-scoring market for all the technologies.

Norway

Open market, already near 100% renewables penetration (hydroelectricity), system is already rather flexible (again, hydroelectricity). Low electricity prices in the North can be interesting for conversion technologies as long as there is an offtaker for the product.

Portugal

Open market, high ambitions in renewables. Hydro provides flexibility. Plans for hydrogen and for CO_2 sequestration not far advanced, but pilot projects proceeding.

Germany

Open market, high ambitions in renewables (onshore and offshore wind, hydrogen), high need for new sources of flexibility. High pressure to implement CCS and future prospects for CO_2 sequestration offshore. A high-scoring market for all the technologies.

UK

Open market, high ambitions in renewables (onshore and offshore wind, hydrogen), high need for new sources of flexibility. Ambitions for CO_2 sequestration offshore 'subject to costs coming down'. A high-scoring market for all the technologies.

U.S. Eastern States (PJM)

Open market, highly dependent on fossil fuels and with plans to decarbonise gradually. Gas-fired provides flexibility (and will continue to do so). Relatively poor prospects for green hydrogen because of lower renewables penetration. Relatively poor prospects for CO_2 sequestration, unless regulation changes to mandate CCS.

U.S. Texas (ERCOT)

Open market, high ambitions for renewables, which are already struggling with frequent curtailment. Inadequate capacity connecting West Texas and Southeast Texas. Potential for blue hydrogen and possibly green hydrogen later on. CO_2 sequestration potential (depleted gas fields) but no state-level support for this.

U.S. California (CAISO)

Open market, high ambitions for renewables, which are already struggling with frequent curtailment. Inadequate capacity at various points in the grid. High ambitions for green hydrogen. CO_2 sequestration falls under State carbon-pricing scheme.

Eastern Autralia (NEM)

Open market, high ambitions for renewables. Inadequate flex sources. High ambitions to produce green hydrogen for export, although business case for this is entirely unproven. Subsidy available for CCS but no such project operational.

Southwestern Australia (SWIS)

Open market, high ambitions for renewables (but lower than in NEM). Subsidies focus on batteries. High ambitions to produce green hydrogen for export, although business case for this is entirely unproven. Prospects for CO_2 sequestration poor. Good location for circular synfuels manufacture.

Japan

Open market, high ambitions for renewables, including offshore wind. Many different grid areas, poorly interconnected. Hydrogen at an earlier stage of development than in Europe. Potential CO_2 sequestration sites have been identified, but no operational large-scale CCS projects.

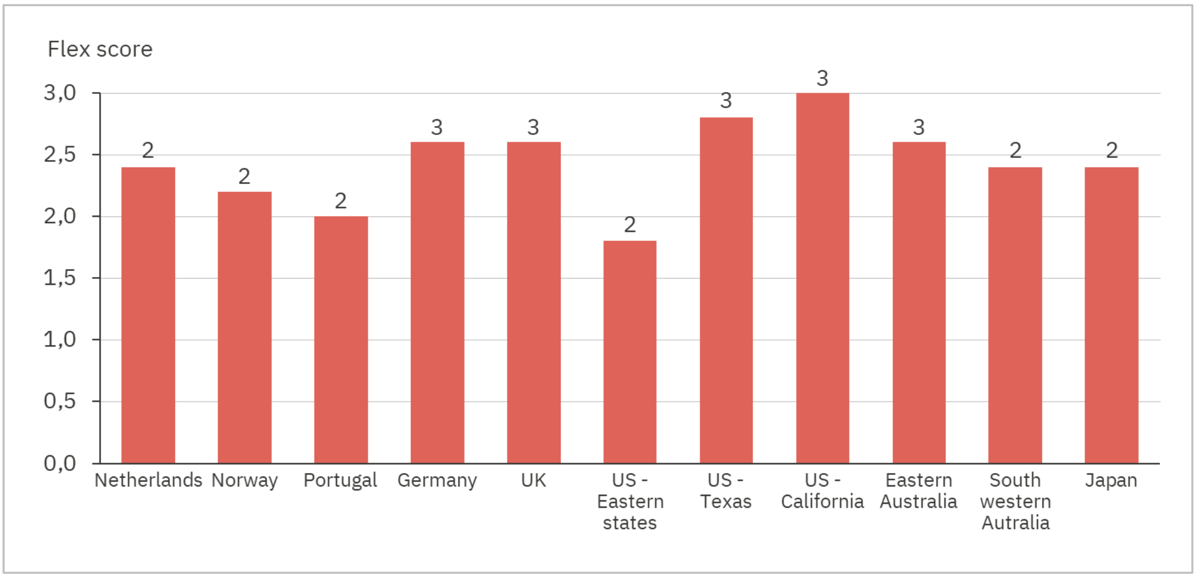

Figure 14 – Qualitative overall market attractiveness score per country or region

7. Conclusions and recommendations

Operating electrical assets flexibly can create value. The earning potential of power-2-X assets is higher for an asset that responds to market prices than for one that follows a pre-set dispatch pattern. This holds for storage assets and conversion assets. The asset can be seen as an option: it can be switched on or off at will. Choosing when to use the asset and when not to, in response to events (such as changes in commodity prices), means the operator can avoid running at times which would be loss-making and only run at times which are profitable. Value arises from one or more of the following:

- Trading: peak shifting and peak shaving
- Capex optimisation: overplanting, reduced curtailment losses
- Portfolio effects: reduced shaping & imbalance costs (at portfolio level and/or grid connection level)
- Potentially, offering fast-response services to the electricity grid, such as Frequency Containment Reserve and Frequency Response Reserve

The earning potential from a flexible asset can be considered as consisting of two components: intrinsic and extrinsic value. Intrinsic value represents the earning potential of the asset, given a specific view of the future. The extrinsic part represents the value of being able to operate flexibly, reflecting that in practice we cannot know the future, and have an asset which we can switch on or off according to circumstances. In the use cases and scenarios investigated, extrinsic value can be significant (up to multiples of intrinsic value). This requires special attention when valuing the business case for a development project. Traditional valuation methods may not give a complete picture of the earning potential.

Contractual agreements should envisage flexible operation. Wherever there is an obligation to take and use electricity (for example, an agreement to take power from a specific wind park) or an obligation to supply (for example, a daily minimum production of hydrogen), earning potential of the power-2-x asset is reduced. This needs to be compensated through monetary or other contractual conditions. Where a power-2-X asset shares a grid connection with another grid user (for example, a wind park), attention must be paid to priority rights at the grid connection.

Conclusions and recommendations – storage technologies

- Longer-duration energy storage (duration of a few days or more) could offer investors better return than short-duration (1 hour to 8 hours). Earning potential is approximately 60% higher for 150 hours duration than for 15 hours duration.

- The technologies studied have lower cycle efficiency than Li-ion batteries and potentially lower capex costs per MWh stored. Therefore, it makes sense to seek applications where extra storage duration is valuable.
- Seek investors who believe in the APS scenario or see it as a hedge, since earning potential is higher in the APS scenario than in the NZE (value is higher with slower rather than faster energy transition). A suitable risk-sharing partner could be a party with electricity load, which will have higher earning potential in the NZE scenario.
- Seek ways to combine storage with wind generation, and in such cases pay attention to priority rights for use of the grid connection, and to the transfer price of electricity between the wind park and storage asset. Under the right contract conditions this use case could have higher earning potential than merchant operation (and also be more robust, with higher earning potential across a range of scenarios). In the case of an undersized grid connection, value arises from avoided curtailment: 8,5% curtailment (by volume) is worth over 100 €/yr per kW of storage capacity in some scenarios. Depending on the relative capex costs of grid connection capacity and electricity storage, this could make for an attractive investment case.
- Internationally, many markets are attractive for such technologies, whose uptake is largely driven by the need for flexibility to absorb an increasing amount of electricity from renewable sources. Areas with weak electricity grids can have local need for flexibility to avoid curtailment of renewables or satisfy demand peaks. Such use cases make parts of the US interesting, as well as Japan, alongside northern Europe.

Conclusions and recommendations – conversion technologies

- Flexible operation adds significant earning potential to power-2-X conversion assets when exposed to spot market prices.
- Even when fully hedged with contracts to purchase electricity and sell product, the ability to operate flexibly has value, which can be realized if the right contractual conditions are in place.
- Combining with an electricity production asset, such as a wind park, removes some of the optionality from the conversion asset and generally lowers earning potential. Nevertheless, this could make sense where suitable contractual conditions can be agreed.
- Combining with an electricity production asset, such as a wind park, in combination with an undersized grid connection, could add value through (partially) avoided curtailment. Our calculations indicate that 8,5% curtailment (by volume) could be worth over 100 €/yr per kW of conversion capacity in some scenarios.

- Seek investors who believe in the NZE scenario, or see it as a hedge, since value is higher in the NZE scenario than in the APS. From a risk-sharing point of view, partners can be electricity production and/or electricity storage, which have higher earning potential in the APS scenario. DAC technology could potentially be seen as a CO_2 price hedge by large CO_2 emitters.
- DAC and electrolysis technologies are at an early stage of development and depend on a mix of fundamentals (cheap electricity, presence of creditworthy customers for the product) and regulatory/government support. While flexible operation adds significant value, these elements need to be in place first. Among advanced economies with open energy markets, promising countries are northern Europe, parts of the US, and Australia.

8. Appendix A – Research methodology

This report addresses the following questions related to five emerging technologies chosen as case studies. The work was supported by the ventures developing the technologies.

Question	**Approach taken**
To what extent can the devices be used flexibly	Questionnaire and interviews with the ventures involved to gather operational parameters
What use cases might this flexibility enable?	Workshop sessions with the ventures and with market experts to list likely use cases
What use cases are likely to have the highest value?	Calculation of future gross margin per use case in The Netherlands, based on internally consistent scenarios of the future energy system (see chapter 6), including the value of flexible operation
What key elements should project developers consider in contractual agreements around these technologies?	Expert legal input based on the use cases and on typical project development set-ups
What countries might be good markets for these technologies?	Desk research on selected countries, peer validation, and qualitative assessment and scoring

9. Appendix B – Power price curve

Announced Pledges Scenario power prices (base case):

Prices	2025	2030	2035	2040
Average	123.65	85.14	96.32	143.18
Min	-25.00	-25.00	0.00	0.00
Max	566.86	453.51	524.64	571.94
PRICES > 1000	0	0	0	0
PRICES > 750	0	0	0	0
PRICES > 500	4	0	2	258
PRICES > 250	11	136	456	729
PRICES > 200	26	0	14	72
PRICES > 150	456	21	352	188
PRICES > 100	7584	628	1096	3399
PRICES > 50	462	7239	4141	3326
PRICES > 0	214	734	2699	788
PRICES > -50	3	2	0	0
MC based on Gas/CO2	121.31	73.85	81.85	89.85
MC based on H2		153.45	134.55	115.45

Table 2 - Distribution of hourly power prices (in €/MWh) in the Announced Pledges Scenario (APS). MC = marginal cost.

Net Zero Scenario power prices (base case):

Prices	2025	2030	2035	2040
Average	107.99	61.11	76.25	102.46
Min	-25.00	0.00	-25.00	-25.00
Max	566.86	425.10	453.76	482.41
PRICES > 1000	0	0	0	0
PRICES > 750	0	0	0	0
PRICES > 500	2	0	0	0
PRICES > 250	0	44	108	114
PRICES > 200	3	1	4	6
PRICES > 150	358	85	250	15
PRICES > 100	5772	152	1290	4550
PRICES > 50	1770	5870	4629	3103
PRICES > 0	830	2608	2478	970
PRICES > -50	25	0	1	2
MC based on Gas/CO2	121.31	62.87	74.51	86.15
MC based on H2		153.45	134.55	115.45

Table 3 - Distribution of hourly power prices (in €/MWh) in the Net Zero Emissions scenario (NZE). MC = marginal cost.

10. Appendix C – International market-fit analysis

10.1. Europe: description

Criterion	Scoring	Unit or scale	Netherlands	Norway	Portugal	Germany	UK
market openness score : wholesale market	easy=3 medium=2 hard=1	easy, medium, hard	easy: many potential service providers [28][29]	medium, DSO facilitates [11][18]	medium, well-regulated wholesale market, in practice have a small choice of service providers [3]	easy: access is possible, many service providers (direct marketers) [2][5]	easy: dozens of potential service providers [17]
market openness score : grid services market	easy=3 medium=2 hard=1	easy, medium, hard	medium: stringent technical prequalification;many potential service providers; aggregation of smaller capacities possible to sell products to Tennet TSO [29][30]	medium: stringent technical prequalification; many potential service providers; products restricted to multi-MW size, aggregation is possible [12]	medium: open for generators, but highly concentrated market (EdP dominates). Demand is not yet able to participate, rules are under development [3]	medium: access is possible but relatively few aggregation service providers and stringent prequalification in each TSO area separately [22][23][24]	medium: stringent technical prequalification; aggregation of smaller capacities possible to sell products to National Grid ESO [11][29]
wholesale cleared market type, structure, coupling		description	part of European flow-based market-coupling mechanism [27]	market coupled to Nordics and continental Europe; Norway consists of 4 separate price areas [16]	Coupled to Spain, with frequent border congestions. [16] Also part of Europe's Single Day-Ahead Coupling (SDAC) mechanism[18], but poor interconnection between Spain and France means little price convergence between Iberia and continental Europe. [17] Iberian peninsula has different fundamental drivers: lots of hydro; lots of AC load in the summer.	part of European flow-based market-coupling mechanism. High renewables penetration leads to many periods of negative prices [10]	Energy market has price levels similar to continental Europe but somewhat more influenced by world LNG prices, entire GB is one price zone [26] Capacity market with long-term contracts.[19] Nodal pricing being considered for the future [25][27]
green attributes market		description & value (Eur/MWh)	Voluntary green certificates scheme (guarantees of origin) [25] Prices typically in the range 2--4 Eur/MWh [26] Imported certificates can be used to 'green up' energy which has no certificate (because it is from small-scale rooftop PV, or because it is from grey sources).	As of end 2021 new RES installations do not qualify for the joint Norway-Sweden certificate scheme [13]. Guarantees of Origin from Norwegian hydro production are exported in large volumes to the continent and Norway is considering ending this practice [19]	Guarantees of Origin system for renewables. Reserve price at auction 0.45 Eur/MWh [19][22][23]	Guarantees of Origin exist [26] but cannot be traded if from installations receiving EEG subsidy.[26] Imported certificates can be used to 'green up' energy which has no certificate (because it is from small-scale rooftop PV, or because it is from grey sources).	ROCs [30][31] is an mandatory green certificate system, with prices set by government (currently > GBP50 per MWh).[33] In addition, REGOs are the GB equivalent of European Guarantees of Origin.[32] REGO prices have been rising and are currently around GBP 2 per MWh.[34]
CO2 pricing		description & value (Eur/te)	EUA scheme plus an additional national CO2 charge on largest industry. This charge starts at 30Eur/te in 2021 and increases yearly [22][23][24]	Norway is part of the EU ETS and has proposed an additional national charge and extending coverage of to sectors not included in the ETS, potentially bringing the price of CO2 to 200 Eur/te by 2030. [22]	carbon tax in addition to EU ETS, and extends to all fossil fuel consuming sectors [3]	EU ETS applies, plus carbon certifcates system for non-EU ETS sectors since 2021 -- this scheme to merge with EU ETS pricing in 2027.[25]	CO2 price likely linked to EU ETS in future [14]
market concentration		number of large energy suppliers and collective market share in supply	3 'large' suppliers with combined > 75% market share [1][13]	no data on number of suppliers; regulator encourages common digitalisation and open market [11][18]; typical retail contract is indexed to hourly wholesale price, although fixed price is also available [17]	1 'large' supplier with 64% market share, 4 'large suppliers together 80%. [3] Recent (2018) full liberalisation, unbundling, and privatisation.[21][13][3]	5 'large' suppliers with combined 65% market share [5]	6 'large' suppliers with combined 82% market share [12]

Criterion	Scoring	Unit or scale	Netherlands	Norway	Portugal	Germany	UK
reliability of (HV) grid		unsupplied energy due to HV grid faults as % of load	unsupplied energy due to grid faults <0.01% [3]	unsupplied energy due to grid faults 0.04% [4]	unsupplied energy due to grid faults <0.001% [6][24]	unsupplied energy due to grid faults <0.01% [4][5]	unsupplied energy due to grid faults <0.0001% [10]
locational issues in grid	major issues=3 medium=2 no issues=1	description	renewables production offshore and in the North-East, demand centres mostly in the West. National 'copperplate'. Capacity of the existing grid is largely allocated (although not necessarily used). New connections must wait years for capacity to become available (once grid strengthening projects have been completed). Congestion management market mechanism currently being implemented (for those with existing capacity rights). [19][20][21][22]	large energy price differences are normal between north (dominated by production) and south (dominated by consumption), with prices in North close to zero, and in South close to continental prices [20]	RES mostly in North and demand in South and West. Grid currently limits at which locations new RES can be connected.[5] [7] No locational incentive in grid tariffs.[8]	Wind concentrated in North, solar in South. North-South constraints require a lot of redispatch actions.[3][5] Currently the whole country is one market area. Grid fees vary by location, but this seems not to be connected to a specific wish to provide incentives, rather it is a consequence of the large number of grid companies (4 HV, ca. 800 MV and LV).[5][19][20]	(renewables) generation concentrated in Scotland while demand concentrated in South of England. [25] Grid tariffs give locational incentives (differences North-South ca. 40 GBP/kW/yr). [28] Currently the whole country is one market area, no zonal or nodal pricing, so this is the only locational price signal.
congestion management: mechanism today and volume today and volume in the future		redispatch or curtailment and % of load affected today and estimate for 2030	Chiefly managed by redispatch, small but increasing amounts through market bids, curtailment is rare today but expected to become widespread in coming years. Redispatch costs were Eur 340 million in 2021 [18]	Statnett investing heavily in grid strengthening.[23] Market-based congestion management, through different bidding zones [16]	Recent improved cross border grid capacity allocation[26]. No published statistics on redispatch. Grid capacities sold as firm.[8]	Redispatch.Volume equivalent to some 3-4% of demand, historically costing 200-300 million Eur/yr [3][5][18]	redispatch and curtailment. [XXX] Nodal pricing being considered for the future [25][27]
interconnection		total in GW and % of peak demand	2400 MW of DC cables (representing ca. 12% of peak demand) plus interconnectors to Germany and Belgium (nominal capacity 7900 MW representing ca. 44% of peak demand today). IC capacity expected to grow to ca. 13000 MW in the next 10 years [2][16][17]	9950 MW interconnection [4], representing ca. 43% of peak demand [calculated from [2][4] and [5]	currently ca. 2 900 MW or ca. 13 % of generation capacity (=ca. 33% of peak demand), will increase to > 15% (ca. 40%) in the next couple of years [1][2][3][6][25]	23 GW import (20GW export) representing ca. 28% of peak demand [5][7]	7.4 GW currently, representing ca. 15% of hourly peak demand. IC capacity is expected to grow by a further 20GW by 2041.[7][8][9][22][23]

Criterion	Scoring	Unit or scale	Netherlands	Norway	Portugal	Germany	UK
renewables penetration		% of yearly demand volume generated by renewables	34% [calculated from 4 and 5]	ca. 99% [2]	60% [3][5]	46% [from 1]	43% (2020) [6]
residual load		TWh/yr not served by RES (current or recent)	74 [calculated from 5]	1.6 [2]	20 [3][5]	265 [from 1]	178 [calculated from 6]
current renewables technologies by generation volume		TWh/yr (current or recent)	biomass 11, solar 11, onshore wind 10, offshore wind 8 [4]	hydro 144, wind 12, thermal 2 [2]	hydro 14 wind 12 biomass 3.5 solar 1.5 [3][4][5]	wind onshore 55GW/102 TWh/yr, wind offshore 8GW/27TWh, PV 56GW/45TWh, biomass 9GW/41TWh, hydro 3GW/19TWh, waste 1GW/5TWh [5][6][8][9][10]	wind&solar 88 (wind onshore ca. 40, wind offshore ca. 35, solar ca. 13); 38 bios&waste, 7 hydro [6]
future renewables technologies by generation volume or capacity (future according to current poicies)	>100% RES=3, >60% =2, <60%=1	GW or TWh/yr in 2030	by 2030, 70% of electricity from renewables; and 35TWh/yr to be from onshore wind and solar -- expect more than doubling in offshore wind, onshore wind, and solar capacity [6]	add 9TWh/yr hydo, 14 TWh/yr wind by 2030 [14]	by 2030, 10-fold increase in PV and doubling of wind capacity, to get to 80% RES (hydro +1GW, wind +4GW, PV +8GW) [3]	add 65GW onshore wind, 22GW offshore wind, 129GW solar, by 2030 [11][12][13]	a world leader in offshore wind, planning to quadruple from 12.7 GW today to 50GW by 2030 [16] all new capacity to be low CO2 - nuclear or renewable, with a small amount of hydrogen-fired generation for exceptional peak times
need for (additional) flex	high=3 medium=2 low=1	GW flex capacity needed (if known) or low/medium/high	high: need to compensate for more than doubling electricity from renewable sources and for increasing heatpump and EV adoption [16][17]	low in winter, higher in summer. Norway has 1439 MW of pumped storage capacity and quite some flexibility in its run-of-river hydro. Most of the time Norway exports flex but in prolonged periods of low precipitation the system needs to import energy and flex. And grid congestion means that additional storage could be valuable in specific places until the grid can be strengthened--expecially in the North [1][2][3]	increasing, but mitigated by interconnection capacity to Spain and by hydro and pumped hydro flex. Local storage may be helpful at congested nodes where new RES wants to connect. [3][7]	high to cope with the continuing transition to solar and wind. Since October 2021 renewable production is required to participate in the redispatch (congestion management) mechanism. Redispatch volumes can reach several % of transported electricity.[21]	high: from 10GW today to 30GW in 2030. Up to 24GW LDES to secure net zero [20] out of a total of 210-230GW flex needed for net zero (including demand and supply flex). [21][2][3][13]
smart meter penetration		% of meters that are smart (current or recent)	high penetration of smart meters (to be near 100% end 2022)[11][13]	high penetration of smart meters (100%)[15]	3.9 mio smart meters (end 2021) or near 70% penetration [3][14]	Germany is slow with roll-out of smart meters (only 50k installed at end 2020, for a country with 41 million households) [16] [17]	penetration of smart meters 42% at end 2020 [6] and 50% at end 2021 [18]
political and regulatory attitude towards energy transition ; subsidies		description	positive - clean energy technologies subsidies through Contracts for Differences; cost of avoided CO2 capped at 300 Eur/tonne [8][15]	neutral (given the already high penetration of renewables) - policy is to go for subsidy-free offshore wind and build interconnector capacity. As of end 2021 new RES installations do not qualify for the joing Norway-Sweden certificate scheme [6][13]	goal: 80% RES electricity by 2030 [3]; and reduced import dependence [3]. Large scale RES concessions by reverse auction with 15-year contract. FiT for small-scale PV and reduced grid fees for communities.[3][12][20]	positive; draft new energy law aims for 80% renewables by 2030 and 100% by 2050. Exsiting EEG subsidies will be revamped to iclude new sectors and offshore wind will be subsidised via CfDs.[13]	positive - for example, government-subsidised innovation in flex; and renewable generation subsidies through Contracts for Differences

Criterion	Scoring	Unit or scale	Netherlands	Norway	Portugal	Germany	UK
prospects for H2 offtake/infrastructure and key locations	good=3 medium=2 poor=1	description	Active hydrogen development based on (1) offshore pipeline infrastructure with potential for blue hydrogen production/import (2) large offshore wind resource to produce green hydrogen and (3) planned conversion of parts of the natural gas grid onshore. Vision to be an exporter of hydrogen. Aim for 4GW electrolysers in 2030, and large-scale infrastructure already in operation by 2030.[8][9][10]	Good prospects for green H2 production in North. Northern Norway+Sweden projected to have >5TWh/yr of electrolyser load by 2030. Further growth depends on development of local demand (eg steel manufacture). Also potential for blue hydrogen production offshore (from natural gas), using existing pipeline infrastructure to transport to the continent.[8][9][10]	prospects to create a H2 hub in Portugal, based around green H2 from offshore wind. Early days.[3][9] National CO2 reduction plan doesn't foresee significant amounts of hydrogen until after 2040. [11]	'national H2 strategy' and 'national H2 board' are in place. 700 million Eur being invested in pilot projects.[14]	H2 seen as critical in the energy transition, 5GW production by 2030 and H2 infrastructure under development [2][15]
prospects for CO2 offtake/infrastructure and key locations	good=3 medium=2 poor=1	description	Good prospects for CO2 storage in depleted offshore gas fields. Also pipeline infrastructure to UK and Norwegian North Sea. Porthos project up for FID in second half of 2022.[7][12][14]	Good prospects in combination with (offshore) blue hydrogen production and potentially CO2 imported by pipeline from Europe. Equinor target 5-10 million tonnes per year CO2 sequestered by 2030 [7][21]	Carbon sequestration underground (offshore) is an option as is forestry [3] [10] [11] [15]. Chemical/process industries around Figueira da Foz in focus for pilot projects. [15]	Government sees CCUS as needed to complete the energy transition, however any carbon captured would be stored in offshore North Sea fields (likely Norway) as there are few suitable sites on land.[15]	Depleted North Sea gas fields and existing offshore gas pipelines could potentially be converted to CO2 storage - aiming for CO2 storage at scale in the 2030s 'subject to costs coming down' [4][5]
prospects for long-duration energy storage	high=3 medium=2 low=1	description	Long-duration flex will be needed in the energy system as NL stops using natural gas. Topography is not suitable for pumped hydro. [8]	Poor, Norway already has 1439MW of pumped hydro storage [3], and total hydro reservoir capacity of around 70% of annual demand [2].	Pumped hydro expansions are being planned [3], and expect the increase in RES (especially solar) [3] to increase storage needs.	Good, especially with electrification of space heating expected to displace gas and oil, and very high RES penetration.[27]	Up to 24GW LDES to secure net zero [20]

10.2. Rest of world: description

Criterion	Scoring	Unit or scale	PJM	ERCOT	CAISO	Australia (NEM - Eastern Australia)	Australia (SWIS - Southwestern Autralia)	Japan
market openness score : wholesale market	easy=3 medium=2 hard=1	easy, medium, hard	easy. In addition to the energy market, there's also a capacity market with long-term contracts. Many service providers offer maket access.[36]	easy, many power marketers and aggregators active [1][12][14]	easy, need a service provider/aggregator.[16] Participation possible with small assets. [17]	easy: choice of service providers, transparent market [42][29][43]	easy: utility-scale assets can take part [1]	medium: open to third-party access [25]
market openness score : grid services market	easy=3 medium=2 hard=1	easy, medium, hard	medium: PJM buys various ancillary services [16] from the market and also a locational demand response product [15]. A proposal is underway for a new 'aggregator' role [6].	easy, many aggregators, competitive market [11][13]	easy, need a service provider/aggregator.[4][14][15][16] Participation possible with small assets. [17]	easy: aggregators have displaced incumbents in offering FCS in some areas, and demand can participate [41][42]	medium - doesn't appear to be possible for small-scale assets [21], larger assets need to go through an incumbent [14] [1]	medium: ERAB mechanism for demand response and aggregation [3][4][27]
wholesale cleared market type, structure, coupling		description	PJM area uses nodal pricing: prices diverge if there's congestion between nodes. Generator offers must include a fuel cost policy (the cost of maintaining adequate fuel supplies is borne by the market). [13] Market mechanism includes socialising the cost of uplift payments to generators in case of grid outages, congestions, etc. [14][19]. In addition to day-ahead and within-day energy markets, PJM also operates a capacity market. [1][2][3][18]	energy market day ahead and real-time with locational pricing. Grid services, congestion revenue rights. Scarcity pricing mechanism caps offers for ancillary services. No capacity market, capacity offering ancillary services/reliability assurance gets compensated a start fee and energy fee [7][8][9][10]	energy market - day ahead and intraday. [6] Grid services: ancillary services (regulation and reserve), financial congestion revenue rights. [5][6] Aggregators can participate with DR capacity. [4]. CAISO also buys capacity products including one-year contracts. [7][8][9][28]	single pool market with market splitting in case of congestion (Eastern Australia NEM has a well-connected grid within its area)[9] no capacity market but this is being considered [18]	energy market (DA and intraday), ancillary services, and capacity market with 1-year product for both generation and load. Reform currently being planned to go live in October 2022 [1][2][15]	cleared market with system price and local prices in each of the 9 main grid areas (market coupled).[5][25] Currently 133TWh/yr (=13% of total load) gets transferred inter-regionally. [6] capacity market has started, first delivery year 2024 [26][27][28]
green attributes market		description & value (Eur/MWh)	green certificates (GATS) [17] priced 300-400 USD/MWh for recent certificates [31]	RECs [15] tied to a supplier target for % RES. Texas has exceeded this capacity, suppliers have an easy time complying, REC prices are low (typically just 0-2 USD/MWh). [16]	green certificates with quota system (RECS). [18][22]	national RECs scheme for utility-scale RES (LGCs) [23][32] Current prices ca AUD 50 per MWh [24]. Also local markets in NewSouthWales [25] and in Victoria [26]	national RECs scheme for utility-scale RES (LGCs) [7] current prices ca AUD 50 per MWh [8]	four different green certificate schemes (non-fossil non-FIT, non-fossil FIT, green certificates and J-credits. Prices typically 1 to 3 yen/kWh (=7 to 21 Eur/MWh)[11]
CO2 pricing		description & value (Eur/te)	Extensive study work done by PJM to incorporate a carbon pricing mechanism. Proposal shelved for now [37]	voluntary bilateral market for carbon credits [17] no quoted prices, but anecdotal evidence shows ca. 9-26 USD/te [18][31]	Cap and trade system in CA. [19] Llinked to Quebec scheme. [21] Recent prices around USD 30/tonne [20]	national cap and trade system [27] Prices well below Europe (ca AUD 30 per ton) [28]	national cap and trade system [9] Prices well below Europe (ca AUD 30 per ton) [10]	voluntary certificates scheme (J-VER and J-credits) covers only a small %age of emissions [13] and over 2018-21 the price was just 0.14 Eur/te CO2 [13]
market concentration		number of large energy suppliers and collective market share in supply	no data found	ca. 50 retail suppliers in customer choice areas [19], competitive market	PG&E 5.5 million electricity meters ; Southern Calif. Edison 15 million consumers or ca. 5 million meters ; SDGE 1.4 million meters = combined share of 89% of households [11][23][24][25]	3 'large' suppliers have combined 64% market share. [2] and large players have ca. 80% market share [29][2]	household customers are not free to choose supplier in SWIS [13], the incumbent (Horizon Power) has 100% of the household market	all incumbents (one large supplier per area) still have over 80% market share in their area [2]

Criterion	Scoring	Unit or scale	PJM	ERCOT	CAISO	Australia (NEM - Eastern Australia)	Australia (SWIS - Southwestern Autralia)	Japan
reliability of (HV) grid		unsupplied energy due to HV grid faults as % of load	ca. 0.5% for US+Canada HV grids. [20] No specific data for PJM.	ERCOT often struggles at times of high demand [2] [20] and has relatively low reserve margin compared to other US grids [10]. HV grid availability targets 99.9%[21] Across US, unsupplied load ca 0.5% from HV grid faults. [22]	Unsupplied load ca. 0.5% for US+Canada HV grids. [35] No specific data for CAISO. Rolling blackouts not unusual in hot periods with high cooling load [30][31][36]. California customers typically without power 200 minutes/year from DSO grid alone. [31][32][33][34]	typically <0.001% within NEM. [38] Many parts of the country have no HV grid (local microgrids or self-sufficient homes). [5]	Western Power reports ASAI given as >99.99% [11], so typically <<0.1% unsupplied energy	implied by data in [14]: unsupplied load ca. 0.1 %-0.3% (but varies a lot year to year due to influence of storms and earthquakes)
locational issues in grid	major issues=3 medium=2 no issues=1	description	Different market prices in different locations (nodal pricing mechanism).[35] PJM also uses nodal pricing to buy curtailment and ancillary services.	West texas is insufficiently interconnected for the volume of wind generation existing and planned. Load centres are East and South, although recently data centres and oil industry hasve increased demand in West somewhat. Ercot applies locational pricing and financial congestion revenue rights. [5]	addressed by locational pricing (congestion pricing). CAISO area not particularly short of HV capacity. [37] Congestion costs historically ca. 1 USD/MWh of demand. [38] CAISO also facilitates trade in financial congestion revenue rights.[47]	Typically no congestion across NEM 90% of the time today. [33] But future RES likely to be in regions with no or little grid connection.	No immediate grid strengthening envisaged except in high growth scenarios [6] Currently no locational pricing but AEMO gathering data on congestions [12]	East and West not ssynchronous, limited HVDC interconnection between these areas (1.2GW). [6] With East and West, distinct grid zones because of island geography. [6] Government is working on a 'masterplan' for strengthening the grid, to be issued end 2022 [9] Offshore wind is expected to be built in Hokkaido and Tohoku, requiring grid strengthening. [6]
congestion management: mechanism today and volume today and volume in the future		redispatch or curtailment and % of load affected today and estimate for 2030	market-based via service providers [33]. Forced curtailment of solar and wind also needed. For wind this is typically in a range 0 -- 6% of generation a monthly basis, much lower for solar [34] , implying curtailments are equivalent overall to around 0.1% of load because of low renewables penetration).	5 TWh curtailed in 2021 [36], or some 1.25% of load; or some 4% of renewables volume, but up to 30% in some areas.	Overall, curtailments are around 0.6% of load (2021), or some 1.8% of renewables volume -- and increasing [2][45][46]	curtailments in case of congestions [34] mainly based on price signals but sometimes forced by the grid [35][36]. Today in the order of 1% [37] but expect curtailment to rise to 20% in 2050 [35]	Forced curtailment in case of congestion. Currently no locational pricing but AEMO gathering data on congestions [12] WEM reform planned in 2022 for more dynamic grid management [15]	curtailment, with Kyushu worst affected, 3-4% of generation in 2021 [22][23][24]
interconnection		total in GW and % of peak demand	interconnected to surrounding areas [21], with ca. 20GW interconnector capacity implied by data in [23]. Volumes are expected to treble, with peak import reaching 20GW (ca. 15% of load). [7] On national level, increased East-West interconnection is being considered to enable RES integration. [22]	peak demand is ca. 80GW [8] Ercot is separate than other grid areas 'interconnections' [23] and is only poorly interconnected	peak demand ca. 50GW [1], max usable interconnection ca 15.5 GW or 35% of peak demand. [13]	none. Eastern Australia region forms one interconnected grid with no interconnectors; peak demand is ca. 34GW, reserve margin is up to 20GW, a much higher ratio than is normal in interconnected system. [1][2][4][9][20] Southwest Autralia (around Perth) has a smaller interconnected grid but serves only 2.3 million customers (see SWIS column). [21][22] Other parts of Australia are either off-grid, or connected to local, self-sufficient microgrids. [5]	peak demand ca. 4GW [5]	none - Japan is an island system itself made up of a number of interconnected island systems. [6]

Criterion	Scoring	Unit or scale	PJM	ERCOT	CAISO	Australia (NEM - Eastern Australia)	Australia (SWIS - Southwestern Autralia)	Japan
renewables penetration		% of yearly demand volume generated by renewables	7.2% [11][5]	wind 24%, other <5% [4]	ca. 33% [42]	in Australia as a whole 29% (2021): wind 10, hydro 6, bio 1, rooftop PV 6, utility scale PV 4.[30] NEM states have highest RES share. [30] NEM represents 203 out of 266 TWh load in Autralia, implying > 33% RES in NEM. [2][30]	ca. 2% hydro, 10% other [4] RES are 34% of production capacity {5}	19.8% [1]
residual load		TWh/yr not served by RES (current or recent)	770 [11][5]	yearly demand is 390 TWh [4] , not served by renewables is 282 TWh	demand is 270 TWh/yr [2][27], not served by RES is 180 TWh	146TWh [calculated from 2, 30]	demand ca. 18 TWh [6]	ca. ca. 800 TWh/yr [1]
current renewables technologies by generation volume		TWh/yr (current or recent)	Wind 30.7, hydro 16.9, solar 6.7, other 5.4 [11][5]	wind 24%, solar 3% other 1% [4][25] or wind 94 TWh, solar 12, other 4	Total demand ca. 270 TWh/yr of which solar 25%, wind 8%, hydro 7%(dry year), geothermal 6%, biomass 3% (in wet year hydro is up to 21%). [26][27][42]	wind 5.4, hydro 3.8, PV rooftop 3.2, PV utility scale 2.2 [calculated from 2, 30]	from [4] and [6], ca 1 TWh wind, 1 TWh solar	ca. 198 TWh/yr, of which solar 79, hydro 78, bio29, wind 9, geothermal 3 [1]
future renewables technologies by generation volume or capacity (future according to current poicies)	>100% RES=3, >60% =2, <60%=1	GW or TWh/yr in 2030	PJM 'policy' scenario calls for 22% RES by 2035, adding 19GW onshore wind, 11GW offshore wind and 24GW solar (policies in place April 2020). PJM 'accelerated' scenario provides for 50% RES by 2050, adding 36GW onshore wind, 29GW offshore wind and 55GW solar. [7] Individual State targets vary. [12]	Huge potential to develop further onshore wind and solar. No mention of offshore wind. Ercot publishes 10-year power and load forecast [26]	add 120 GW RES in next 2 decades [1] 60% RES by 2030 [2][22] and 100% by 2045 [3]. 2040: 53GW solar, 10GW offhsore wind, 2GW onshore wind, 2GW geothermal, plus 12GW out-of-state wind. [3]	82% RES in the mix by 2030 [16] Roughly doubling wind and rooftop PV volume to 2030. Annual target 33 TWh/yr additional large scale RES each year to 2030. [17][32] Offshore wind licensing regime just installed (June 2022). State of Victoria plans 2GW offshore wind by 2032, and has potential for 13GW nearshore, plus 20GW in deep water [12][13]	70% of capacity to be RES by 2040. [5] As much as 8 GW solar and wind + 2GW batteries + 0.8GW gas-fired to be added by 2030 in growth scenario.[5]	max realistic additions to 2030 (in line with current policy) : solar 145GW, onshore wind 18, offshore wind 10 [6]. Current capacities are solar ca. 50GW, onshore wind ca. 3.5GW, offshore wind 0 GW [7][10] huge potential for offshore wind -128 GW for fixed and 424GW for floating [8]
need for (additional) flex	high=3 medium=2 low=1	GW flex capacity needed (if known) or low/medium/high	medium: implied by [7]: PJM expects RES to take part in system services in future, and to continue managing load-following with gas-fired and batteries	high to complement wind/solar build-out and given the inadequate reserve margin. Currently a rush for fixed battery investments [27]	2031: 9.6 GW battery and 0.6 GW long-duration storage (LDES). 2040: 37GW battery and 4 GW LDES. LDES aims at pumped hydro but 1600MW has no identified site (yet). [3]	high: new RES is all wind/solar, while coal plants are due to be retired (although mostly after 2030) [40]. Clear focus on utility- and community-scale batteries [16]. Value of flex going up [38][42]	high, planned to be partly satisfied by gas-fired and mostly by batteries. Range of forecasts at 2030: 0 to 2 GW batteries. [5] As a relatively small islanded grid, high penetration of RES is especially challenging for system stability [15]	63 GW of battery expected by 2030 (from a few hundred MW today) [6]. Gas-fired still expected to play an important part in flex.
smart meter penetration		% of meters that are smart (current or recent)	>65% across the US [24]	Ercot covers ca. 90% of Texas [6] which has 7.4 million households [2] more than 50% smart meters [24]	2020: 11.9 smart (advanced) meters activated [10] out of ca. 30 mio consumers [2][11][12], >50% deployment [43]	varies by state from 25% to 100% (2021) [44]	1.1 million connected customers [3]	over 75% smart meters [14]
political and regulatory attitude towards energy transition ; subsidies		description	varies by State and city. Virginia aims for 10GW offshore wind by 2030. [25] Nationally, aim is 30GW.[26]	state support for RES through tax credits [34]	positive: clear aim to phase out fossil fuels and electrify. [44]	policy focuses on building more wind, solar and storage, rather than retiring fossil fueled plants [6][40]	some support for rooftop solar and small scale assets through certifcates and obligation scheme [18] [19]	FIT for RES investments, long-term (10-20 years) [15] . Current ceiling price ca. 90 Eur/MWh for solar.

Criterion	Scoring	Unit or scale	PJM	ERCOT	CAISO	Australia (NEM - Eastern Australia)	Australia (SWIS - Southwestern Autralia)	Japan
prospects for H2 offtake/infrastructure and key locations	good=3 medium=2 poor=1	description	policy focus is on R&D to lower H2 costs. [27] Lower RES penetration compared with Europe makes green H2 less likely.	Good prospects from converting exsiting (natural gas) infrastructure. Blue hydrogen potential as well as green. [28] World's largest (60GW) green H2 project announced, including UGS [29]	mechanism in place for hydrogen to be used within LCFS framework for transportation fuel (avoided CO2) prices have been as high as 180 USD/ton, currently around 100 USD/ton [40][41]	ambition to become a world leader in green hydrogen, exporting even to Europe. Many initiatives at pilot stage.[7][8]	Potential for green hydrogen for export. Commitment from government to support [16][20]	Serious government attention to hydrogen, but projects are at pilot stage.[19]
prospects for CO2 offtake/infrastructure and key locations	good=3 medium=2 poor=1	description	government support for DAC research. [28] Various CCS projects shown in [29] show CCS chiefly of interest where sequestration can be combined wiith enhanced oil recovery.	potential to create a CO2 pipeline hub by reusing existing oil & gas infrastructure. Only federal 45Q subsidy is mentioned, no state-level incentives. [32] huge underground sequestration potential [33]	sequestration can be eligible for the LCFS (low carbon fuel scheme) and may become viable - prices have been as high as 180 USD/ton, currently around 100 USD/ton [39][40]	Industry/power genertion CCS is eligible to apply for subsidy (awarded by auction), but no such project is operational.[3][10][11][12][14] Heavy investment in CCS technology to support fossil fuels industry [31]	Potential sequestration in saline aquifers [17]	Policy currently being formulated. [20] . Various pilot projects for CCS, and potential geological sites identified. No pre-existing pipeline infrastructure that could serve to transport CO2 [17][18]
prospects for long-duration energy storage	high=3 medium=2 low=1	description	storage targets set in States of Virginia (3100MW), New Jersey (2000MW) [30]. Capacity market offers long term contracts. Flow battery tech is not yet mature [32]	LDES clearly needed to decarbonise the grid [30]. Currently around 44% of Texas generating capacity is from natural gas. [4] And this is hardly able to provide the reliabilty required.[2][20]	0.6GW LDES wanted by 2031. No indication how to solve LDES requirement in areas where pumped hydro is not possible. [3]	Good. NewSouthWales prioritises 2GW of LDES (defined as 8 hours storage)[45] Pumped hydro schemes being built [46][47]. NEM is already curtailing renewables production.[35]	LDES clearly a help to decarbonise the grid, but only batteries considered in planning [6]	Japan seen as a market for LDES after 2030 [21]

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