Beyond LCOE: New Assessment Criteria for Evaluating Wind Energy R&I

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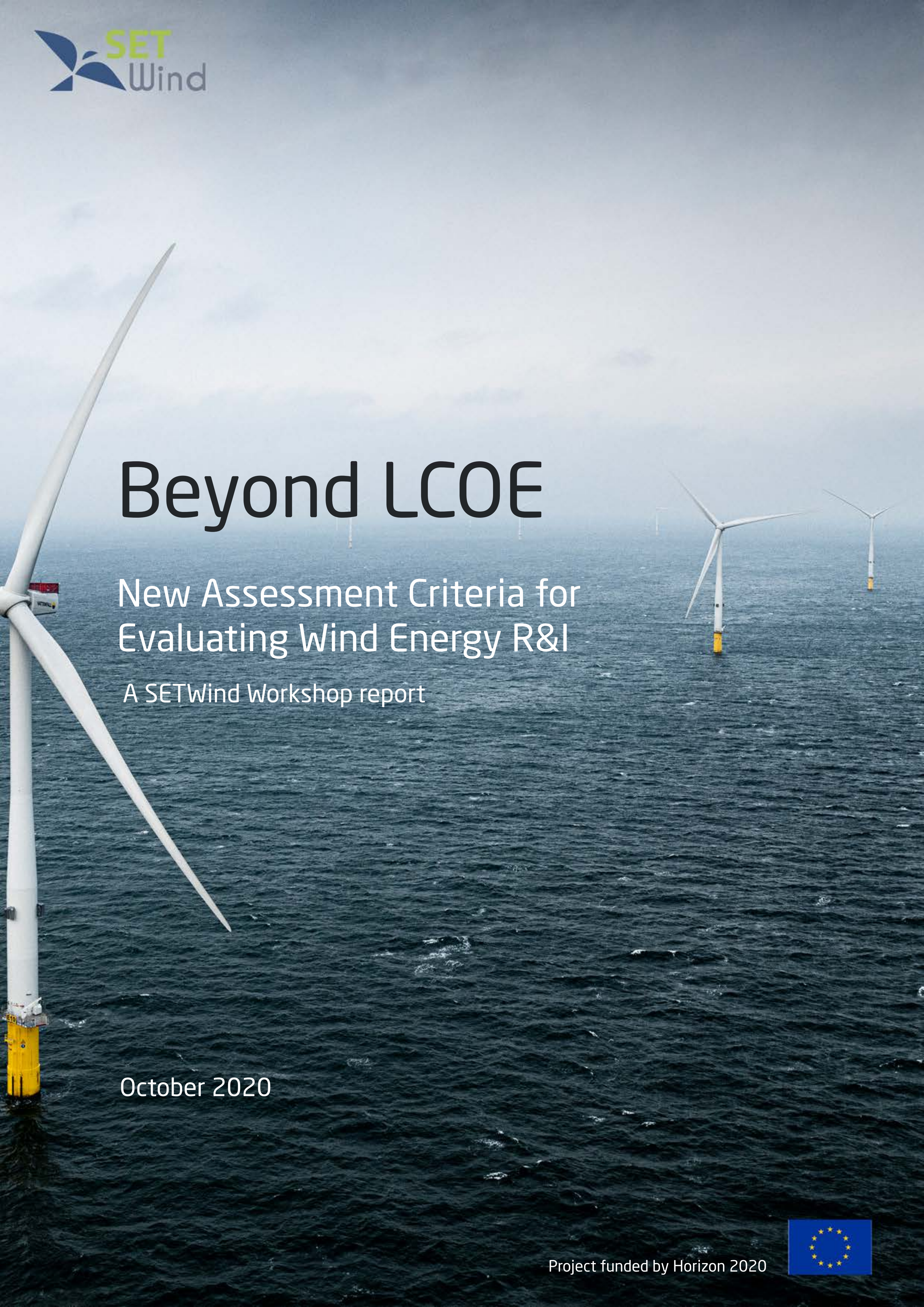

Beyond LCOE

New Assessment Criteria for Evaluating Wind Energy R&I

A SETWind Workshop report

October 2020

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

A number of factors drive the adoption of renewable energy, such as wind and solar PV, in electricity systems and markets. From providing security of fuel supply to addressing climate change, wind energy is poised to become the foundation of the 21st electricity system. However, even as the levelized cost of wind energy (LCOE) continues to fall and make it competitive with fossil-fuel and other conventional generation, new concerns are developing around the value of wind energy in systems with high variable renewable energy shares. Large shares of wind energy in a system have been shown to have an inverse correlation with average energy prices. Going forward, wind farms will more and more participate in low-subsidy and even subsidy-free markets and the *value* of the energy will be just as, if not more, important as LCOE. Thus, throughout the entire wind energy value chain, from manufacturers to developers to policy makers, there is a need to go “Beyond LCOE” and address the value that wind energy brings to electricity systems and society more broadly.

In a two-day “Beyond LCOE” workshop held in Brussels, Belgium the 23-24th of January 2020, a group of experts from the wind energy research and industry community came together to talk about the challenges and opportunities of looking at the value of wind energy to electricity systems and society. This involved first mapping out key causal relationships related to *industry dynamics* as well as *energy system and market dynamics* that influence system objectives related to value and sustainability. Keeping the system perspective in mind, workshop participants then brainstormed potential metrics for evaluating wind energy innovations, technologies and projects that capture broader system and societal value. A preliminary evaluation of these metrics were performed and the results are presented in this report.

Key findings of the workshop included:

- Context matters: Even for LCOE, there is significant variation in the impact that different innovations and technologies can have in a specific context based on local geographic (e.g. the wind resource, metocean) and market conditions (e.g. permitting, grid codes). However, going beyond LCOE to system value introduces additional variation depending on the generation mix, transmission infrastructure, market structure and more elements. Not only this, these systems are changing and thus, so does potential value from wind energy. In addition, different stakeholders have different needs in terms of how they evaluate their R&D, product and project portfolio. Going beyond LCOE, a one-size-fits-all solution is unlikely, and, instead, developing standard and transparent methods for assessment is important.
- The scope is large: moving from LCOE to metrics on system value and sustainability can result in a huge number of metrics. On the value side, there is value to electricity markets in the form of impacts to electricity prices, security of supply, grid reliability, stability, and resiliency, and more. On the sustainability side, there are impacts from wind energy

development to local and global environments, economies and citizens. No single metric can capture everything, but there cannot be so many that it becomes impossible to evaluate technologies and projects. A relatively small set of key metrics across the categories of value and sustainability are needed.

- Beyond LCOE is not coming, it is here: Particularly for industry, the need to evaluate technologies and projects for metrics Beyond LCOE is already here. Many projects are already expected to participate in low-subsidy and subsidy-free electricity markets where high shares of variable renewable energy are already placing downward pressure on electricity prices, and thus realizable project revenue. Industry urged the research community to move forward quickly to identify metrics and develop tools for their assessment that could be used by industry in the near term.

On the last point, the workshop culminated with a recommended action plan of next steps. Firstly, a short document outlining the call-to-action around Beyond LCOE should be created and disseminated to key stakeholders – including funding agencies and policy makers. Secondly, a taxonomy should be developed that provides a breakdown of the potential landscape for metrics beyond LCOE. Thirdly, methods and models for assessment of these metrics should be developed. In the near term, such a beyond LCOE tool should provide a rough assessment of the impacts of a project to key metrics. Longer term, the tool could then be developed with increasing fidelity and scope. The development of the capability was proposed to be a joint effort between the research and industry community – in order to ensure the relevance to industry. The overarching goal would be to provide a Beyond LCOE metric set and standard assessment methods and toolset for use by stakeholders to evaluate innovations, products and projects.

INTRODUCTION

On 23rd to 24th of January, the Strategic Energy Technology Wind (SETWind) project[1] brought together 20 senior experts from academia, EU institutions and the wind energy sector. The aim was to advance international discussions on how to move "beyond LCOE" towards a more comprehensive set of metrics for evaluation wind energy projects, technologies and innovation. Such metrics should take into account the overall costs, energy system value and impacts to sustainability of wind energy. Ultimately, the goal of the effort is to provide improved decision-making criteria for wind energy companies assessing their R&D pipelines and public funding agencies' assessing the value of new R&D projects.

LCOE has been instrumental in making comparable the cost of producing energy from a broad variety of energy sources, from renewable energy sources such as wind and solar, to legacy sources such as coal, gas and nuclear. Reducing LCOE to become cost competitive with legacy sources has been driving advancements in wind energy. As a result, deployment of wind energy has grown exponentially up to a Terawatt of global installed capacity by the end of 2019.

However, as renewables have increased market shares in several regions, additional criteria beyond LCOE become important – including the impacts of the technology on the larger regional electricity system (its system value) and impacts to local, regional and even global sustainability (environmental and social impacts). New metrics are needed that not only captures the cost of electricity production but also its full value and impacts to society.

While continued LCOE reductions will remain a key driver for the industry, the discussions during the two days emphasized the need for new and more comprehensive metrics. During the two-day intensive workshop, the workshop participants discussed the types of metrics that are needed by industry, academia, public research funding bodies as well as regulators and policy makers to fully support the green transition.

The following report provides a comprehensive proceedings of the invited presentations, break-out sessions and plenary discussions for the workshop. Importantly, the key findings of the workshop and the report are a clear call from senior industry participants to develop such metrics and methods for their evaluation as soon as possible.

As workshop organisers we would like to thank the participants for their engagement and stamina during the two days. A special thanks to PhD students Cristian Pons-Seres de Brauwer from DTU and Helena Canet from TUM for their meticulous report on the workshop. The present report is based on their extensive notes and write up of the workshop.

Katherine Dykes, Lena Kitzing & Mattias Andersson – DTU Wind.

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[1] SETWind is a European Union (EU) Horizon 2020 project supporting the SET-Plan Implementation Plan for Offshore Wind.

AGENDA

Day 1: Thursday 23 January 2020

10:00	Welcome and outline of the workshop *Mattias Andersson, SETWind coordinator*
10:15	Assessing the impact of R&I in the EU framework programme *Carlos Eduardo Da Cunha, European Commission*
10:30	**Plenary talk:** Driving innovation – LCOE and Beyond LCOE at Vestas *Lars Chr. Christensen, Vestas*
11:00	**Plenary talk:** Innovation Impact Assessment and Evaluation *Katherine Dykes, DTU*
11:30	Coffee break
11:45	Plenary discussion of input from morning session
12:30	Lunch
13:30	**Plenary talk and discussion:** Value of Energy and other new metrics *Lena Kitzing, DTU*
14:15	Overview of breakout session programme *Katherine Dykes and Lena Kitzing, DTU*
14:30	Coffee Break
14:45	**Breakout session 1**: System description and identification of feedback loops (casual loop diagramme) - **Group 1:** Industry dynamics *(Katherine Dykes)* - **Group 2:** Energy systems and market dynamics *(Lena Kitzing)*
17:00	Report back from breakout session 1 and full system casual loop diagramme
17:30	End of Day 1
19:30	Dinner

Day 2: Friday 24 January 2020

9:00 Summary of day 1 and plenary discussion

9:30 **Breakout session 2:** Brainstorming metrics (define and assess metrics relationships)

- **Group 1:** Industry dynamics *(Katherine Dykes)*
- **Group 2:** Energy systems and market dynamics *(Lena Kitzing)*

10:45 Coffee break

11:00 Report back from breakout session 2 and assess metrics relationships across groups

12:00 Lunch

13:00 **Breakout session 2:** Brainstorming metrics (define and assess metrics relationships)

- **Group 1:** Industry dynamics *(Katherine Dykes)*
- **Group 2:** Energy systems and market dynamics *(Lena Kitzing)*

13:30 Report back from breakout session 3 and overall balanced score cards

14:00 Coffee break

14:15 Final overall discussion and development of action items

15:00 End of workshop

LIST OF PARTICIPANTS

The meeting was attended by 22 participants from the wind energy research and industry community as well as representatives from the European Commission.

Name	Country	Company/Organization
Aidan Cronin	DK	SiemensGamesa
Alexander van der Berge	BE	WindEurope
Andrew Clifton	DE	Uni.Stuttgart
Bernard Bulder	NL	TNO
Berthold Hahn	DE	Fraunhofer IEE
Carlo Bottasso	DE	Technical University of Munich
Carlos Eduardo Lima da Cunha	BE	European Commission
Christina Aabo	DK	Ørsted
Cristian Pons-Seres de Brauwer	DK	DTU
Flaminia Riccioni	BE	EERA AISBL
Gavin Smart	UK	ORE Catapult
Helena Canet	DE	Technical University of Munich
Juha Kiviluoma	FI	VTT
Julia Walschebauer	BE	European Commission
Justine Beauson	DK	DTU
Katherine Dykes	DK	DTU
Lars Chr. Christensen	DK	Vestas
Lena Kitzing	DK	DTU
Mattias Andersson	DK	DTU
Ola Carlson	SE	Chalmers University
Thomas Hjort	DK	Vattenfall
Thomas Telsnig	NL	Joint Research Center (PETTEN)

PLENARY PRESENTATIONS

The workshop began with four key-note presentations by speakers from the European Commission, the wind industry and academia to frame the workshop breakout sessions. The following provides a summary of the presentations and follow-on discussion.

1.1. ASSESSING THE IMPACT OF R&I IN THE EU FRAMEWORK PROGRAMME

Presentation by Carlos-Eduardo Lima Da Cunha, European Commission DG-RTD

The market potential of renewable energy (RE) solutions is often estimated based on calculations of the levelised cost of electricity (LCOE). LCOE, defined as the ratio between the sum of costs and the sum of electrical energy produced over lifetime, has been an important valuation tool to help compare and demonstrate the increased competitiveness of variable renewable energy (VRE) sources, such as wind and solar PV, compared to legacy energy production units such as gas, coal and nuclear. However, the LCOE as a metric of comparison is becoming inadequate. Firstly, LCOE doesn't reflect the full value that different energy sources provide to the electricity grid in terms of resource adequacy, time-varying correlation of energy supply and demand, and provision of ancillary services. In addition, LCOE doesn't capture many other key performance metrics for energy sources including, but not limited to, sustainability, social acceptability, and economic development.

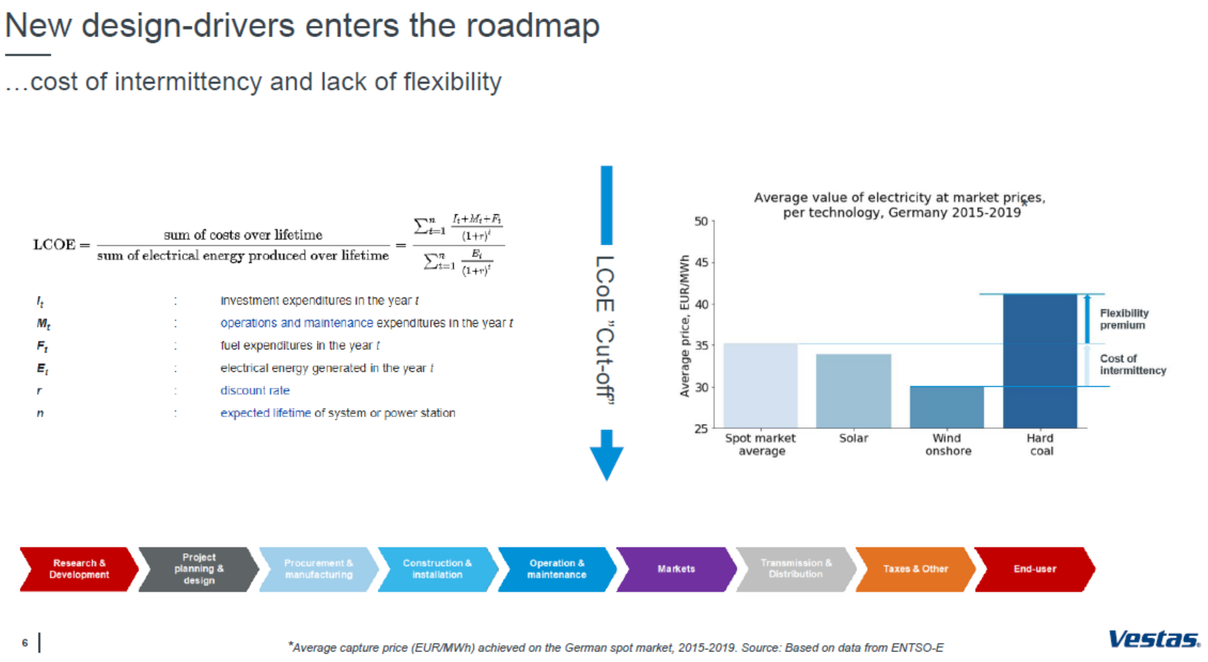
In light of this, the community is actively searching for new metrics that go "Beyond LCOE" that better capture the full value and costs that different energy sources provide to the electricity system and society more broadly. This will in turn facilitate the formulation of evaluation criteria to assess future research & development (R&D) and innovation projects, contributing towards a more systemic approach to the valuation of VRE technology. As the European Commission prepares the next EU Framework programme for Research and Innovation, HorizonEurope, we look with great interest on the result of this workshop and similar efforts to identify the best framework for assessing the full cost and value of renewable energy sources and the criteria for evaluating most promising R&D to support this.

1.2. DRIVING INNOVATION – LCOE AND BEYOND LCOE AT VESTAS

Presentation by Lars Chr. Christensen, Chief Specialist, Energy Management & Storage Innovation & Concepts

Historically, merchant market conditions determined by a Feed-in-Tariff (FiT) support scheme (and similar support schemes) have been the main driver of Vestas' product value chain and business model. The increasing share of renewable energy in European electricity systems and markets clearly change the context, leading to the necessity of a value chain that takes a holistic view of the energy system value. As a consequence, current merchant market conditions go beyond the FiT-driven product value chain. This is pushing Vestas to expand and re-focus its current business model. Current merchant market conditions require a different, more expansive product valuation approach that moves beyond simply reflecting the cost of energy towards capturing its broader value (and revenue). As with its benefit counterpart, a similar process needs to be conducted for capturing the broader systemic costs, including market costs incurred from balancing, intermittency of supply, insufficient flexibility of variable wind energy, transmission and distribution costs, as well as taxes & levies and other costs.

To illustrate this, a comparative analysis across energy technologies showed the average price per MWh commanded by solar, wind and coal compared relative to the spot market average price.



New design-drivers enters the roadmap

…cost of intermittency and lack of flexibility

$$\text{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : investment expenditures in the year t
M_t : operations and maintenance expenditures in the year t
F_t : fuel expenditures in the year t
E_t : electrical energy generated in the year t
r : discount rate
n : expected lifetime of system or power station

*Average capture price (EUR/MWh) achieved on the German spot market, 2015-2019. Source: Based on data from ENTSO-E

FIGURE 1: ASSESSING THE LCOE+ FOR WIND ENERGY

In general, the LCOE that must be achieved by wind or solar to be competitive is lower than that for coal because of the challenges of intermittency and flexibility. Solar fares somewhat better than wind energy when using avoided cost calculations because of the stronger correlation with demand (due to daytime peaking). To enhance the potential of wind energy, different technology solutions that allow wind projects to capture more value (and revenue) should be investigated. However, these will require a different evaluation metric than LCOE.

However, a complete reformulation of LCOE entails a steep learning curve for the entire industry and, in that respect, it may risk disruptiveness and eventual contestation from different industry players along the value chain. Furthermore, it is highly unlikely that a reformulation of the LCOE tool will result in a single numerical value that works for all industry stakeholders, as such a scenario would most likely inevitably miss key system costs/benefits derived from e.g. differing demand-side flexibility requirements and different adjustable consumption patterns depending on different RE penetration scenarios. It is therefore difficult to develop one single value for market/industry stakeholders who are not fully on board to adopt drastically different LCOE indicators/metrics.

Therefore, Vestas advocates for a more paused, step-wise, nested approach that facilitates standardisation throughout the industry via the addition of new indicators/metrics that build on the current LCOE, rather than its complete reformulation and/or substitution. The concept proposed by Vestas is LCOE+ which brings additional costs into the calculation associated with the intermittency and flexibility limitations.

Using LCOE+, different technology solutions can be compared in a relatively straightforward set of calculations. Energy storage and management services, for instance, are positioned as a potential solution, yet they involve additional capital costs incurred from the implementation of such services. Another approach could be the development of lower specific power turbines (i.e. larger blades on smaller rotors) that produce more energy at lower wind speeds to reduce intermittency. Comparing these technologies on LCOE+ would provide a picture of which of these innovation pathways holds greater potential system value.

In summary, LCOE is not enough, but an extension of LCOE (LCOE+) is preferable to a full overhaul of evaluation metrics. The introduction of LCOE+ by Vestas is focused on the immediate and near-term needs of the company. They need something now to support developing their next generation product-line. Innovation at Vestas is driven by analytics and needs to reflect as much as possible the evolving market conditions. More complex (albeit more robust) metrics may be challenging to develop – especially "one-size-fits-all" solutions. No matter what is developed, it is important to keep it simple and robust to application in a large range of system and market contexts.

Presentation Discussion

The presentation kicked off a lively discussion on a number of points summarized here. Key points included:

- LCOE+ as an appropriate metric: LCOE includes things you can control (from a wind industry perspectice). If you add things you cannot control and are system / market dependent to cost (intermittency and flexibility costs), then you may do a disservice to wind energy relative to other energy sources. Put another way, in a different system context (i.e. with significant demand side management, storage, etc), traditional baseload technologies such as coal or nuclear might be penalized for their inflexibility. From a broader communication of the value of wind energy, LCOE+ could be misleading. On the other hand, the benefits of its simplicity and ease-of-use for near-term business decisions was recognized – companies, such as Vestas, need something now that they can use effectively and easily to evaluate the competitiveness of their product offerings in a wide range of markets with a variety of remuneration schemes.

- Time horizon and specification of scenarios: The discussion over appropriateness of the LCOE+ led to a discussion on the need to think about different stakeholders, time horizons, and market/system scenarios for metric definition. Different stakeholders (OEM's, developers, researchers, funding agencies) focus on different time-horizons for one thing. There may be a need for different metrics with different levels of aggregation – i.e. LCOE as a baseline, then an additional metric for electricity, or even energy system, "fit", and even climate, environment, etc. A suggestion of use cases and user stories was introduced that might help identify the different needs for metrics across stakeholder groups and temporal / market contexts.
- "One-size-fits-all" metrics: There was a lot of discussion related to the above two points that finding universal metrics will be particularly challenging because of the dependency on the particular stakeholder and context. Multiple industry representatives recommended the participants keep that in mind
- "You get what you measure": Finally, a good point was brought up at the end of the discussion: "you get what you measure." In other words, if we introduce metrics that measure certain quantities, they will drive technology and innovation in a certain direction and we need to be cognizant of that.

1.3. GRAND CHALLENGES OF WIND ENERGY

Presentation by Katherine Dykes from DTU

What will it take to achieve a 50% wind energy penetration by 2050? A group of wind energy scientists from across the world addressed this question in a series of workshops that identified the wind energy science and innovation challenges that need resolution to achieve shares of wind energy at 50% or more in our future global energy systems. The results of workshop led to identification of grand challenges in wind energy science (articulated in a recent Science article and summarized in the presentation).

At present, the main source of revenue for wind farms come from energy production – often on a fixed per kiloWatt payment schedule. Other electricity markets, for forward capacity and system (ancillary) services play a smaller role in current business operations. However, merchant energy markets, forward capacity and ancillary service markets are positioned to increase in relevance in systems with increasing shares of VREs. Eventually, capacity and service markets may even become a significant share of revenue for projects in systems with extremely high VRE shares (see figure below). This will result in a disruption to existing business models, which will have to evolve in order to adapt to the changes in and redistribution of revenue streams.

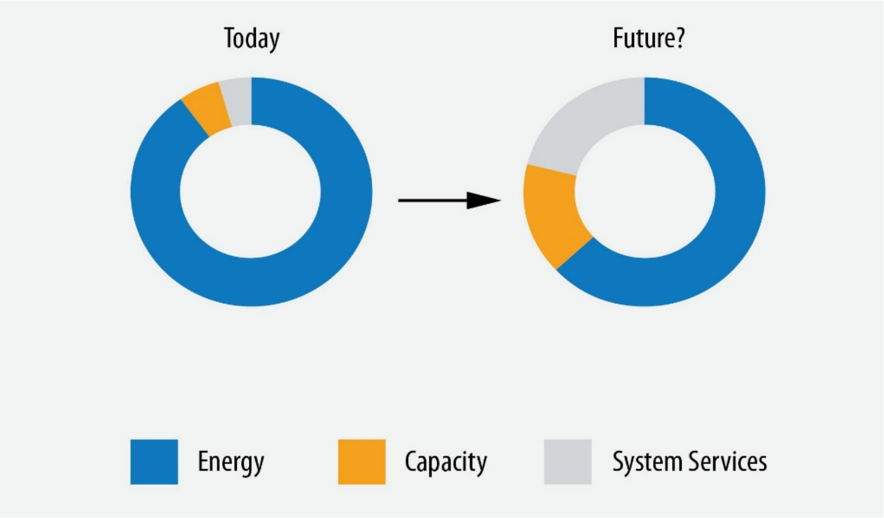


FIGURE 2: MAKE-UP OF REVENUE SHARE FOR ELECTRICITY GENERATION ASSETS TODAY AND WHAT THEY MAY LOOK LIKE IN A HIGH VRE FUTURE SYSTEM. SOURCE: DYKES ET AL. (2019) BASED ON AHLSTROM ET AL. (2015).

Understanding the intricacies of future energy/electricity market structures will become a necessary pre-requisite to properly assess the value that wind energy research and innovation can bring to the broader electricity system. The presentation concluded with a discussion on the scientific challenges for wind energy research that will position wind energy to support the future energy with low cost energy as well as high value energy and increased provision of resource adequacy and ancillary services.

Presentation Discussion

A Round-table discussion from the industry highlighted the tension between producing cheap electrons and providing increased system value. In the "Grand Challenges" work, the author group set forth two "bookend" scenarios for the future: one where storage and demand-side management is widespread, sector coupling is significant and producing cheap electrons (i.e. low LCOE) is the main metric for evaluation of wind energy systems (similar to today). In another extreme, a future where storage, demand-side-management and sector coupling are limited would imply that the system value that an asset can supply is key to VRE business cases. The round-table found:

- Industry is looking at the near-term. A longer term view is important for broader system issues, but in the near-term value will be important as systems are constrained and impacts by the effects of high VRE shares.
- Industry still needs to create cheap electrons, but also need to change the way wind farms are designed. Everyone in the industry is working on this but moving along different

innovation pathways. Sector coupling, for example through power-to-x, is one pathway currently being pursued by a variety of industry players. To catalyse change of the overall system, support from governments are needed, but without picking winners. As a result, it is very difficult to predict what the electricity and energy sector make-up will look like in 10 years or more.

- It would be nice to focus on cheap LCOE, but in the short term, realistically industry has to embrace these bigger issues – not just of value but of climate and energy. In addition to the LCOE and system value, we need to increase the attention to the benefits of wind on regional, national and global levels to society more broadly.
- The two “big jokers from a helicopter view” are 1) advanced storage technologies for all time-scales (short term, diurnal and seasonal) that is also inexpensive - whether its batteries or other technologies, and 2) floating wind, as there is a huge amount of value to be released far offshore if the cost can be brought down. Depending on where these jokers land, the future outcome and needs from wind technology in cost and value may vary substantially.

1.4. VALUE OF ENERGY AND OTHER NEW METRICS

Presentation by Lena Kitzing from DTU

Energy systems are highly complex socio-technological systems with complex dynamics. Several different levels interact and influence the assessment of energy technologies (see the below figure). LCOE takes the perspective of the technology at niche level and does not capture the interactions of that technology within the overall energy system (regime). LCOE becomes problematic when technologies cause different external costs and benefits at system level. Then, broader, system-wide value analysis is required to identify the true value of technologies and technology innovation for society, and inform choices that contribute to the transition towards the politically desired targets – such as the green transition.

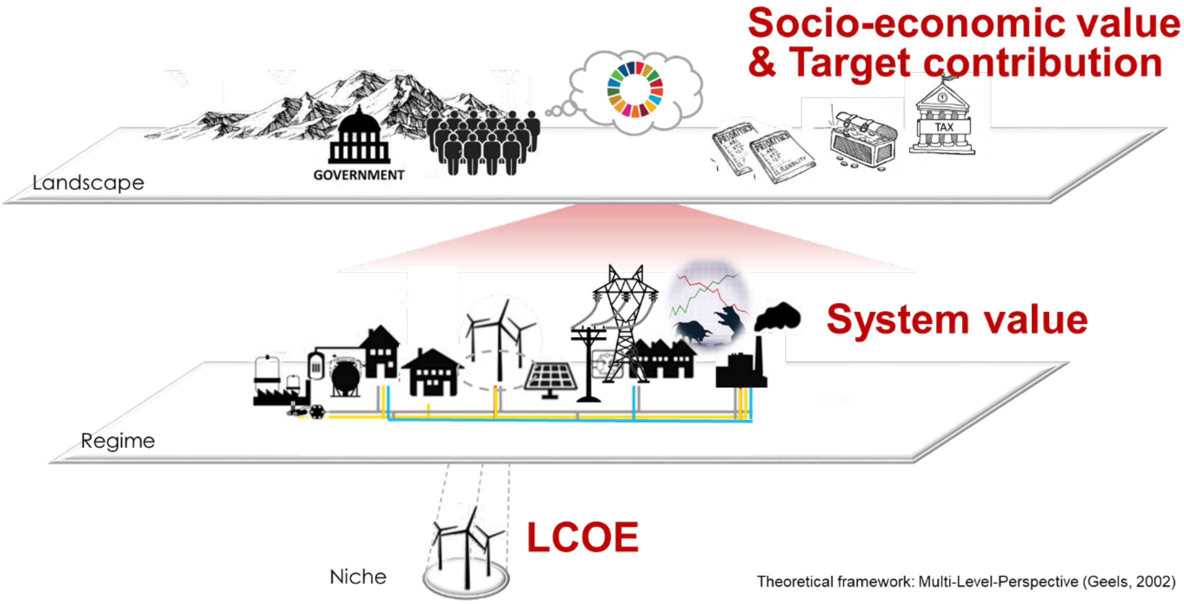


FIGURE 3: A MULTI-LEVEL PERSPECTIVE OF ENERGY SYSTEMS AND RELEVANT KEY INDICATORS ON EACH LEVEL CONCEPTUAL FRAMEWORK ADAPTED FROM THE MULTI-LEVEL PERSPECTIVE (MLP) ON SOCIO-TECHNICAL SYSTEM CHANGE (GEELS, 2002).

At present, the regulatory framework forwarded by the Energy Union serves as the main guiding framework for operationalising Europe's energy transition towards carbon neutrality by 2050. Its 5 key pillars include: 1) Energy security, solidarity and trust, 2) A fully integrated internal energy market, 3) Energy efficiency contributing to moderation of demand, 4) Decarbonising the economy, 5) Research, innovation and competitiveness. Building on the regulatory architecture provided by the Energy Union, recent EU legislative efforts have led to the approval, in December 2020, of a European Green Deal (EU-GD). The EU-GD aims to make Europe the first carbon neutral continent in the world by 2050. Some of the relevant aspects of the Green Deal for the discussion at hand include targets for: a climate neutral Europe, circular economy, pollution-free environment, preservation of ecosystems and biodiversity, smart sector integration, and a just transition.

One example that advocates for the need to look beyond LCOE when assessing technology innovation is the system value. The remainder of the presentation explored some details of system value aspects relevant for assessing wind energy technology.

While LCOE is a useful metric to characterize and compare technologies in a system, this figure does not include important information on the economic value of technology. Two technologies might have the exact same production cost (LCOE), but one technology may produce electricity mostly at times when there is already abundant electricity in the system (supressing energy prices), while the other may provide valuable electricity in scarcity situations (supporting resource adequacy). The latter technology will realize more revenue through providing electricity when prices are potentially payments for capacity value as well. This can be measured by the "Market value", defined as the ratio between total revenues and production. Another indicator is the relative "value factor", defined as the ratio between market value and average price.

A technology may systematically achieve lower market values than the average market price (i.e. a value factor of below one) due to a 'cannibalisation effect'. For wind, this occurs when there are many wind plants producing with a similar pattern, so that they all typically produce a lot of electricity when the other wind plants do the same, driving down prices in these particular times. In these situations, electricity produced by wind energy is on average 'worth less' than e.g. electricity produced by gas peak plants that are only requested at scarcity times with very high prices. This difference between the average electricity price and the market value has been coined "profile costs" – although it should be noted that no actual cost are involved here, it is more related to the concept of opportunity cost (i.e. foregone value).

The system value of a technology is furthermore influenced by its balancing costs and grid-related costs. In future energy systems, we expect the concept of system value and its elements to gain much more importance: "Profile cost" will become more relevant due to the increasing variability of production of VRE sources, "Balancing cost" will become more relevant due to the uncertainty of production by wind as main driver for need of balancing and reserve services, "Grid-related costs" will become more relevant as the insufficiencies of the current system topography (that is built around large central and flexibly power stations) will become more and more prevalent.

An application example that demonstrates the usefulness of market value as leading indicator for innovation is related to advancing the design of wind turbines towards lower specific power and higher turbine hub height. An analysis undertaken by the IEA TCP Task 26 on Cost of Wind (Dalla Riva & Hethey, 2017) shows that low specific power turbines with high hub heights, when implemented across a whole jurisdiction (in this case Germany), lead to fundamental changes in the optimal power mix, with higher baseload production and less need for peak plants, prices in the low range become higher, and the market value of wind increases significantly. Interestingly, the optimal mix shows higher cost for wind energy (due to the larger relative capital and operational costs for these turbines), but minimized overall system cost.

Another aspect that we should consider is the interdependence of system metrics. This is an emerging issue when moving from LCOE to a broader set of indicators. Such interdependence was illustrated with the two indicators "system cost" and "curtailment". From the perspective of a single technology, such as wind energy, curtailment is mostly to be avoided, as it decreases the amount of marketable production and also socio-economic value creation by the technology. However, in a full systems context, some curtailment could be acceptable when it maximizes overall system value. A recent analysis by DTU (Gea-Bermúdez et al., 2019) showed that in the future North Sea massive build out, a radial project-based connection of each offshore wind plant to shore would lead to much higher overall system cost (and lower socio-economic value) than a fully integrated meshed offshore grid, even if that would entail a significant increase of offshore wind curtailment.

Presentation Discussion

Several key points from the conversation included:

- The Green Deal: there is a lot of imprecision and lack of clarity right now in terms of what realistic scenarios will result. This effort could be valuable if it can provide some transparency and take a high level view of the overall system transformation and impacts. For instance, providing more concrete definitions and metrics on sustainability.

- Curtailment: the issue of curtailment was briefly discussed, with industry representatives expressing the challenges (in terms of the financial viability of their operations) of facing curtailment that might occur in high VRE scenarios where there is limited flexibility in the system, lack of storage, and lack of interconnectivity across balancing areas. Curtailment constraints affect the value creation that wind can capture, particularly in the context of unsubsidised energy markets, where curtailment requirements translate into reduced revenue for market players and are therefore actively avoided. It was also suggested that if wind is curtailed, someone will likely figure out a way to capture value from the spilled energy – i.e. as an investment opportunity for alternative routes-to-market.

- High capacity factor technology: capacity factors are seen as a bit fictitious. Profile costs are associated with a particular system. Building an "inflexible baseload" nuclear plant in a particular system would also face profile costs. The idea of "integration costs" are very contextual since they depend on the historic development of the system to date. A "clean-slate" view would result in very different estimation of these costs. In a fully flexible system, the inflexible generation asset is the problem.

2. WORKING SESSIONS ON METRICS

Following the presentations and general discussion, the workshop participants split into two groups: one to focus on *industry dynamics* with an emphasis on sustainability, social acceptance and other deployment related topics, and a second to focus on *electricity and energy systems and market dynamics* and the system value of wind (and other technologies) in particular.

Before, moving directly into the breakout sessions, a presentation was provided on a method for analysis of complex systems known as "system dynamics."[2] The method is used to model socio-technical-economic systems and captures nonlinear and dynamic feedback behaviour of the system. A first step in modelling such systems is to establish "causal loop diagrams" that represent in a qualitative way the exogenous and endogenous relationships of the system. As an example, a very simple feedback system was presented where CO2 emissions are reinforced or mitigated (balanced) as temperatures rise due to increasing heating and cooling requirements and their respective impacts on energy use and then additional CO2 emissions (see illustration below).

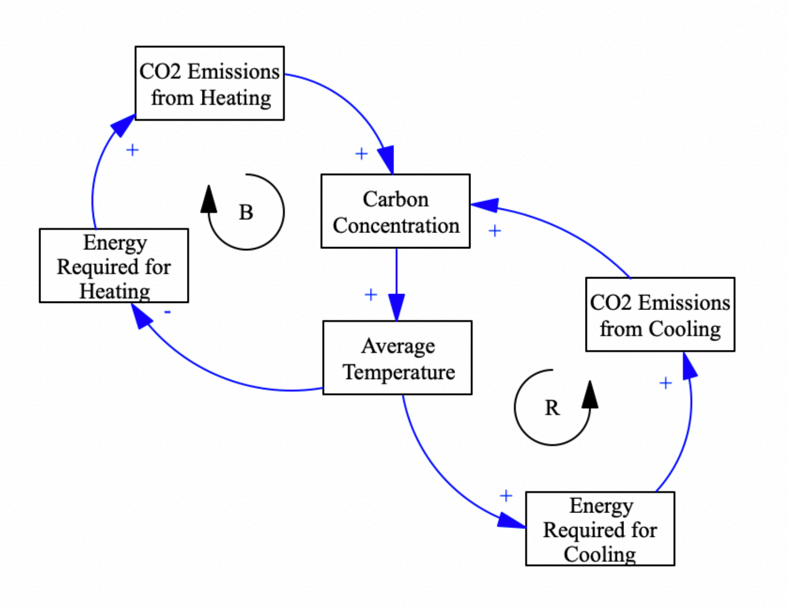


FIGURE 4: A SIMPLE CAUSAL LOOP DIAGRAM WHERE INCREASING TEMPERATURES INCREASE ENERGY REQUIRED FOR COOLING WHICH INCREASES EMISSIONS AND "REINFORCES" TEMPERATURE RISE (R LOOP). ON THE OTHER HAND, INCREASING TEMPERATURES REDUCE ENERGY NEEDED FOR HEATING WHICH REDUCES EMISSIONS AND SUPPRESSES OR "BALANCES" TEMPERATURE RISE (B LOOP). (CREATED WITH VENSIMPLE® SOFTWARE)

The groups were asked to develop causal loop diagrams for industry and energy system dynamics to help develop the system thinking of the group before moving to identification of metrics. The

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[2] For more information on system dynamics, see a primer here: https://en.wikipedia.org/wiki/System_dynamics

key output from this type of system thinking is the ability to identify trade-offs between metrics that may be counter-intuitive and may also have opposing effects on system behaviour.

Once the causal loop diagrams were established, each group then brainstormed metrics that might be used to evaluate wind energy technology from an electricity and energy system viewpoint as well as sustainability and other societal viewpoints. The groups pursued the brainstorming in slightly different ways as reflected in the below summaries. Group one focused on a sub-set of specific issues related to environmental and social issues of wind energy whereas group two took a more holistic approach to looking at energy and electricity system metrics.

After the identification of the different variables, metrics for their quantification are defined and evaluated according to the following four criteria:

- Impact/Efficacy/Importance: These criteria ensure that the metric will ultimately achieve its objective. For a given objective, a wide variety of metrics might be used but the sensitivity of the objective to success for a given metric may be higher or lower.
- Ease of implementation/Tractability: Some metrics are harder to assess than others. Metrics that are easy to measure directly at the site and in a quantitative way will be much easier to use in practice than those that are qualitative or rely on intangible information.
- Universality/Applicability to other technologies: While the focus of this effort is on wind energy, the applicability of the metrics to other technologies is of interest if they will be eventually used for cross-comparison of different energy technologies.
- Understandability/Presentability: The ease with which metrics can be understood by various stakeholders is important in terms of communicating the results of any assessments using the metrics.

Other criteria were considered and could be used in future efforts, but the above were selected to support a preliminary prioritization of the metrics.

2.1. GROUP 1: INDUSTRY DYNAMICS

This group mainly focused on the industry sector and the technology itself (the turbines and the full farm) for different stages of the overall turbine and project life cycle including: design, manufacturing, installation and logistics, operation and maintenance, and end of life. Additionally, this group also tackled the impact of wind turbines and farms in society and communities, from technical impacts such as noise levels to economic effects such as to workforce development. The section is divided into two parts. The first part corresponds to the first breakout session, whose goal was to identify the sub-systems of interest and define the main variables and their interactions. The second part includes the activities of the second and third breakout session, where the identified variables are translated into specific metrics for consideration in evaluation of wind energy innovations, technologies and projects.

2.1.1. SESSION 1: SYSTEM DESCRIPTION AND IDENTIFICATION OF CASUAL LOOPS

Even though many sub-systems can be identified within the industry dynamics of wind energy systems, the group decided to focus on social acceptance and sustainability, due to their large impact on present and future development of wind energy.

Social acceptance

Social acceptance of wind energy and wind farms is a key challenge for the deployment of wind energy. A large range of influential factors can be identified, including subjective elements such as perception of community benefits, perceived impacts on landscapes, health or biodiversity and degree of public participation. Due to the large complexity of the topic, it is not possible to tackle all factors with the deserved depth in a single breakout session. Therefore, this session tries to include all general parameters that could play a role in social acceptance. This was first achieved through a causal loop diagram brainstorming exercise with the resulting diagram as shown in the below figure. It is important to note that social acceptance is a very broad topic and the brainstorming effort of the workshop was meant only to promote system thinking about the issues rather than to map all social acceptance issues associated with wind energy systems.

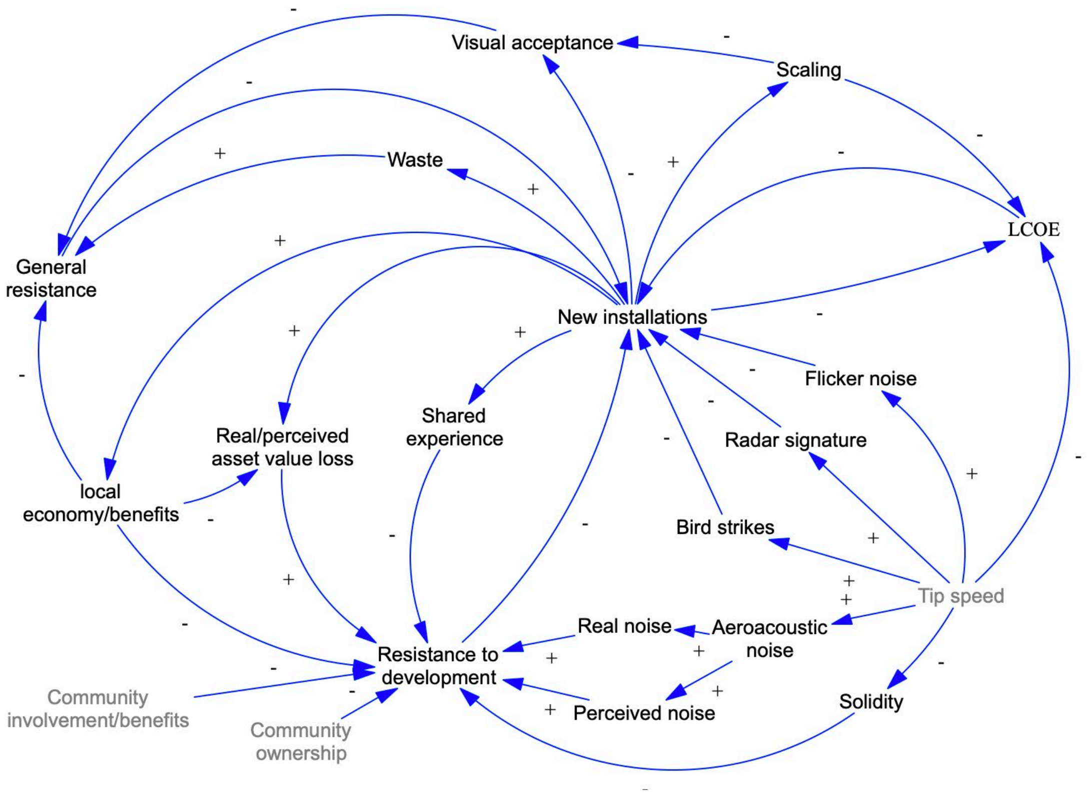

FIGURE 5: RELATIONSHIPS BETWEEN THE VARIABLES IN THE SOCIAL ACCEPTANCE SUB-SYSTEM. SEVERAL REINFORCING AND BALANCING LOOPS WERE IDENTIFIED. A FEW EXOGENOUS VARIABLES SUCH AS TIP SPEED AND COMMUNITY OWNERSHIP / INVOLVEMENT WERE ALSO INCLUDED.

One key outcome of the discussions was the identification that various aspects of wind energy systems can have real and/or perceived impacts to people and the surrounding environment. The group felt that both were equally important in terms of social acceptance and thus both were included in the diagram in various places. The multiple variables included in this diagram can be grouped into three separate impacts that shape social acceptance:

Welfare impact

This includes several effects that can impact the health and wellbeing of communities, in a real and/or a perceived way:

- **Sound impact:** One of the main sources of sound impact is aeroacoustic noise, which is linked with tip speed. As shown in the diagram, an increase of tip speed results in a higher wind turbine rated speed, which increases both real and perceived sound impact, leading to lower social acceptance. Tip speed here is shown as an exogenous influence though it could be considered endogenous if linked, for example, to increasing turbine sizes.

- **Viewshed:** The effect of disruption to landscape depends on a myriad of variables, such as wind turbine color, rotor size and orientation, hub height, specific power and plant layout. In this breakout session the group focused on the impact of blade solidity, which is related to the choice of tip speed. In fact, a higher design tip speed will lead to the design of blades with lower solidity, i.e. thinner blades that will most likely be better accepted by the community due to their less disruptive appearance. Thinner blades will also have a lower CAPEX, leading to a lower LCOE, an economic metric that can impulse the installation of new turbines.

- **Shadow flicker:** Defined as the moving shadow of the sun passing through the rotating blades of a wind turbine. This effect, related to tip speed, can create important nuisances for the community, decreasing social acceptance.

- Radar interference: Large wind farms can create dangerous interferences for radars, creating problems for the surrounding communities. This effect is also related to tip speed.

Socioeconomic impact

A community’s acceptance of wind energy also depends on the real and perceived socioeconomic benefits. Communities that see positive benefits in their economy, such as job creation, development of infrastructure or even the development of a new identity around this green energy source, are more prone to have a positive attitude towards the installation of new turbines. Community involvement and shared experience is also key in increasing social acceptance of wind turbines. On the other side, the loss of asset values, either perceived or real, increases the general resistance to the installation of new machines.

Environmental impact

The footprint of wind energy in the surrounding environment, real and perceived, is also a key parameter to understand social acceptability. Both the interaction with wildlife and wind turbine sustainability should be here considered. This impact is analysed in further depth in the sustainability loop.

Sustainability

Wind energy has often been associated with clean and sustainable energy as it uses a renewable resources and its direct process of producing electricity does not produce pollutant emissions. While wind farms do generate electricity with lower CO_2 emissions than fossil fuel plants, they still impact sustainability in potentially negative ways including limited recyclability of some components such as blades, use of rare-earth materials in components such as generators, and more. This sub-system identifies the different variables that play a role in the sustainability of a wind farm during its lifetime. The causal loop diagram shown below captures high-level relationships between the variables for sustainability.

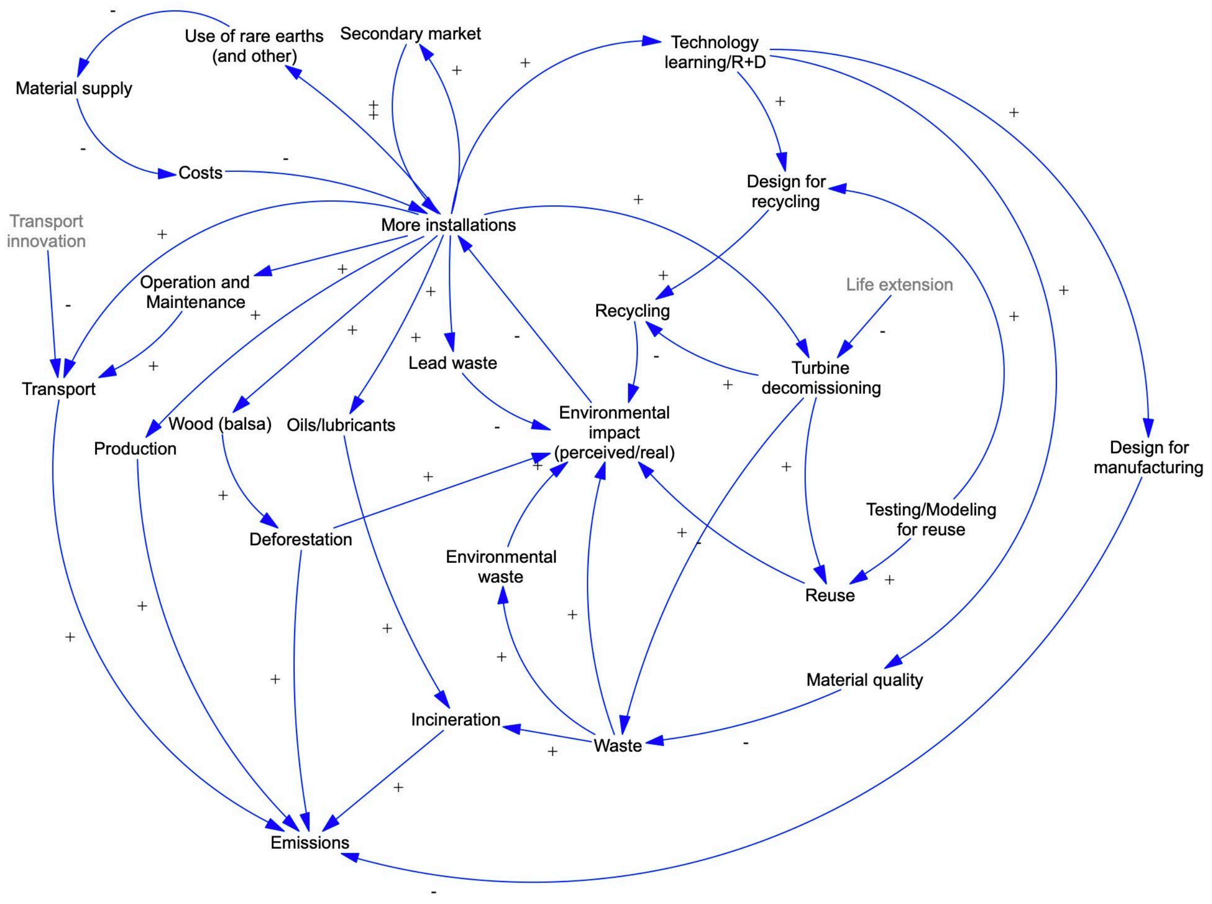

FIGURE 6: RELATIONSHIPS BETWEEN THE VARIABLES IN THE SUSTAINABILITY SUB-SYSTEM

The variables identified during the breakout session are described in the lifecycle stage in which they play a main role.

Design and manufacturing

Already at the design stage some of the decisions taken will largely influence the sustainability of a wind turbine during its lifetime. For example, the choice of materials can affect waste and pollution at the end of a component's lifetime. Efforts in technology learning and research and development (R&D) are required to reduce potentially negative impacts. Some examples of material selection processes that can impact sustainability include:

- Blade structural components such as spar caps or shear webs are generally manufactured today with carbon and glass fibre-reinforced polymers due to their good mechanical properties. The binding polymer of these composites is usually epoxy resin, which cannot be recycled. Even though these materials can be reused in applications such as concrete, alternatives to this polymer may improve blade circularity.
- Balsa wood is also used within multiple blade structural components, such as shear webs or external shells. The choice of this material, even if used in small quantities, can lead to deforestation.
- Other materials with a large environmental footprint are included in the different components of a wind turbine, such as rare earth materials or heavy metals. The scarcity of rare earth elements has already been acknowledged as an issue as the deployment wind turbines scale exponentially. However, impacts from mining these materials already have negative impacts to the environment in terms of pollution and habitat disruption.

Innovation in materials, design, and manufacturing processes are important levers to enhance the machine sustainability.

Installation, operation and maintenance, and decommissioning at the farm end-of-life

Large emissions can be emitted during installation, operation and maintenance activities. Indeed, these activities, especially offshore, require the utilization of special vehicles, which are usually oversized and require large quantities of fuel. Consideration of the full life-cycle of the wind farm needs to look not just at the machines themselves, but all systems used in the installation and operation of a windfarm including transportation of components to site, site preparation, assembly and installation of the wind turbines, support structures and balance of system infrastructure including electrical collection system and interconnect, maintenance of the wind turbines and balance of system infrastructure, and decommissioning and disposal of all components at the wind farm end-of-life.

At the end of its life, the different parts of a wind turbine can be processed in different ways. Life-extension, may prolong the turbine life but ultimately, all turbines will be decommissioned, with their parts being sent to a landfill, incinerated, recycled or reused.

2.1.2. SESSIONS 2&3: METRICS IDENTIFICATION AND EVALUATION

The breakout group developed and created a preliminary evaluation of metrics for social acceptance and sustainability respectively as discussed below.

Social acceptance

The metrics identified in the social acceptance sub-system are here sorted in the categories described above. An overview of these metrics and their assessment is shown in Tables 1 and 2 below, followed by explanation for the assessment results.

Welfare impact

The group first identified and evaluated metrics for impacts of wind energy to the welfare of a community and its citizens.

TABLE 1: EVALUATION OF METRICS DEFINED FOR SOCIAL ACCEPTANCE. * REPRESENTS DEPENDENCY ON THE CONTEXT. H STANDS FOR "HIGH", M FOR "MEDIUM" AND L FOR "LOW".

			Impact	Tractability	Universality	Presentabil.
SOCIAL ACCEPTANCE	Sound impact	Actual / perceived impact	H	L	N/A	L
	Shadow flicker	Actual / perceived impact	H	H	L	H
	Viewshed	Actual / perceived impact	H*	L	H	L
	Safety & health	Actual issues	H	H	H	H
		Perceived issues	H	L-M	H	L
		Health issues (actual and perceived)	H*	L	H	L

Additional details for the ranking are provided for sound, viewshed and safety and health:

- **Sound impact:** Actual noise is a multi-faceted metric where certain specific combinations of conditions may be the most problematic. Literature describes multiple metrics that can be used to quantify several aspects of actual noise, such as noise frequency (Hz) or noise level (dB). While these metrics can be implemented, the perceived noise also plays a key role in shaping social opinion. In practice, noise can often be a limiting factor in the successful development and acceptance of a project.

- **Viewshed:** Actual and perceived disruption to landscape can be found due to the installation of turbines, substations or power lines. Metrics to quantify the perceived impact present may be difficult, but can have a high impact in shaping social acceptance, depending on the specific circumstances.

- **Safety & health:** Real issues such as ice throw, catastrophic failures or fires, and the associated perceived danger can highly impact a community's opinion of wind energy. While real threats can be quantified following objective standardized procedures, metrics to understand perceived risks are less understandable and tractable.

Socioeconomic impact

Next the group identified and evaluated metrics for socioeconomic impacts of wind energy to a community.

TABLE 2: EVALUATION OF METRICS DEFINED FOR SOCIAL ACCEPTANCE. * REPRESENTS DEPENDENCY ON THE CONTEXT. H STANDS FOR "HIGH", M FOR "MEDIUM" AND L FOR "LOW".

			Impact	**Tractability**	**Universality**	**Presentabil.**
SOCIAL ACCEPTANCE	**Community Impact / Involvement**	Level of community ownership	H	H	H	H
		Local economic growth	H*	H	H	H
		Symbolism / green identity	L-M			
		Local infrastructure	H*	H	H	H
		Local content	H*	H	H	H
		Planning input	H	L	M	H
		Multi-use	H	M*	H	H

Additional details are provided for the rankings on the various metric categories and metrics:

- **Community involvement:** Metrics to quantify the active involvement of a community in the deployment of wind energy are found to have a high impact in shaping social acceptance. The multi-usage of lands in wind farm projects or the participation of the community in project planning are examples of community involvement.

- **Community identity:** Some communities might find the deployment of wind turbines as a positive impact to their community identity. The implementation of adequate metrics is found to be challenging due to the topic subjectivity. The impact of this metric in influencing social opinion is expected to be moderate; other socioeconomic metrics, such as local economic growth, are expected to have a higher efficacy.
- **Local economic growth**: Communities may experience local economic growth thanks to increment of tourism, creation of new jobs or introduction of tax benefits. Metrics to represent local economic growth can highly influence social acceptance, but can require a complex implementation. Even though these metrics have already been defined in the literature, association with the deployment of wind energy may be hard to demonstrate.
- **Asset values**: The loss of asset value, both real and perceived, has a high impact in social acceptance. Perceived metrics are subjective and more difficult to implement.
- **Infrastructure development**: These metrics can have a high impact in shaping the community’s opinion of wind energy, depending on the specific community context. It is also found to present a high ease of implementation, universality and understandability.

Sustainability

The sustainability of wind turbines is here assessed in terms of material usage, emission, and wildlife impact. the description of the identified metrics and their assessment is here given and an overview can be found in table 3.

TABLE 3: EVALUATION OF METRICS DEFINED FOR THE SUSTAINABILITY SUB-SYSTEM. * REPRESENTS DEPENDENCY ON THE CONTEXT. H STANDS FOR "HIGH", M FOR "MEDIUM" AND L FOR "LOW".

				Impact	**Ease of implement.**	**Universality**	**Presentability**
SUSTAINABILITY	**Materials**	Quantity/ usage of scarce materials		H	H	H	H
		Envir. footprint of raw materials	Extraction	M*	H	H	H
			Processing	M*	H	H	H
			End-of-life	M	H	H	H
	Emissions	CO_2 and THC		H	M*	H	H
		Particulates		H	M*	H	H
		VOCs		H	M*	H	H
		Hydrocarbons		H	M*	H	H
	Wildlife	Migrating species		H	H	H	H
		Local indigenous species		H	H	H	H

Materials

Within the range of topics related to material sustainability that could be here addressed, the group focused on scarcity of materials and environmental footprint of raw materials:

- **Scarcity of materials:** Metrics to quantify the scarcity of materials has a high impact in the overall wind turbine sustainability. These metrics are relatively easy to implement if there is transparency in the supply chain. This attribute also facilitates the applicability to other energy technologies.
- **Environmental footprint of raw materials**:
    - **Material extraction:** Metrics to evaluate the sustainability of material extraction (such as deforestation or mining) highly impact wind energy sustainability. Their ease of implementation, however, depends on the process analysed. These metrics can be easily applied to other technologies and have a high understandability.

- **Material processing**: Metrics to quantify the environmental impact of the material processing, for instance, in terms of water, energy and emissions, are found to be very efficacious in capturing sustainability. The tractability of the metrics depends on the process analysed. These metrics are found to be highly applicable to other energy technologies and easy to understand.
- **Material end-of-life**: the circularity of the materials used is also an important variable to understand sustainability. Metrics to assess the environmental impact (water, energy, emissions), volume and cost of the different end-of-life processing techniques (landfill, recyclability, incineration, reuse) largely impact the overall sustainability. The tractability of these metrics is however process-dependent.

Emissions

The various sorts of emissions (CO2, THC, particulates, VOCs, hydrocarbons) that are emitted during the different stages of a wind turbine lifetime are here included. Metrics that quantify these emissions have already been defined in the literature and are found to be highly efficacious at capturing the machine sustainability. Even though their applicability might prove challenging for some supply chain processes, they are universal and understandable metrics.

Wildlife

Metrics are here identified to quantify the effect of wind energy in both migrating and local indigenous species. These metrics should consider all impacts in the life of wildlife, including changing migration pattern, habitat displacement and creation, and collision and deaths. The metrics are found to have a high impact in sustainability, ease of implementation, universality and understandability.

2.1.3. Summary of Industry Dyanmics (Group 1) findings

Industry dynamics can include many topics including traditional innovation and deployment dynamics, industry development and more. The group choice to focus largely on the external impacts of wind energy developments to communities, the environment and broader society in two topic areas: social acceptance and sustainability. In each of these areas, causal loop diagrams helped to identify some reinforcing and balancing dynamics related largely to increasing deployment of wind energy and its feedback effects on various social and environemental variables. This provided a foundation for brainstorming potential metrics for evaluation of wind energy from the lense of social acceptance and sustainability. Resulting metrics were evaluated in terms of their ease of implementation and other criteria. By and large, while many metrics for social acceptance and sustainability are easy to implement, they can include perceived effects which are more difficult to assess. In addition, some metrics require far-reaching understanding of the supply chain and other system elements that can be difficult to trace. The group acknowledged that the wind industry is already addressing many of these issues but standards in terms of metrics and methods for their assessment will improve adoption and use.

2.2. GROUP 2: ENERGY SYSTEMS AND MARKET DYNAMICS

This group mainly focused on energy systems, economics and the political realm. The first session of this group started with setting the scene, understanding the problem at hand, and defining the scope of analysis. The group then identified several areas for discussion, including markets, policies, and systems, which were then discussed in more detail.

2.2.1 SESSION 1: SYSTEM DESCRIPTION AND IDENTIFICATION OF CASUAL LOOPS

The participants agreed quickly that the main system of enquiry is the electricity system. As the first step, the group produced an overview graphic (shown below), providing a simplified overview of the layered/nested relationship between systems along with some general cross-system interactions, as well as a more granular disclosure of the energy system itself.

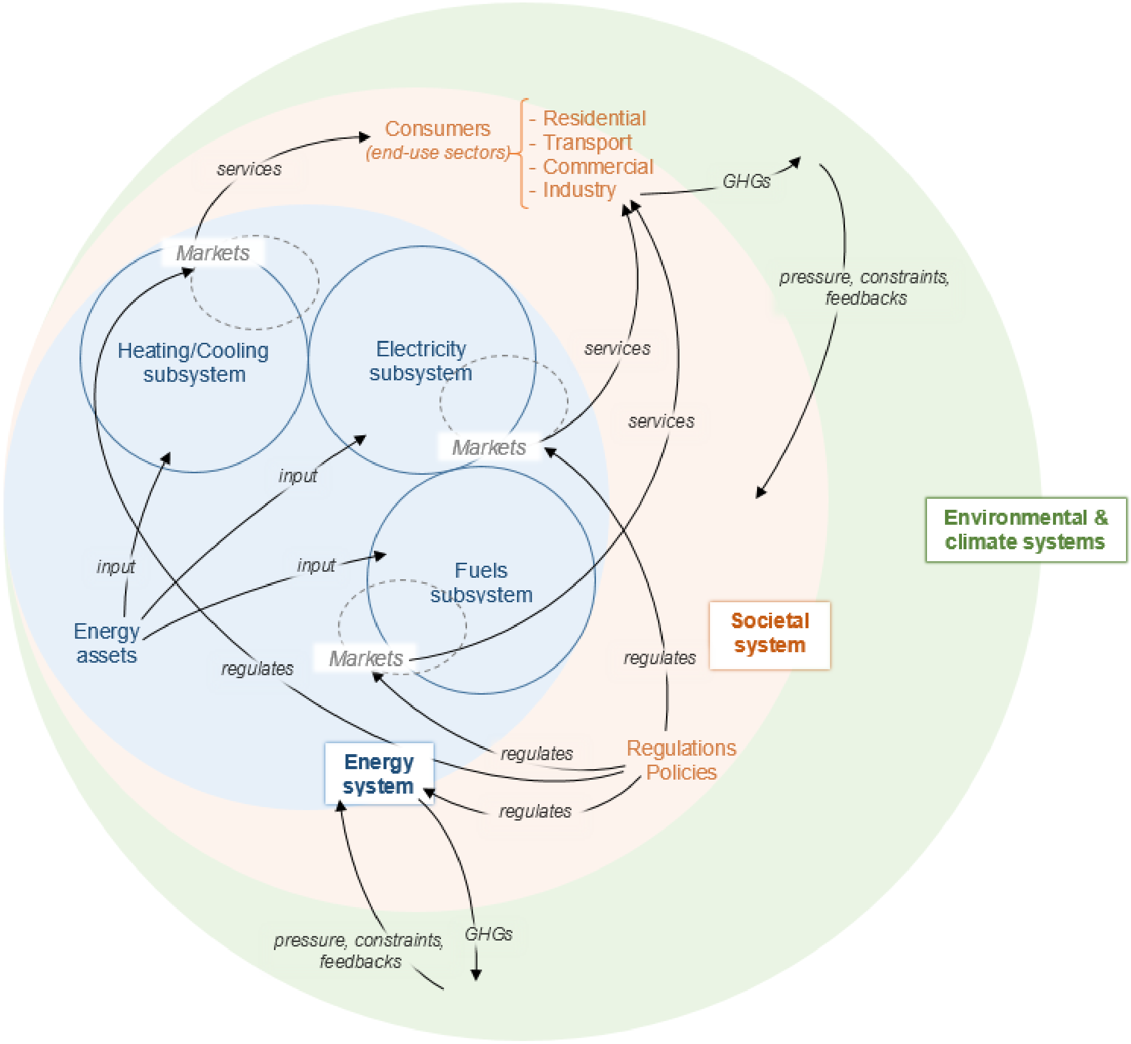

FIGURE 7: SYSTEM BOUNDARIES WITHIN A NESTED FRAMEWORK OF SUBSYSTEMS, INCLUDING ENDOGENOUS AND EXOGENOUS ELEMENTS; ALONG WITH KEY SYSTEM COMPONENT INTERACTIONS.

The relevant systems outside the boundaries of the electricity system itself include: broader society, the global ecological and climactic systems, energy resources, energy consumers and consumer behaviour, broader policy and regulatory systems (including emissions trading systems). In addition, the group decided the broader energy system (beyond electricity) to be out of scope since it is itself composed of various subsystems organised around different energy carriers (i.e. electricity, heat, fuels). The energy system therefore hosts the heating and cooling subsystems (and their infrastructure), the fuel subsystem (and its infrastructure, incl. gas networks), as well as the electricity subsystem itself (i.e. transmission grid infrastructure).

These exogenous elements interact with the electricity subsystem in the form of market (e.g. tariff structure and balancing obligations) and infrastructure regulations (e.g. grid connection and operational reserves), service provision for end-use consumption, resource inputs (wind, sun, fossil fuels, uranium, etc), carbon credit transfers, etc.

Scenario assumptions and uncertainty

The group found important to note that when adopting a systems-thinking approach there is a need to reference system behaviour against a previously set reference scenario. This will not only serve to map the mechanisms through which the new system operates, but as a key starting point from where to assess, for instance, the capacity deployment needed to guide/inform and narrow down key research and innovation priority areas.

Importantly, the scenario assumptions and related uncertainties stemming from them will differ substantially between countries, with important implications affecting the re-design of different system components such as, for instance, electricity markets.

Electricity markets

The first theme of discussion revolved around electricity markets. The group viewed electricity markets as an effective valuation mechanism, mediating the buying and selling of electricity through their demand-supply pairing function. Electricity markets therefore effectively operate as the medium through which wind resources (the system's main input) are commodified into tradeable electrons (i.e. electricity) and subsequently fed into the transmission grid infrastructure[3]. Markets are structurally allocated outside the physical boundary of the electricity system, yet bound to it as a key enabler of the system's commodity exchange process. The group made an effort to decompose the relevant elements on electricity markets:

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[3] Depending on the resource fuel/input/commodity it mediates, a market can be categorised, understood, and framed as i.e. an energy only market, a capacity market, or a system services market (balancing and other ancillary services), but also as a financial market (i.e. mediating the financial availability, conditions, and risk and therefore exerting an influence on, for instance, the weighted average cost of capital (WACC) of different energy assets).

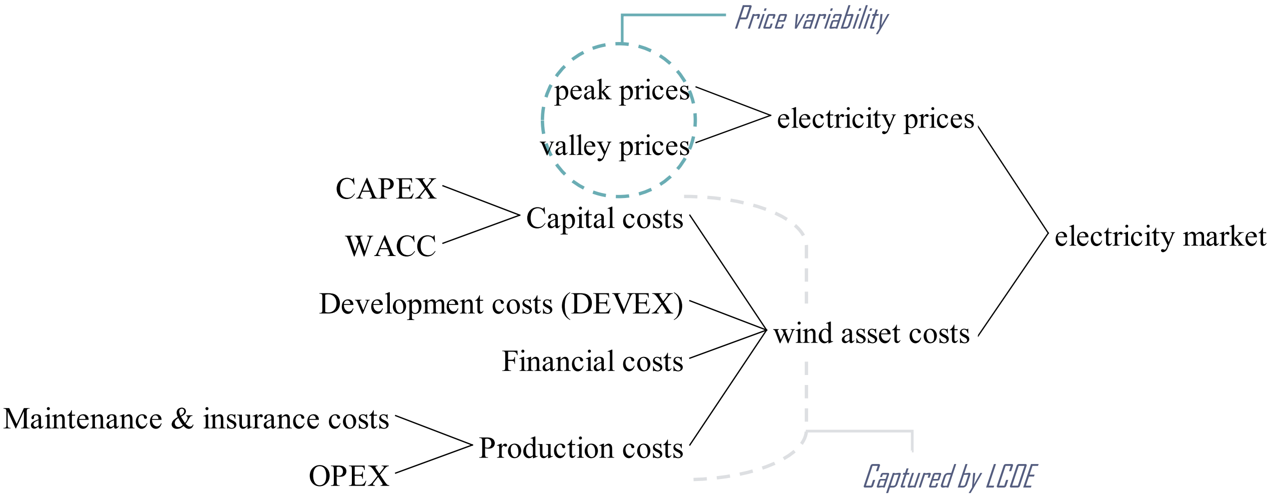

FIGURE 8: BREAKDOWN OF THE KEY ELEMENTS OF ELECTRICITY MARKETS

It was noted that the LCOE only captures the cost side of the relevant factors, and it is thus a poor indicator for "value" in the markets. The electricity price was appointed as the key variable of the market subsystem. It is co-determined by production costs and resource availability, and further influenced by competing technologies like solar PV, oil and gas, etc. A major outcome of the discussion was the simplification of price dynamics on the spot electricity markets into 'peak' and 'valley' prices. It was argued that by considering the average market price, as well as the peaks and valleys separately (including the ratio or share between them), one can reasonably well capture most of the relevant characteristics of a market in terms of attractiveness and potential to integrate renewable energy. The group then identified and analysed some causal relationships between peaks and valleys and relevant influencing factors, as well as the average market prices and their (overlapping) factors, which we have here (based on the drawings made during the workshop) merged into the following preliminary causal loop diagram shown in the next figure.

One loop effect that was discussed in detail involves the negative price impact that high volumes of wind-generated electricity can have, mostly through triggering more severe and prolonged valley prices. This also drives down average prices. On the other hand, systems with very high shares of wind energy also see periods of high peak prices, an effect further amplified by retirement of fossil fuelled power plant capacity triggered by the lower average prices. These effects may be mitigated by flexibility options such as time shifting capability for generation and expansion of demand response programs. Such efforts would likely reduce the magnitude and frequency of valley prices and also help to reduce curtailment that occurs in systems with high shares of wind. Other variable renewable energy technologies (such as solar PV) have a similar impact on electricity prices. In the long term, low (valley) prices may de-incentivise new investments in variable renewable generation capacity.

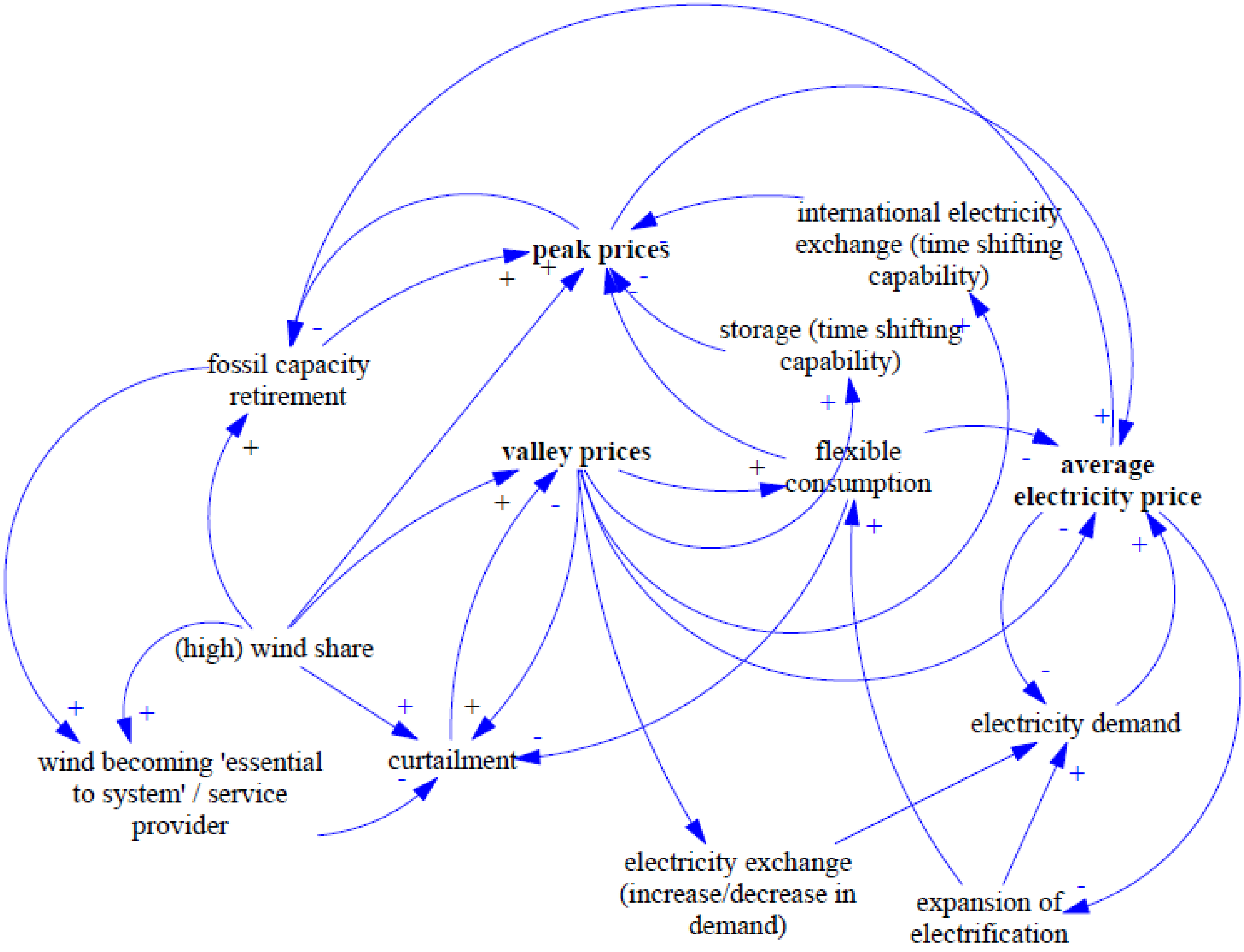

FIGURE 9: CASUAL LOOP DIAGRAM ASSOCIATED WITH ELECTRICITY PRICES DEVELOPED BY GROUP 2 IN SESSION 1.

It was mentioned that it is important here to distinguish between flexible and inflexible demand. In the case of inflexible demand, higher consumption results in higher (peak) prices and thus more costly electricity. Peak prices in turn reduce demand and have a reinforcing effect on flexible consumption and a balancing effect on inflexible consumption. Flexibility of demand (e.g. in terms of time shifting) has a fundamental role to play in future electricity markets. A peak/valley electricity price concept could be an interesting way to roughly evaluate the impact on the extent of demand flexibility that can be mobilised: deeper valley prices as well as higher peak prices may induce more flexible demand, while ‘flatter’ price structures may not.

Yet another element affecting electricity price variability is the availability and deployment of electricity storage. The increased deployment and use of storage capacity ’flattens’ electricity prices (i.e. reduces the difference between peak and valley prices), which in turn de-incentivises the investment in additional storage. The relationship between storage capacity and electricity price thus generates a balancing loop. The participants appreciated the causal loop thinking applied in the group discussion to surface these reinforcing and mitigating effects and enable a targeted discussion about them.

Energy policy and support schemes

The second theme of discussion revolved around energy policy and support schemes. The group agreed that we are currently experiencing a disruptive change in the value creation process stemming from an important paradigm shift in the existing policy regime (the Feed-in-Tariff (FiT) system with administratively-set support) is being replaced by a new competition-driven framework brought about with the introduction of auctions schemes. This paradigm shift makes the discussion about markets, market prices and value creation relevant in the first place, as guaranteed revenues from support payments are replaced by merchant market income. Indeed, subsidy-free wind farm development has already begun in some jurisdictions.

The group analysed these effects and their causal relationships in two steps, one focused on the support schemes and their different effects on cost and production, and the other one on ‘energy market driven wind farm design.’ These are shown in a single causal loop diagram below.

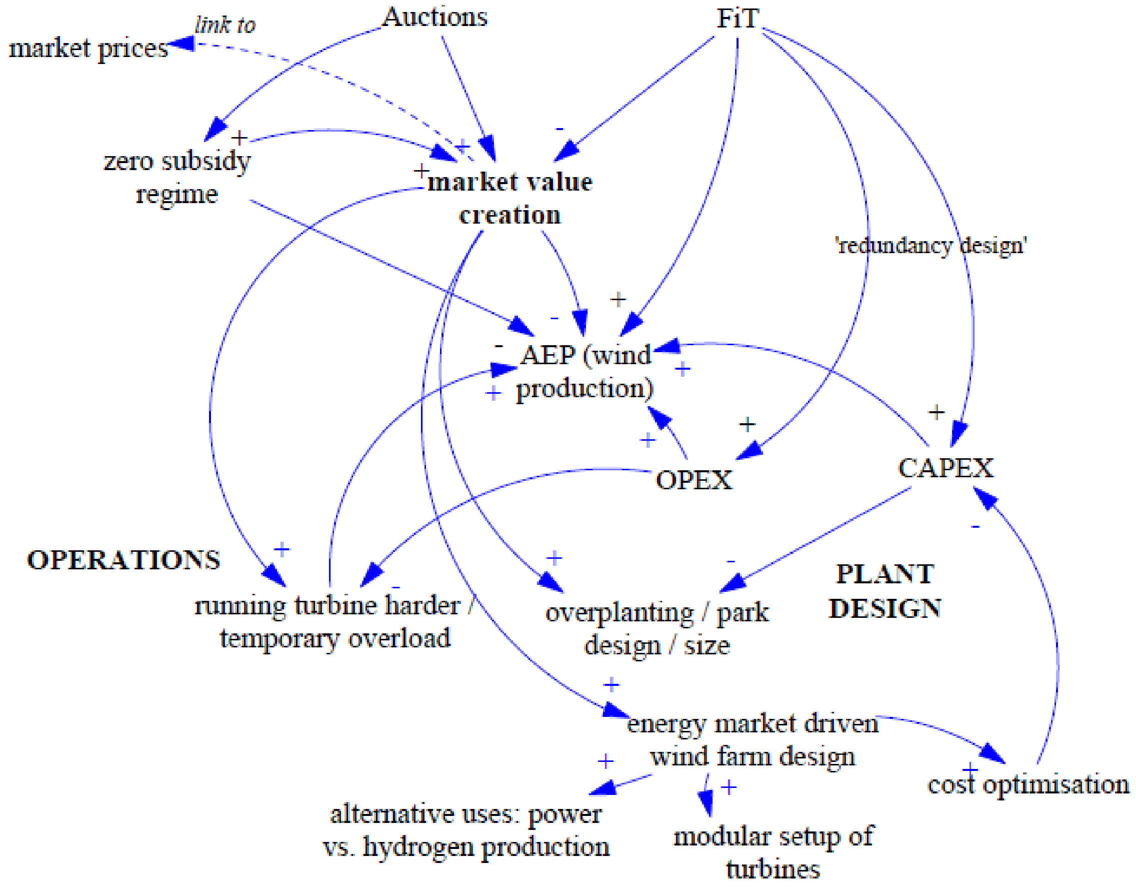

FIGURE 10: CAUSAL LOOP DIAGRAM FOR SUPPORT SCHEMES AND MARKETS

FiTs have been a critical element driving the increased deployment of wind generation capacity by stakeholders aiming to maximise the production of their wind assets. In such a context, developers' mindsets and operations focused on maximising and prolonging electricity output during the maximum amount of time possible. With the change in the support system, this rationale has been challenged from the developers' perspective. While FiTs supported maximizing AEP, the auction system (and with it the increased share of market income) incentivises value creation in a different way.

It became clear in the discussion that the paradigm shift in energy policy brings about several important changes in wind plant operations as well as in wind plant design. For instance, the peak/valley price dichotomy was largely irrelevant in a pure FiT context. In a premium-based-subsidy or non-subsidised context, however, the influence of price fluctuation on operations and behaviour of electricity producers becomes extremely relevant: with valley prices, utilities schedule their service in low value times, and remove that service from high value times, which works to the benefit of the grid and affects levelised energy revenue positively but may simultaneously also increase LCOE.

2.2.2. SESSIONS 2&3: METRICS IDENTIFICATION AND EVALUATION

In sessions 2 and 3, the group moved from mapping the interdependent elements to identifying which indicators and metrics could be relevant in the future when moving beyond LCOE.

It was mentioned that untangling the structure of different renewable energy costs and benefits (including the new social/environmental/economic variables), and adapt these according to the national context of different countries is a necessary prerequisite for any reformulation of the current LCOE methodology. The idea is to disclose all the subcomponents, each one with its corresponding metric, and make it comparable across countries in order to benefit from standardisation and resulting in a wider use as the main tool to evaluate innovation beyond a purely economic (traditional) cost perspective. Capturing the external costs and benefits of electricity generation was mentioned as absolutely crucial in this regard.

We structured the discussion broadly into five steps:

1) *Assumptions: target/audience setting and reference case*
2) *What do we want to measure (variables)? For whom?*
3) *Define several metrics for each variable*
4) *Map relationships between metrics (via variables)*
5) *Assess relationships (direction, strength)*

Scenario assumptions & uncertainty

The need for wind development based on previously established future scenarios was emphasized as a starting point. These scenarios are key to drive the research priorities stemming from the capacity deployment needs in response to a prescribed future. Different scenarios change the underlying assumptions during the design/planning of the wind farm, which will effect cost structure and revenue streams. The spread of the potential/hypothetical solutions is huge and still relatively unknown. Uncertainty is currently playing an important effect on the planning and design of new power plants (wind-based or otherwise).

Importantly, the group agreed that these uncertainties, scenarios, and assumptions will substantially differ between countries and so the development of their electricity markets will also be substantially different.

Target/audience setting and reference case

It was mentioned that, in order to develop a meaningful new way of measuring innovation, we first need to fundamentally understand our goals. We discussed what new measures are going to be used for, and for whom is the new tool being developed (wind developers, policymakers, and others). The group agreed that new beyond LCOE metrics would target business and political decision makers who need to prioritise investments in innovation activities.

This means that high-level mission statements are needed to address policymakers at the EU/National level. The group agreed that the biggest objective and main target is avoiding irreversible climate change: reducing CO2 emissions to stabilise atmospheric concentrations and remain within the global warming threshold set in the Paris agreement. Additionally, the SDGs can be used for developing the variables and their corresponding metrics.

Whatever targets are established, it was agreed that we need a reference case and benchmark to evaluate against (for instance, a fossil fuel based system or other reference system). Furthermore, before setting targets we should need to know the market structure. The market context is itself influenced by the policy regime and regulatory framework, and also need to be defined.

These considerations all touch on the contextuality of the metrics selected to operationalise a new assessment tool. How broadly applicable are the metrics we come up with given the market context, policy regime, and regulatory framework of the targets? The preferred approach expressed by industry participants is to adapt the different scenarios/targets to the variables we are working with, rather than adapting the variables (and by extension the metrics we use to measure them) to the different scenarios/targets we have set.

This means that the new assessment methods and metrics need to be thoroughly described and detailed for transparency. This includes outlining the assumptions in terms of reference scenario and target-setting, the methods used to quantify the metrics, missing/incompleteness of metrics, description of the scale of the metrics (absolute or relative, arbitrary), skewness & biases, etc.

Value creation

The group discussed a key question to be asked: How do we measure value creation, and what is the optimal market value creation? From an industry perspective, one can say that it comes down to return on investment (ROI) and (as a secondary consideration) market entry costs. High costs preceding even higher revenue will be prioritised over lower cost followed by lower revenue.

Furthermore, while minimising costs is a desirable objective for society as a whole, it is not the main driving target behind the development of wind energy. It was even asked if we should be using a business case for wind energy development on its own right, or rather see it connected to the overall targets outlined above. If the driving purpose behind the low-carbon energy transition is climate change mitigation and sustainable development, then creating additional value from alternative sources of energy competing with fossil fuels is only one solution of many. The assessment methods and metrics that we would like to develop should also be capable of objectively comparing different solutions to reaching the overarching targets.

Variables & metrics definition

The group focused mainly on systems, markets and policy. The below is a summary of the discussion and also contains diverging opinions and suggestions that were brought forward.

Economics metrics

The first set of metrics explored focused on the perspective of the wind industry and evaluation of technologies and projects. These were not evaluated further as they are already, to an extent, adopted by industry and in use. The metrics included:

- Classic LCOE
- Classic ROI
- ROI of R&D
- Profile costs (these are marginal costs)
- Financing availability.
- Project bankability (OPEX and CAPEX directly playing into this variable/indicator).
- Reduced uncertainty (touches on OPEX and CAPEX, and therefore directly on the bankability).
- Reduced uncertainty of price variability predictions (e.g. price forecasting, production forecasting).

Uncertainty was a topic of extensive discussion. One potential solution would be an uncertainty premium in the production costs (applied to consumption as well). There was also a discussion on cost due to the increasing uncertainty of successfully realising projects from previous investments and the related risk of stranded assets.

System and market metrics

The group looked at metrics related to value, markets and policy. The below table summarizes metrics developed and evaluated during the session. These represent a preliminary evaluation and are not comprehensive given the time constraints. Some metrics for market and policy were identified but not evaluated – they are described in the text that follows.

TABLE 4: METRIC CATEGORIES AND EVALUATIONS FOR ENERGY SYSTEM

			Impact	**Ease of implementation**	**Universality**	**Presentability**
ENERGY SYSTEM* **	**Resilience (security of supply)**	Unserved demand	Low	High	-	-
		Fuel import indep.	High	Medium	High	High
	Demand / Supply matching	Wind variability	High	Low	High	Low
		Wind intermit.	High	Low	High	Low
	Policy-making use	Contribution to RE targets	Medium-High	High	Medium/High*	Medium/High
	Grid infrastructure	Grid services	High	Low	Medium	High
		Grid code complian.	Low	High	High	Medium
			High	Medium	High	High
		Demand response	High	Low	N/A	Low
	New demand tech	Green Power-to-X	Very High	**	High	High
	Flexibility		Very High	Low	High	Medium

*Medium for some non-renewable technologies.
**Not on aggregated level (would need more detail, maybe good for benchmark against reference energy system)
***Market metrics identified but not included due to time constraints include profile costs, value factor, capacity adequacy, system cost and more.

The resulting table developed from a discussion that sought to identify the most important decision-making criteria for influencing system development. This began with a discussion on the over-arching mission of addressing climate change. A key metric should be to deliver national CO2 targets at the lowest system cost possible (that points towards numerous economic metrics including, not least, investment costs, profile costs, etc.). This might be too broad a target and may need to be broken down into tractable smaller targets. One suggestion was the creation of a renewable energy share per CO2-equivalent metric. In other words, for a given system, the share of renewables in the system relative to CO2-equivalent emissions (RE/CO2-eq) might indicate how much impact renewables are having on CO2 emissions in a given system. This also includes enabling resource and utilisation/consumption. However, some felt that an indicator of contribution of renewable energy was quite difficult to understand and would score low from that perspective. Another broad metric discussed was around system / supply security. A metric used to quantify the reduction of risk and uncertainty from a resource supply perspective was suggested.

A key concern with variable renewable energy such as wind energy is the correlation, or matching, between its production profile and system demand. The fit-to-consumption patterns, how fit variable renewable energy is to consumption, manifests in electricity prices as discussed earlier. Or flexibility to fit consumption patterns (a more refined development from the initial fit-to-consumption pattern). This could be measured through different metrics: as a relative rating compared to other technologies. Some metrics already exist to describe this fit, such as value factor. Value factor tends to be lower for variable renewables such as wind and solar as compared to fossil-fuel. Why not turn around the generation fitness metric and instead adjust consumption to new RE generation patterns? A metric that captures the potential demand flexibility in response to variable production patterns could potentially change the dialogue – potentially shining light on inflexibility in demand and/or conventional generation.

Wind variability and intermittency was discussed as its own topic. While the impact of wind energy variability and intermittency is realized in terms of the impacts on prices in the market (as previously discussed) direct metrics on these features of wind production profiles would go directly to something that can be directly affected by innovation, technology and project design. However, metrics in this area were perceived to be difficult to establish because there is not one single number that captures this well and thus the universality of the metric could be low. In addition, understandability by the broader stakeholder community was also perceived to be low.

Another area variable renewable energy can impact systems and markets is on the reliability and stability side. Firstly, system stability at a fundamental level is critical and generation sources can be evaluated based on their provision of system and ancillary services including voltage management, frequency management, grid forming/support, black start, balancing, inertia backup, and more. Some of this is embodied already in grid code requirements and compliance, but this could be expanded. Grid compliance determines the licence to operate and is always a binary outcome (yes or no). A suggestion was made that instead metrics for grid code governance could be used. Finally, capacity adequacy in a system is another key system objective and this is realized in the capacity value a particular generation asset provides. Metrics related to capacity and energy adequacy will be needed. The market value factor is okay but insufficient to capture the capacity adequacy of wind and more direct metrics on this variable are needed.

All of the above scenarios focus on a system that is at least to some degree inflexible. The group also discussed metrics related to overall system flexibility that would incentivize storage, demand response and other technologies. Improving such metrics would then enhance the system's ability to absorb increasing renewable energy shares. This potentially could even expand into the broader energy system where the line between electricity and other energy systems is blurred. Wind power fed into next generation energy systems would see new demand options (e.g. green power to green fuel, electric vehicles fuelled from clean electricity as opposed to dirty electricity). Metrics for this would include serving incentive schemes for green electrons in new uses – focusing on the quality of energy delivered from wind and other sources.

Finally, the group discussed additional topics that will be important in the coming years. These included:

- Avoided costs: Avoided infrastructure costs/investments (e.g. using/upgrading existing gas infrastructure for liquefied hydrogen distribution and consumption). Avoided investment cost in other technologies. Impacts on infrastructure cost (rigid) or impact on other carriers.
- Cybersecurity: an increasingly important issue and emerging risk for the grid system of the future. This topic may merit its own major research effort.
- Resilience: Maintaining system resilience in the face of outages including activation of emergency units, or reserve requirements. A high variable renewable energy system still must be resilient. Demand response and storage technologies may play a key role here.

As a final point, the group discussed who we need to involve to make that prioritisation and take the corresponding decisions. All agreed that this should be a joint effort between industry, research and political organisations, reflecting also the representation at the workshop.

2.2.3. Summary of Energy System and Market Dynamics (Group 2) Findings

Energy system and market dynamics are challenging because they go beyond wind technology and projects to the larger system context – which can vary considerably in different regions of the world and over time. The group focused on two key aspects of these systems including electricity price and factors that affect it, and energy policy and market structures. A preliminary brainstorming of metrics around these topics was performed with many interesting suggestions for novel metrics addressing different system issues including market prices but also reliability, stability, and even resilience. Additional work is needed to more comprehensively explore options for metric and to prioritize them.

3. SUMMARY AND NEXT STEPS

The two-day workshop first of all revealed an overwhelming consensus amongst all participants about the need to move beyond LCOE. In particular, the industry representatives at the workshop emphasised the need for usable solutions as soon as possible.

While solutions here and now was at the top of the wish list, there was also a clear understanding that a long term effort to overhaul current LCOE driven calculations is needed. Here, a set of challenges were identified.

Firstly, the presentation by Lars Christian Christensen from Vestas had raised a question at the outset of the workshop which remained a recurring theme: should we adopt a step-wise approach to gradually changing the system, using a *LCOE+* approach, or should a more radical overhaul towards a full beyond LCOE evaluation approach be targeted from the outset. The solution at the workshop was to pursue a dual approach towards both short time optimised solutions based on an LCOE+ approach and a long term efforts towards the full beyond LCOE system.

Secondly, any change from an LCOE to a LCOE+ or Beyond LCOE must be adopted by the energy sector beyond wind energy to be useful. This poses numerous challenges in terms of finding common ground between technologies that are currently LCOE driven and those that rely on other metrics. At the workshop it was agreed, that a first approach must be to develop a working model for wind energy which can then be presented to other energy technology communities for inspiration and open discussion.

Thirdly, any shift to Beyond LCOE metrics depends on the future energy system scenarios. Will we have a 'cheap electron scenario' where the issue is simply to develop as much electricity as cheaply as possible (maintaining LCOE as the main driver) or will we see a 'flexibility constrained' system in which wind and other technologies need to focus on how to capture a higher market price by improving the value of the power produced. Workshop participants agreed that while a cheap electron scenario is possible with dramatic drops in the price of storage, a flexibility constrained scenario will remain the realistic situation for the foreseeable future.

Lastly, a successful move towards beyond LCOE will require a change at the discursive level. Current language about energy system integration places renewables in the position of "system immigrants" that are burdening the system with costly requirements of flexibility. However, in reality, the ongoing evolution of the energy system towards carbon neutrality is better described as a system transformation towards a flexibility driven system where inflexible demand and baseload production can be just as costly as intermittent renewables are considered today.

With these four elements in mind, the participants agreed that the following four tangible results should be pursued as a follow-up to this workshop:

1. A high level one-pager outlining the concept and core elements of Beyond LCOE needs to be produced to present the idea to politicians and policy makers.
2. There is a need to develop a set up simple LCOE metrics that funding agencies and companies alike can use to assess the potential impact of new research and innovation.
3. A collaborative project between academia and industry is needed to develop an industry standard framework for beyond LCOE including a *Beyond LCOE calculator*.
4. The international research community should develop an open platform research model for beyond LCOE

2.3. HOW WILL THE WORKSHOP RESULTS BE USED?

The four action points listed above outline the four main tools that the workshop participants indicated as desired outcome of the further process. As a way to achieve this, both the SETWind project and the workshop participants will translate the workshop outcome into further initiatives.

Importantly, the Beyond LCOE framework outlined in this report will be used in the update of the EU SETPlan Implementation Plan for Offshore wind, which is due in autumn 2020.

The academic participants at the workshop plans a scientific publication on the topic in a peer reviewed journal, likewise to be submitted in autumn 2020. This will help fuel already ongoing discussions towards actions in the international research community.

The Industrial representatives plans to join forces with experts scientists at the workshop to work towards a first industry standard beyond LCOE toolbox.