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Circular business models and technology pathways for the hybridisation of wind farms: integrated wind and solar systems, power-to-gas and power-to-liquid solutions

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Abstract. The hybridisation of wind farms (HWF) through the implementation of multiple renewable energy production, storage and distribution technologies can optimise the performance and efficiency of the entire renewable energy system. Likewise, the implementation of wind-based Power-to-X (PtX) technology solutions represents an instrumental strategy to facilitate fossil fuel and pollutant emission savings in high-energy and high-carbon intensive sectors (e.g. transportation, industry and buildings). Nevertheless, the shift towards innovative renewable energy production and consumption systems should be pursued through the implementation of circular economy (CE) strategies driven by circular business models (CBM) to optimise resource efficiency and sustainability performance. However, none of the research studies available on the HWF, and/or the development of hybrid renewable energy plants or PtX systems, have yet provided an overview of all the potential CBM typologies and configurations that can facilitate this process, including the market uptake of Power-to-Gas (PtG) and Power-to-Liquid (PtL) products. Building upon the analysis of 82 documents, including journal papers, industrial reports, R&D projects and business cases, this paper provides a comprehensive categorisation and characterisation of CBMs for the deployment and management of integrated wind and solar plants, and PtG (hydrogen and methane) and PtL (methanol, ammonia and e-fuels) systems. The major industrial, market and policy challenges for a resource-efficient and sustainable HWF and deployment of PtX solutions are also discussed. The findings are relevant to the renewable and low-carbon energy sector, the industry and transportation sectors, and all the stakeholders and policymakers pursuing the sustainable energy transition.

Keywords. Circular economy, e-fuels, green hydrogen, hybrid renewable energy systems, life cycle management, literature review.

Highlights.

- Comprehensive revision of 82 academic papers and industrial reports
- The value creation, delivery and capture mechanisms, and the potential sustainability benefits of integrated wind and solar energy, Power-to-Gas and Power-to-Liquid solutions are evaluated
- Industrial, market, policy and environmental challenges are discussed

Abbreviations.

CAPEX: Capital Expenditure

CBMs: Circular Business Models

CE: Circular Economy

E-fuels: Electric fuels

EU: European Union

GHG: Greenhouse Gases

HWF: Hybridisation of Wind Farms

LCOE: Levelized Cost of Electricity

OPEX: Operational Expenses

O&M: Operation and Maintenance

PtG: Power-to-Gas

PtL: Power-to-Liquid

PtX: Power-to-X

PV: Photovoltaic

R&D: Research and Development

WSES: Wind and Solar Energy Systems

WTs: Wind Turbines

1. Introduction

The installation of wind energy production capacity during the period 2008-2016 in the European Union (EU) has contributed to avoid the consumption of 3,838 TWh of primary energy and the emission of over 828 Mt of CO_2 eq.; both representing an economic saving of €84,142M, while creating more than 2.5 million jobs (Ortega-Izquierdo and del Río 2020).

Thus, an accelerated deployment of wind power, coupled with deep electrification of the economic sectors, could support over one-quarter (≈ 6.3 Gt CO_2 eq.) of the annual greenhouse gas (GHG) emissions reductions needed in 2050 to reach the carbon neutrality targets (IRENA 2019a), while reducing the economy´s vulnerability to supply chain disruptions and price volatility related to imported fossil-fuels (IPCC 2011).

Nevertheless, wind energy production imposes relevant economic, technical and environmental challenges that must be overcome for a sustainable energy transition (Mendoza et al. 2022a). For instance, the current levelised cost of electricity (LCOE) is high (€41-89/MWh for onshore and €57-106/MWh for offshore wind energy, Badouard et al. 2020) due to the large capital expenditure (CAPEX) that can determine up to 75% of it (Tyler et al. 2020).

The wind turbines (WTs) also require frequent maintenance costing around €10,000 per year and asset (Karavida and Nõmmik 2015). Downtimes due to system and/or component failures requiring reparation or refurbishment further affect the economic performance of wind farms due to lower energy production (IRENA 2012, Chan and Mo 2017). Accordingly, repair and maintenance costs can increase by 20% the LCOE (Jensen 2018).

Finally, the conventional operational lifetime of WTs is short (20-25 years ≈ 120,000-150,000 operational hours) and around 34,000 installed units (36 GW) in the EU are already over 15 years old (Wind Europe 2020). Assuming that all these WTs have a power rating of 2 MW, the number of WTs currently in need for life-extension or decommissioning and waste management would correspond to 18,000 units. Considering that a single 2 MW unit can weigh around 318 tonnes, (excluding the foundations, site cables and switchgears and the transformer) (Razdan and Garrett 2018), the decommissioning of these old WTs could generate 5.72 Mt of wastes by 2025, including composites, metals, plastics and electronics. Forecast studies also indicate that 185 Mt to 325 Mt of WT wastes will be generated between 2030 and 2050 in the EU, considering only the blades (Lichtenegger et al. 2020).

Accordingly, WT life cycle resource consumption and waste generation are important and urgent environmental aspects to address in order to facilitate the deployment of resource-efficient, cost-effective and environmentally sustainable wind energy systems (Hao et al. 2020). In this regard, the hybridisation of wind farms (HWF) represents a relevant technological strategy that can substantially improve the economic and environmental performance of wind energy systems and the renewable energy market (Uusitalo et al. 2017).

The HWF refers to the implementation and management of multiple renewable energy production technologies in combination with energy storage and distribution solutions to optimise the system performance by increasing the flexibility of clean energy supply (Dowling et al. 2020, Lux and Pfluger 2020, Mendoza et al. 2022a). Accordingly, the HWF can make a more efficient use of the land, infrastructures and technologies, while extending the lifetime of the assets, optimising the load management of the grid, increasing and ensuring a more stable electricity output over time, delivering multiple renewable energy products, and supporting self-sustaining energy systems (Wind Europe 2019a, Tschiggerl et al. 2018).

The HWF can also generate fossil fuel and GHG savings in high-energy and high-carbon intensive industries using the cleaner energy carriers produced in hybrid wind power plants (IRENA 2019b). Besides, the HWF can have a positive social impact due to job creation through market diversification and people upskilling in highly specialised activities (Mendoza et al. 2022b).

Nevertheless, the HWF must be pursued through the implementation of circular economy (CE) strategies driven by circular business models (CBMs) in order to truly optimise the system resource efficiency and sustainability performance.

A CE can be understood as an economic system that targets zero waste and pollution by using resources efficiently (Nobre and Tavares 2021). Thus, CBMs are aimed at narrowing (reducing resource consumption), slowing (using resources for the longest possible) and closing (facilitating effective recycling and recovery) resource loops to mitigate negative impacts (Konietko et al. 2020).

Compared to linear business models based on take-make-use-dispose, CBMs can deliver greater economic benefits (e.g. by reducing overall costs and risks, opening new revenue streams, and improving competitive advantage), environmental benefits (e.g. by complying with environmental regulations, improving resource efficiency and increasing the supply chain environmental performance), and social benefits (e.g. by enhancing reputation and brand value, developing local communities, improving health and safety and increasing sustainability awareness) (Rosa et al. 2019, Mendoza et al. 2017, Heyes et al. 2018).

However, despite the potential benefits that the implementation of CBMs can bring for the sustainable HWF (Tschiggerl et al. 2018), the research studies on hybrid renewable renewable energy systems have been mostly technological-oriented, leaving the analysis of CBMs out of scope.

For instance, some authors have evaluated the technical, economic and environmental feasibility of location sites and configurations of hybrid renewable power plants based on the integration of i) wind and solar energy (e.g. Ludwig et al. 2020, Wang et al. 2019), ii) wind, solar and biomass resources with energy storage systems (e.g. Waewsak et al. 2020, González et al. 2018), or iii) wind, solar and diesel with batteries (e.g. Almutairi et al. 2021, Nsafon et al. 2020). However, these studies usually concentrate on small standalone hybrid (micro-grid) energy systems (Mazzeo et al. 2021) to facilitate rural energy transformation (e.g. Edwin and Sekhar 2018, Wang et al. 2019, Zhang et al. 2022) and/or to power local businesses and buildings in developing countries (e.g. Jahangiri et al. 2019, Jumare et al. 2019, Pandyaswwargo et al. 2022).

Other authors have focused on analysing Power-to-X (PtX) solutions (Uusitalo et al. 2017), understood as the implementation of complementary technology pathways and process chains for the conversion of renewable electricity into alternative energy carries to substitute fossil-based energy and material products in mobility, industry and building applications (Burre et al. 2019, Koj et al. 2019, Decourt 2019).

For instance, the electrolysis of water by using the surplus electricity produced by WTs (and/or combined WTs and photovoltaic panels (PVs)) leads to the generation of green hydrogen that can be used as feedstock to produce methane (Power-to-Gas: PtG), bulk chemicals (e.g. methanol and ammonia) or carbon-neutral liquid fuels (e.g. gasoline, diesel and kerosene) (Power-to-Liquid: PtL).

According to Wulf et al. (2020), who evaluated 220 PtX research and demonstration projects in Europe, the planning and commissioning of PtX projects is expanding at a rapid rate. However, the authors provide only a snapshot of the projects by indicating their commissioning year and location, the electricity sources and production technologies used, and the targeted field of application.

A more focused analysis of the techno-economic and environmental performance of PtX systems is provided by Can Ince et al. (2021). Through the revision of 79 PtX studies, the authors conclude that using green electricity to produce methane is the preferable PtX technology pathway because synthetic methane can be injected in the existing gas network and utilised in multiple industrial applications. Nevertheless, methane systems have a higher contribution to metal and water depletion, and terrestrial, marine, and human toxicity compared to the conventional natural gas production systems (Can Ince et al. 2021).

Focusing on environmental performance, Koj et al. (2019) highlight, after analysing 32 life cycle assessment (LCA) studies, that PtX solutions can decrease climate change contributions compared to conventional energy production technologies but this is case-specific and depends on the suitability of the implemented solutions (e.g.

combination of low-carbon electricity production with carbon capture). Likewise, although Uusitalo et al. (2017) suggest that GHG emissions can be reduced in the industry and transport sector by using PtX energy products, the authors did not evaluate what type and configuration of business models is more suitable to facilitate PtX technology uptake and upscaling.

Although, Tschiggerl et al. (2018) have evaluated alternative PtG business models, the authors consider a particular system based on hydrogen storage in an underground reservoir (pore space of a geological formation) and hydrogen and methane production for use in the chemical and transport sectors, lacking the provision of an overview of all possible PtX business models driven by the HWF.

Finally, Mendoza et al. (2022a) have analysed the HWF as a strategy to facilitate the optimisation of the life cycle management of wind farms. However, the authors did not comprehensively analyse the scope of each possible technology pathway.

Accordingly, none of the studies available on the HWF, and/or the development of hybrid renewable energy plants or PtX systems, has yet provided a comprehensive business model analysis of all the potential technology pathways.

This paper provides a unique categorisation and characterisation of all the CBM alternatives and configurations that can drive the HWF, including an analysis of the potential sustainability benefits and trade-offs, and the industrial, market and policy challenges for a resource-efficient and sustainable life cycle management of wind farms and PtX systems. Access to such information is crucial to support further technology, industrial, business and policy innovation to support the sustainable energy transition (IRENA 2022a).

2. Methodology

A methodology comprising four major analytical steps (Figure 1) was applied for the identification, categorisation and characterisation of CBMs for the HWF.

2.1. Systematic review of the academic and grey literature

According to Bocken et al. (2014) and Guzzo et al. (2020), the definition of business model typologies for a particular sector requires the identification and analysis of meaningful categorisations from the scientific literature and the industrial practice. Thus, a comprehensive revision of academic literature (journal and review papers) and grey literature (conference proceedings, company and business association websites, and CE databases), was performed, as illustrated in Figure 2.

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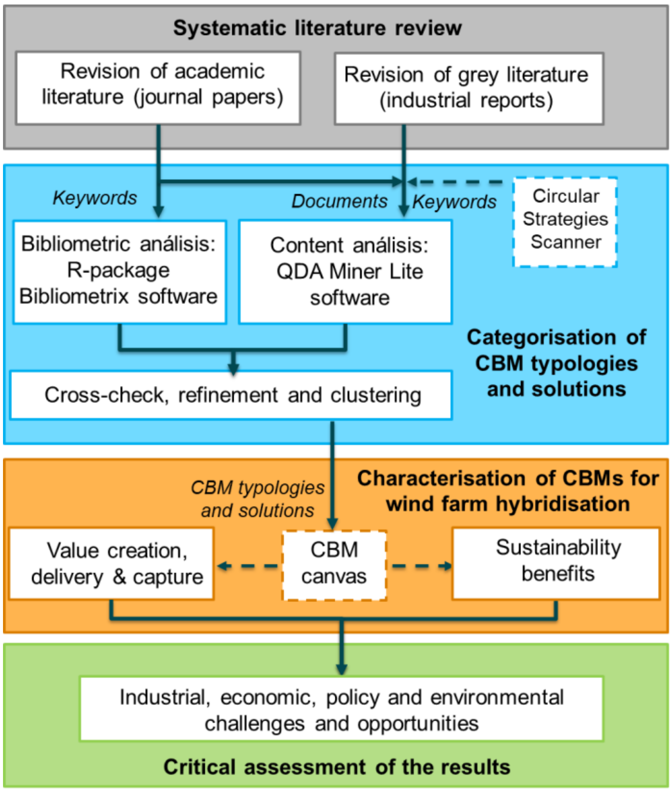

Figure 1. Research methodology.

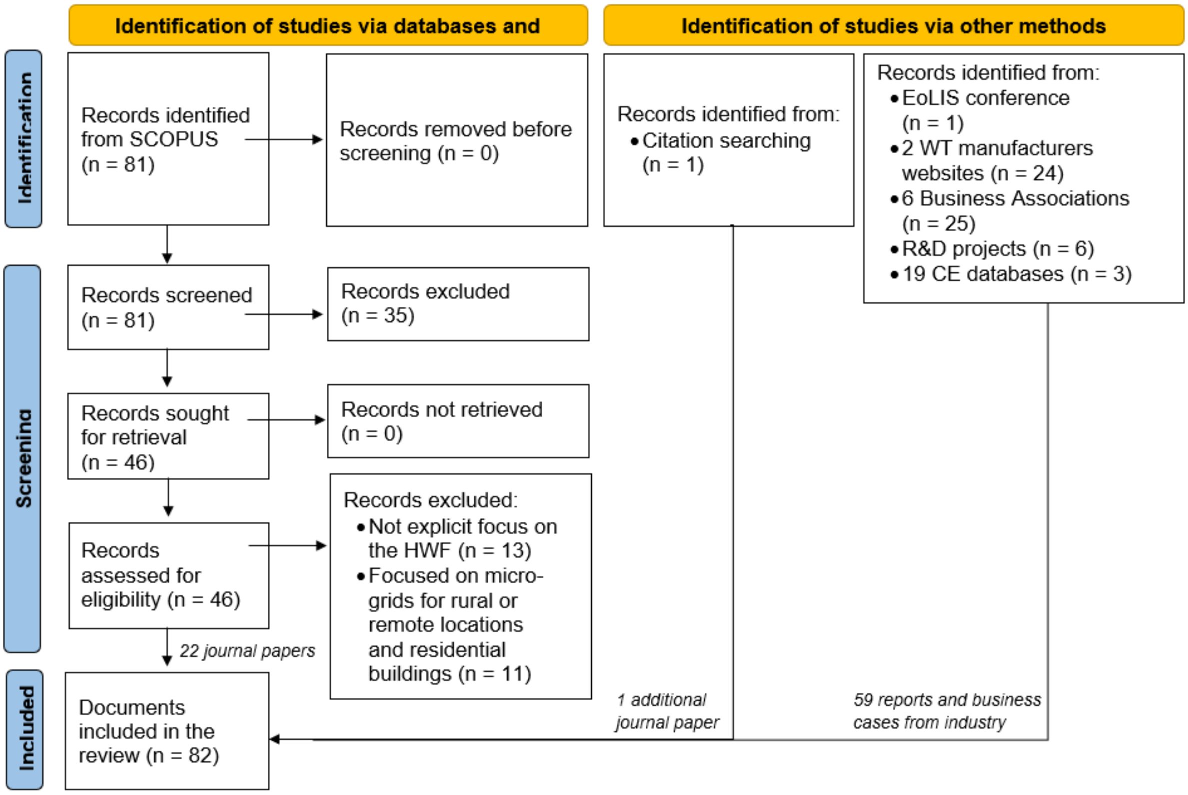

Figure 2. Systematic literature review procedure and outcomes. Based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al. 2021).

2.1.1. Review of academic literature

Wind energy-related keywords (first search stream) were crossed-linked with business model-related keywords (Rauter et al. 2017, Díaz-López et al. 2019) (second search stream) and keywords related to hybrid wind energy systems (third search stream), to identify relevant business-oriented journal papers on the HWF, using SCOPUS as search engine. The resulting keywords, which are presented in Table S1 of the Supplementary File (SF), were searched within article title, abstract and list of keywords. No time or geographical restrictions were applied. However, only journal and review papers written in English were considered for evaluation.

Accordingly, the academic literature search (performed on 21/03/2022) returned 81 hits. By reading the papers´ abstracts and excluding those papers out-of-scope (no explicit focus on business and/or business model innovation), the sample was reduced to 46 papers for evaluation. Once these papers were completely read, a further 24 papers were removed due to the lack of information to support the identification, categorisation and characterisation of CE strategies and CBMs for the. Accordingly, the final sample of academic papers used in the research corresponded to 23, including 22 papers from the literature search and one paper gathered through snowballing (Mourão et al. 2020) (Figure 2).

2.1.2. Review of grey literature

The review of academic papers was complemented with the consultation to the websites of WT manufacturers and renewable energy business associations, including CE databases to gather real-life business cases on the HWF (Figure 2).

A comprehensive exploration of the websites of the two major European manufacturers of WTs (GWEC 2021), including Vestas (2022) and Siemens Gamesa Renewable Energy (2022a), led to the identification of 24 industrial reports for analysis. The consultation to the websites of six major international renewable energy associations, including Wind Europe (2022), ETIPWind (2022), the Global Wind Energy Council (GWEC 2022a), the International Renewable Energy Agency (IRENA 2022), the International Energy Agency (IEA 2022a) and Hydrogen Europe (2022), resulted in 25 additional business documents for evaluation.

Likewise, 19 CE and sustainability case study databases, including Circle Economy Lab (2022a), CIRCit (2022), European CE Stakeholder Platform (2022), Global Opportunity Explorer (2022a), State of Green (2022), Circulator (2022), EMF (2022a), MATChE (2022), CE Club (2022), ERN (2022), Reflow (2022), EIT Climate KIC (2012), CSIRO (2022), Circular X (2022), WBCSD (2017) and BMIX (2022), Biomimicry 3.8 (2022), Ask Nature (2022) and The Blue Economy (2022), were screened to identify industrial business cases. However, this search yielded only three results (Global Opportunity Explorer 2022b, Circle Economy Lab 2022b, and State of Green 2017), which demonstrated the lack of CE databases available documenting solutions for the HWF.

Finally, the proceedings (36 presentations) from the End-of-Life Issues & Strategies online seminar (EoLIS 2020) (18-20 November 2020) were also screened leading to one additional resource for analysis.

Consequently, a total of 82 documents were comprehensively evaluated to categorise and characterised CBMs for the HWF, as described in the following sections.

2.2. Categorisation of CBM typologies and solutions for the hybridisation of wind farms

The identification and categorisation of CBM typologies and solutions for the HWF was carried out through an iterative process combining bibliometric and content analysis (Chakraborty et al., 2021; Koberg and Longoni, 2019; Lode et al., 2022).

In the context of this paper, a CBM typology is understood as a grouping of CBM solutions to address a particular end-goal (Bocken et al. 2014), whereas a CBM solution represents a unique configuration of CBM elements (Mendoza et al. 2022a, Mendoza et al. 2022b). Thus, each CBM typology integrates a set of CBM solutions around a specific technological pathway for the HWF, which combine different CE strategies to address specific market needs and business challenges (Ludeke-Freund et al. 2018).

The software R-package Bibliometrix v. 3.1.4 (Aria and Cuccurullo, 2017) and QDA Miner Lite v2.0.9 (Lewis and Maas, 2007) were used to examine the academic and industrial literature for the identification of technological pathways and CE strategies for the HWF and define the corresponding CBM typologies and solutions. This process comprised the development of three interrelated activities.

First, a bibliometric analysis of the 23 academic articles (section 2.1.1) was conducted, which involved an examination of the most frequent keywords provided by the authors, the evolution of such keywords over time and their co-occurrence (Aria et al., 2022; Bretas and Alon, 2021). Keywords were manually revised prior to the analysis to avoid typographical errors and to homogenise the spelling (Henry et al., 2021). Table S2 in the SF presents the original authors keywords that were manually replaced by more generic but meaningful keywords. As a result, the most relevant technological trends and pathways for HWF, as reported by the academics, were identified.

Secondly, a content analysis of the academic and grey literature (section 2.1.2) was performed by relying on a predefined set of keywords to identify CE strategies driving the HWF. This set of keywords were gathered from the Circular Strategy Scanner developed by Blomsma et al. (2019). This scanner presents a comprehensive set of keywords, definitions and examples, of 30 CE strategies organised into four innovation goals that can support the development of CE innovations, namely: 1) Recirculate, 2) Reinvent, 3) Rethink and Reconfigure and 4) Restore, Reduce and Avoid. The suitability of using this scanner as baseline to screen the literature content has been demonstrated by Kristoffersen et al. (2020), who used it to align digital technologies with CE strategies for improving resource efficiency and productivity. Table S3 in the SF presents the list of keywords gathered from Blomsma et al. (2019).

Finally, the results of the bibliometric and content analysis were cross-checked and refined throughout the full reading of the documents (journal papers and industrial reports), leading to the resulting categorisation of CBM typologies and solutions for the HWF presented in section 3.1. For a more detailed explanation of the methodology applied and the corresponding findings, see Ibarra and Mendoza (2023).

2.3. Characterisation of CBM solutions for the hybridisation of wind farms

A business model describes the rationale of how an organisation creates, delivers, and captures value (Osterwalder and Pigneur 2010). Value proposition refers to the products and service offering which distinguishes a company from others into the market. Thus, value creation refers to the key activities, resources and partners, which enable businesses to generate value propositions to satisfy customer needs (Sjödin et al. 2019). Accordingly, value delivery refers to the transactional model between the company and the customers through strategic relationships and communication channels (Bocken et al. 2018). Finally, value capture is the process of earning revenues and securing profits from the provision of goods and services (Teece 2010). Nevertheless, the value management mechanisms of CBMs should lead to long-term competitive advantage considering triple bottom line impacts (Elkington 1998).

Accordingly, the characterisation of CBMs for the HWF was addressed by relying on meaningful approaches for the examination of conventional (e.g. Gassmann et al. 2014, Remane et al. 2017), circular (e.g. Ludeke-Freund et al. 2018, Pieroni et al. 2020) and sustainable (e.g. Bocken et al. 2014) business model typologies. In all the cases, the use canvases or templates (Osterwalder and Pigneur 2010, Daou et al. 2020, Pieroni et al. 2021) represents a best practice to structure the data collection and analysis process. Thus, an Excel-based template was designed to structure the evaluation of the academic and grey literature (section 2.1), by following the method described in Mendoza et al. (2022a) for the characterisation of CBMs with application to the wind industry.

The resulting CBM template comprised three main analytical blocks:

i) CBM typology description and CBM solutions with the corresponding technological pathways and CE strategies.
ii) CBM value management mechanisms, including the value proposition, value creation, value delivery, and value capture for each CBM solution, and
iii) CBM sustainability screening, including the potential benefits to society (people), economy (profit) and the environment (planet), as discussed in the revised literature.

The structure of the CBM template can be consulted at Table S4 in the SF, including the complete list of the documents analysed (section 2.1.) and the corresponding categorisation and characterisation of the CBM typologies and solutions (section 2.2.).

2.4. Critical analysis of the technical, socio-economic and environmental challenges and opportunities for the hybridisation of wind farms

A critical assessment of the selected documents and results (sections 2.1-2.3) was performed to define the most relevant challenges and opportunities for the resource-efficient and sustainable HWF and uptake of PtX products. This analysis integrated a comprehensive evaluation of the inter-links between the CBMs´ value management mechanisms and the corresponding industrial, market, policy and environmental sustainability benefits and trade-offs. Special attention was placed on analysing the pros and cons related to the resource requirements (equipment, facilities, infrastructure) for the HWF, considering these systems are technology and capital intensive. As a result, a number of guidelines for industrial, policy and academic action were defined to support future decision-making processes for the deployment of sustainable hybrid renewable power plants.

3. Results and discussion

3.1. Categorisation of technology pathways, CE strategies and CBM typologies for the hybridisation of wind farms

3.1.1. Technology pathways addressed in the academic literature

Of the total of 79 keywords identified through the bibliometric analysis (Table S5 in the SF), the top-10 keywords most frequently used are listed in Table 1.

Table 1. Results of the bibliometric analysis, including keywords frequency, period and clustering (resulting from co-occurrence analysis).

Rank	Keywords	Occurrences (nº of times named)	Relevance within the 79 keywords (%)	Occurrences within the 23 articles (%)	First year named	Cluster
1	wind energy	9	11,4%	39,1%	2008	1
2	power-to-gas	8	10,1%	34,8%	2016	2
3	hydrogen	6	7,6%	26,1%	2008	2
4	electrolysis	5	6,3%	21,7%	2008	2
5	hybrid system	4	5,1%	17,4%	2017	1
6	solar energy	4	5,1%	17,4%	2018	1
7	energy storage	3	3,8%	13,0%	2016	2
8	power-to-liquid	3	3,8%	13,0%	2017	2
9	methanol	2	2,5%	8,7%	2018	-
10	offshore wind	2	2,5%	8,7%	2020	2

As Table 1 shows, the most frequent keywords mentioned in the academic studies on the HWF are technology-related. The exploration of the keywords evolution over time (see Ibarra and Mendoza 2023 for further information) also reveals that research on wind energy until 2015 was closely aligned with the research on hydrogen and electrolysis solutions, while the research on Power-to-Gas, hybrid system, solar energy, energy storage, Power-to-Liquid and methanol started to gain relevance later on, doubling in frequency from 2020 onwards. These results evidence the growing interest in the HWF and PtX systems by academics, which seems to have gained momentum after the release of the CE Action Plan in 2015 (European Commission 2015) and the climate action targets specified in the European Green Deal adopted in 2020 (European Commission 2020).

Besides, the analysis of the keywords co-occurrence (i.e. keywords jointly used by the authors) allows the definition of two clusters of research activities (Table 1). The first cluster is linked to wind energy, solar energy, hybrid systems and renewable energy keywords, which encompasses research focused on solutions that combine WTs and PVs at the same location, with or without energy storage systems. Consequently, a first CBM typology was defined as Wind and Solar Energy Systems (WSES), as described in Table 3.

The second cluster of research activities integrates studies focused on Power-to-Gas, hydrogen and electrolysis including wind energy, energy storage, Power-to-Liquid and off-shore wind as additional keywords. Accordingly, a second CBM typology was defined as PtX, which can be further divided into CBM sub-typologies: PtG and PtL systems (Table 3), being consistent with the way these systems are addressed in the general literature on PtX solutions (e.g. Koj et al. 2019).

3.1.2. CE strategies addressed in the academic and industrial literature

The content analysis of the 33 predefined CE keywords (Table S3 in the SF) demonstrates that only 16 keywords (48%) are mentioned in the academic and grey literature, as shown in Table 2.

Table 2. Most frequent CE strategies mentioned in the academic studies and industrial reports on the HWF. The definitions for each CE strategy can be consulted at Table S3 in the SF.

CE categories	CE strategies	Academic literature	Grey literature	Academic literature (23 documents)	Grey literature (59 documents)
Recirculate	Retrofit	1	7	4,3%	14,6%
	Refurbish	1	2	4,3%	4,2%
	Repair	1	1	4,3%	2,1%
	Maintenance	14	13	60,9%	27,1%
	Reuse	1	4	4,3%	8,3%
	Upgrade	6	11	26,1%	22,9%
	Repurpose	0	7	0,0%	14,6%
	Recycle	0	4	0,0%	8,3%
	Recover	4	9	17,4%	18,8%
Restore, reduce and avoid	Recycle	5	3	21,7%	6,3%
	Restore	0	3	0,0%	6,3%
	Cleaner production	0	1	0,0%	2,1%
Rethink and reconfigure	Rethink	1	0	4,3%	0,0%
Total		34	65	100,0%	100,0%

The most common CE strategy mentioned and/or addressed is the reuse of parts and products, through maintenance, upgrading and end-of-life recovery. CE strategies focused on the recycling of materials and other resource flows (such as CO_2 and water) in PtG and PtL systems are also reported in both the academic and grey literature. Products´ lifetime extension through retrofitting and repurposing strategies has been also addressed in the grey literature. Further information of the bibliometric analysis, including the keywords co-occurrence over time and the deductive content analysis of CE strategies, is provided in Ibarra and Mendoza (2023).

3.1.3. CBM typologies and solutions for the hybridisation of wind farms

Building upon the integrated assessment of the academic and industrial literature, an overview of the three major CBM typologies, with their corresponding technology pathways (solutions) and CE strategies for the HWF, including demonstrative industrial projects and business cases, is provided in Table 3.

The simplest CBM typology for the HWF refers to the combination of i) WTs and PV panels, ii) WTs and batteries, or iii) WTs, PV panels and batteries on a single location (WT-PV-B) (Petersen et al. 2018) (Table 3). This CBM typology can be extended further by integrating PtG and PtL technologies.

At the core of the PtG and PtL technology pathways is green hydrogen production through water electrolysis (Power-to-Hydrogen). If paired with CO_2 capture, green hydrogen can be further synthetised into methane (Power-to-Methane) to support clean transportation and/or low-carbon heating processes in the industry and residential sectors (Lux and Pfluger 2020, IEA 2019, IRENA 2019b).

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Under the PtL technology pathway, green hydrogen can be used to synthesise liquid energy carriers, such as methanol (Power-to-Methanol) (also used in the chemical industry to produce polymers and high-value chemicals) (Hydrogen Europe 2021) and Fischer–Tropsch-fuels or hydrocarbons (Power-to-Hydrocarbons) (e.g. diesel and kerosene) used as electric fuels (e-fuels) in the transportation sector (IEA 2019, IEA Hydrogen TCP 2020, ETIPWind 2021). Also, ammonia (Power-to-Ammonia) for use as feedstock in industrial processes, including the production of fertilisers in the chemical sector, can be produced by using green hydrogen (Hydrogen Europe 2021).

Consequently, CBMs for the HWF can be defined as business models aimed at optimising the resource efficiency and sustainability performance of existing and/or new wind energy systems and energy-demanding processes by increasing the flexibility of renewable energy supply through the integration of multiple clean energy production, storage and distribution systems. As such, CBMs for the HWF belong to the so-called circular supplies business model category that groups business models focused on providing fully renewable, recyclable or biodegradable resources to replace fossil-based products in production and consumption systems (Accenture 2014, Lacy et al. 2020, Pieroni et al. 2020).

Thus, CBMs for the HWF could contribute to fulfil the three major principles of the CE including: i) design out of waste and pollution, ii) keep products and materials in use for the longest possible, and iii) regenerate natural systems (EMF 2022b).

For instance, the HWF involves the implementation of diverse technological solutions for the production and delivery of renewable energy carriers and products (electricity, gas, chemicals, and liquid fuels) (ETIPWind 2021), which fits within the CE principle of regenerating natural systems by avoiding the use of non-renewable and fossil-based resources.

Likewise, the clean electricity and additional energy carriers delivered by hybrid wind power plants can help decarbonising high energy- and carbon-intensive economic sectors, such as the chemical, steel and cement industry, as well as mobility (passenger, heavy-duty, maritime and aviation transportation) and commercial and residential buildings (GWEC 2021) (see section 3.2). This fits therefore with the CE principle of designing out of waste and pollution by mitigating or minimising negative impacts that can cause damage to human health and natural systems, such as the release of energy-related GHG and pollutant emissions.

Finally, one of the major reasons for the HWF is the need to optimise the wind (and renewable) energy system performance through the strategic and efficient management of infrastructure requirements, including the use of ageing assets (e.g. WTs) (Mendoza et al. 2022a). Thus, the lifetime extension of ageing assets facilitated by the hybridisation of existing wind farms, can contribute to fulfil the CE principle of keeping materials and products in use for the longest possible by preserving the value of the resources.

Nevertheless, the sustainability performance of these CBMs should be carefully evaluated by analysing all their life cycle management requirements from a holistic perspective, as discussed in section 3.3.

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Table 3. CBMs typologies, technology pathways (solutions) and CE strategies for the HWF. Acronyms: CBMs – circular business models, WSES – wind and solar energy systems, PtX – Power-to-X, WTs – wind turbines, PV – photovoltaic, B- batteries, EU – European Union.

CBM typologies		**Technology pathways**	**CE strategies**	**Brief description**	**Industrial projects and business cases**
WSES	Wind and solar energy systems with or without energy storage systems (Wind Europe 2019a)	Wind and solar energy (WT-PV)	Infrastructure, equipment and grid upgrading & maintenance; repurposing of technology components; recycling & recovery; multi-offering business models; displacement of conventional power	WTs and PV panels coupling or colocation to increase the flexibility and productivity of green electricity (Wind Europe 2019a)	Wind (3.0 MW WT) and solar photovoltaic (372 kW) hybrid demonstrator for sustainable energy production and consumption (VESTAS 2018a)
		Wind, solar energy and batteries (WT-PV-B)		WTs and PV panels coupling or colocation with battery energy storage technologies to optimise the assets and infrastructure performance, and increase the flexibility, productivity and cost-efficiency of green electricity supply by avoiding power curtailment (Wind Europe 2019a)	WT and PV integration with large-scale battery systems in Tonga to increase renewable energy penetration up to 50% nationwide, without negatively affecting the island grid loads (Global Opportunity Explorer 2022b)
		Wind energy and batteries (WT-B)		Integration of battery energy storage technologies in wind farms for more stable wind power output (Vestas 2017a)	Innovative hybrid plant in the Philippines to provide stable renewable electricity supply to reduce fossil fuel use in remote locations (SGRE 2020)
PtX	**Power-to-Gas:** convertion of renewable energy into gaseous energy carriers for different applications (IRENA 2019b)	Power-to-Hydrogen	Same as WSER plus retrofitting & refurbishment of pipelines; recycling and recovery of materials, energy, water, heat, and CO_2; cleaner production of energy carriers and products; displacement of conventional fossil-based gaseous energy products.	Surplus wind and solar energy is used to produce green hydrogen through water electrolysis (IRENA 2019c)	Green hydrogen (500 MW electrolyser capacity) to replace coal-based blast furnace technology (direct reduction of iron ore pellets) in iron and steel production. Approximately, 1.2 Mt of crude steel could be produced annually, representing 25% of Sweden's overall production, with the potential to avoid the emission of 14.3 Mt CO_2 eq. over the first ten years of operation (HYBRIT 2022)
		Power-to-Methane		Conversion of green hydrogen into synthetic methane through CO_2 capture and catalytic methanation (Balan et al. 2016).	Green methane production at industrial scale through an integrated system of conversion of water to hydrogen through renewable energy powered electrolysers and CO_2 supply from biomethane upgrading processes, with subsequent methanation and feeding into the gas network (SGI 2022)
		Power-to-Power		Reconversion of green hydrogen and methane back into electricity (re-electrification) using gas turbines and fuel cells (Hydrogen Europe 2021)	Fully integrated power-to-hydrogen-to-power industrial-scale power plant, including an advanced dry-low emissions hydrogen gas turbine with the goal to produce 12 MW electrical energy using fuel mixtures that contain up to 100% green hydrogen (ARTTIC SAS 2022)
	Power-to-Liquid: conversion of a gas into a liquid energy carrier for different applications (Dieterich et al. 2020)	Power-to-Methanol	Same as PtG, plus displacement of conventional fossil-based liquid energy products.	Methanol production by using green hydrogen and CO_2 captured from the air through a reverse water-gas shift (ETIPWind 2021)	Green methanol production from captured CO_2 and green hydrogen using surplus renewable energy. The pilot plant is able to produce 1 ton of methanol per day by capturing 1.5 tons of CO_2/day, being one of the largest flue gas CO_2-derived methanol synthesis plant in the EU (MefCO$_2$ 2016)
		Power-to-Hydrocarbons		Conversion and upgrading of green methanol into diesel, gasoline, jet fuel (kerosene) and olefins or waxes (Fasihi et al. 2017)	Production of 100 kt of e-fuels (naftha, diesel, kerosene) using green hydrogen and the conversion of 300 kt of CO_2 eq. per year in the Port of Dunkirk in France (ENGIE and INFINIUM 2022)
		Power-to-Ammonia		Green ammonia production from green hydrogen and nitrogen uptake from air (Siemens Energy 2021).	5 GW of wind and solar production capacity powering 2 GW electrolysers to produce 160 kt of green hydrogen per year (30% of Spanish hydrogen demand) for use in ammonia production (green ammonia plant with annual capacity of 200 kt) with the potential to save 1 Mt to 2.5 Mt of CO_2 per year and create up to 5,000 jobs (Ammonia Energy Association 2019)

In the following sections, a detailed analysis of the value proposition, creation, delivery and capture of each CBM typology and technology solutions is provided (sections 3.2), including an evaluation of their potential sustainability benefits (section 3.3) and a discussion of the most relevant industrial, market and policy constraints (section 3.4.) to be addressed for a circular (resource-efficient) and sustainable (economically, socially and environmentally fit) HWF and uptake of PtX products.

3.2. Characterisation of CBMs for the hybridisation of wind farms

Figure 3 illustrates the main i) resource flows (inputs and outputs), ii) industrial requirements (equipment, facilities and infrastructure), and iii) partners (suppliers) and customers (end-users) of the alternative CBMs and technology pathways for the HWF, as identified through the systematic literature review (section 2.1-2.3).

3.2.1. Wind and solar energy systems (WSES)

Table 4 provides an overview of the business model configurations to support the implementation and management of WSES, as identified in the literature review.

3.2.1.1. Business offering and drivers

The widespread adoption of wind and solar energy technologies increases the intermittency problems associated with the daily fluctuations and seasonal variability of these natural resources (Xu et al., 2021). While some countries are facing wind energy overproduction (surplus) (e.g. Denmark supplying 130% of the required load within a 24-hour window), other countries face underproduction issues (Dieterich et al., 2020). As a result, grid congestion and power curtailments increase the costs of balancing the time mismatch between energy supply and demand (Balan et al., 2016; Schnuelle et al., 2020).

Moreover, owners of 20+ years old wind farms no longer benefiting from feed-in tariffs, are not able to generate profits from their assets due to market prices' volatility and production volume risks (Kristensen 2020). As wind farm repowering projects are lengthy and costly, some wind farm owners that have exceeded the 20-year of subsidy benefits opt for WTs decommissioning (Rasmussen et al., 2020), even though the technical lifetime of the assets could be longer or extended further through retrofitting, refurbishment and/or remanufacturing (Mendoza et al. 2022a).

Consequently, the HWFs by integrating WTs, PV panels and batteries (Table 3) can optimise the assets and infrastructure performance, increase the capacity factor, flexibility and cost-efficiency of the green electricity system, and further reduce fossil fuel consumption and GHG emissions by avoiding renewable power curtailment (Wind Europe 2019a).

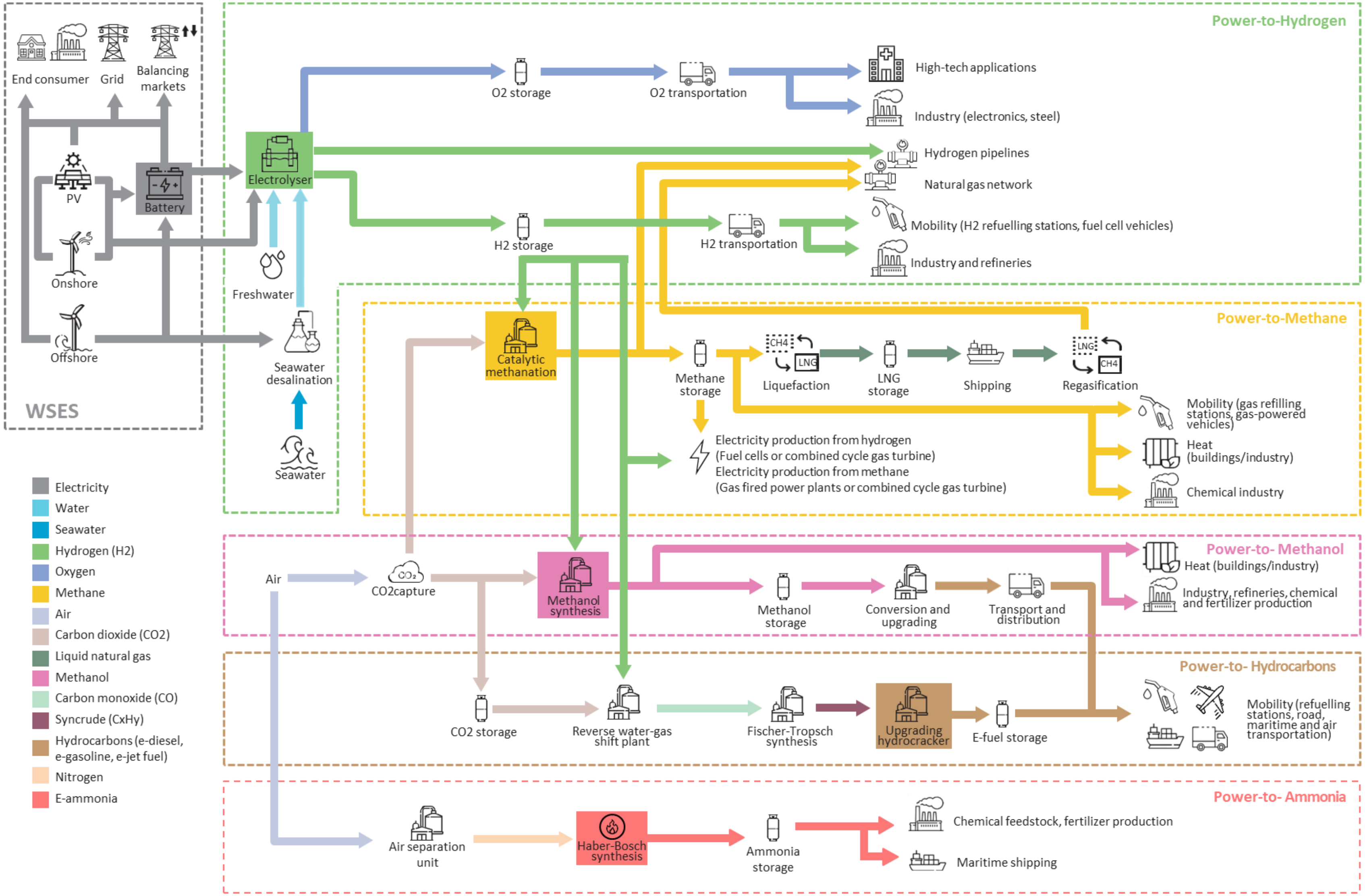

Figure 3. Main technological pathways and requirements for the hybridisation of wind farms. Acronyms: WSES – Wind and Solar Energy Systems, LNG – liquified natural gas. Note: The icons have been designed using resources from Flaticon.com.

Table 4. Wind and Solar Energy Systems (WSES) business model configurations. Acronyms: B – batteries, CAPEX – capital expenditure, CE – circular economy, HPPC - hybrid power plant controller, LCOE – levelized cost of electricity, OPEX – operating expenses, O&M - operation and maintenance, PV – photovoltaic, SCADA - Supervisory Control and Data Acquisition, WTs – wind turbines.

WSES systems	Technological alternatives	a) wind and solar energy (WT-PV), b) wind and solar energy and batteries (WT-PV-B), c) wind energy and batteries (WT-B).
Value proposition	Problems addressed	Mismatch between energy generation and supply, low energy efficiency and reduced productivity, dependence on fossil fuels, land scarcity, climate change impacts
	Business offering	Increased renewable electricity production and grid penetration due to wind and solar energy complementarity; enhanced predictability, reliability and stability in the power output; optimisation of land, equipment, control systems and supporting infrastructure requirements; reduced LCOE due to lower CAPEX and OPEX.
	Products & Services	On- and off-grid tailor-made hybrid wind and solar solutions (with or without batteries), including techno-economic feasibility studies, engineering support, and provision of ancillary services (e.g. frequency control and network support) facilitated by intelligent, real-time power plant controllers.
Value creation	Key activities	i) Hybrid plant design using proprietary tools, ii) meteorological and forecasting analysis, iii) technical and economic assessments, iv) engineering, procurement, and construction, v) integrated O&M activities and assets optimisation over time, vi) power conversion, distribution and management.
	Key resources	i) HPPC based on SCADA, ii) WTs, PV panels, batteries, including inverters and supporting infrastructure and facilities, iii) advanced forecasting tools for energy, technical and economic assessment, iv) multidisciplinary teams for optimising the project hybrid wind farm life cycle management, v) licences, permits and metering systems.
	Key partners	WTs, PV panels, batteries and supporting infrastructure suppliers, energy managers (e.g. transmission system operators and distribution system operators), engineering companies, local governments.
Value delivery	Customer segments	Wind farm owners and grid operators, industrial facilities, local governments and communities
	Channels	On- and off-grid energy delivery network
	Customer relationships	Customizable and highly flexible hybrid wind and solar solutions to meet individual and system requirements, integral maintenance and service contracts, power purchase agreements, secured 24/7 renewable electricity supply, utilisation of existing equipment. Also payment options for energy consumption (in off-grid applications).
Value capture	Cost structure	Technologies, management tools and labour
	Revenue streams	CAPEX reduction by more efficient use of infrastructure, OPEX reduction by simultaneous maintenance and control operations, and new revenue streams through selling higher amounts of renewable energy, which can be increased further through forecast error reduction, energy trading and arbitrage, load/demand monetarisation and peak shaving/load shifting, frequency support and curtailment reduction.

3.2.1.2. Value creation and delivery

Depending on the farm layout, the grid connection, the control strategy and the functionalities pursued, WSES can be configured in different ways with a different cost structure and revenues streams (Table 4).

WSES can be deployed as consumer-directed stand-alone units (microgrid) or grid-integrated power plants (Figure 3). In the former, hybrid wind energy solutions (e.g. WT-PV-B or WT-B) are usually oriented to support renewable energy production and consumption in islands, rural areas and/or communities in remote locations to cut diesel use, costs and GHG emissions (SGRE 2020, Wind Europe 2019a).

However, grid-integrated renewable power plants are focused on supplying larger amounts of clean electricity to satisfy the needs of a region. In this case, PV panels can be coupled with WTs (e.g. in small plants with low solar/wind ratio), which allows a more efficient utilisation of the wind farm converter as it can operate at full-load. Nevertheless, large hybrid wind farms require the co-location of WTs and PV panels to share the same substation and grid connection infrastructure (Wind Europe 2019a).

While solar technologies can be used to deliver power during day peak, wind technologies can supply power during the evening peak and night load (Vestas 2018b, SGRE 2018). By adding batteries, WSES can generate a continuous and stable flow of renewable electricity to the grid over the 24-hour cycle, solving intermittency problems and maximising asset revenues (Cao et al. 2018, Xu et al. 2021, GWEC 2022). Nevertheless, WSES can operate without the installation of batteries, although a more robust forecast and power control system must be in place to avoid power curtailment (due to under or overproduction) and optimise the system efficiency (Petersen et al. 2018, Vestas 2018a).

Alternatively, wind farms can be hybridised by implementing energy storage systems alone, such as lithium-ion or redox flow batteries (WT-B). For instance, Vestas, through a partnership with Northvolt, is integrating lithium-ion battery solutions into their WTs to increase certainty and predictability in wind power output in order to match supply and demand for a greater grid stability (Vestas 2017a). Alternatively, excess energy can be used to compress air which can be stored in tanks and caverns (Sun et al. 2011). However, this solution has spatial restrictions and can only be installed if the site conditions are suitable (Cao et al., 2018).

A potential location-independent and cost-efficient WSES alternative is the so-called Electric Thermal Energy Storage (ETES) (SGRE 2022b) to supply low-cost and low-carbon electricity, steam (process steam) and/or heat (process heat or district heating) (Arabzadeh and Lund 2020, Cao et al. 2018, SGRE 2022c). ETES can be managed through a virtual power plant, whereby wind and solar energy production is sited in areas of optimal resource, and energy storage is sited closer to demand centres to improve price competitiveness (GWEC 2022). Further information about this particular solution is provided in section S6.1 of the SF, including additional descriptions of the configuration of WSES when energy storage is integrated.

In any case, the implementation of an integrated hybrid power plant controller (HPPC) and supervisory control and data acquisition (SCADA) system is crucial for the management and optimisation of hybrid wind farms, which require high levels of digitalisation and big data analytical capabilities (Wind Europe 2019a).

The implementation of WSES also requires an active collaboration and partnership between technology and equipment suppliers and operators, energy management specialists and government and certification bodies to obtain licences and permits. The main customers of WSES are the owners, operators and managers of renewable energy production plants (Table 4), which are offered customisable technology and management solutions, including multi-year maintenance contracts covering all the technology components (SGRE 2020, Vestas 2017b) and service agreements (e.g. power purchase agreement) (Wind Europe 2019a).

3.2.1.3. Value capture

Hybrid wind farms can continue to sell green electricity to the main grid or end-users. However, in times of energy overproduction (solar, wind or both), the surplus can be stored in a battery and distributed during moments of renewable energy underproduction or higher energy demand (Mendoza et al. 2022a).

In both cases, there is a potential to reduce the LCOE (SGRE 2018) and generate larger revenues compared to pure wind or solar energy plants due to i) increased annual energy production (AEP) through the complementarity of generation profiles and the storage of surplus energy, ii) CAPEX reduction through the optimisation of the generation and transmission capacities, and iii) Operational expenses (OPEX) reduction by undertaking simultaneous maintenance, control and operation activities, while delivering power output despite WTs or PV panels downtimes (Petersen et al. 2018). Additional project financing costs, including resource assessment and site conditioning, can be also reduced as the WTs and PV panels are located in a single site or in close proximity, using the land more efficiently.

When PV panels are coupled with the WTs, the solar inverters can be eliminated leading to cost savings, while the AEP per m^2 can increase further. However, the shading of the PV panels by the WT blades and tower may neutralise the overall AEP increase over time (Wind Europe 2019a). Besides, this configuration is not suitable for the hybridisation of existing wind farms due to space constraints for PV panels integration and capacity limitation due to the existing WTs evacuation gear. Accordingly, Carvalho et al. (2019) indicates that a hybrid system comprising 81.8% of wind energy and 18.2% of solar energy has an 89% chance of being a profitable.

Beyond hybrid wind farms, economic savings and revenues can be generated through optimisation of the grid network and the reduction in the balancing costs (Wind Europe 2019a). See section S6.1 (SF) for further information on the potential economic savings and revenues.

Focusing on the cost structure, the major aspects determining the costs of WSES include mostly i) labour (a multi-disciplinary team is required with expertise on wind and solar generation technologies, storage devices and the interoperability between them), and ii) technologies and infrastructures (e.g. renewable energy production and storage technologies, supporting facilities and distribution networks) (Cao et al., 2018) (Table 4). Batteries alone can cost ≈ €260/kWh (e.g. lithium-ion batteries with 10 MW capacity, 90% charging efficiency and 20 years lifetime) (Enevoldsen and Eichmann 2018). However, technology costs can be easily offset by the wind and solar energy complementarity in renewable energy production. Likewise, further improvements in energy density, weight and volume will reduce battery costs in the near future (ETIPWind 2021).

3.2.2. Power-to-Gas (PtG)

PtG solutions are aimed at facilitating the conversion of renewable electrical energy into a gaseous (chemical) energy carriers, such as green hydrogen and methane, for subsequent energy delivery in different applications (IRENA 2019b) (Table 3). Thus, PtG (as well as PtL) (see section 3.2.3.) solutions can support long-duration renewable energy storage (defined as systems with a discharge range from five to more than 1,000 hours), to ensure the supply of high amounts of renewable energy to displace fossil fuel consumption and mitigate GHG emissions (Dowling et al. 2020, GWEC 2022, IRENA 2019c).

Table 5 provides an overview of the business model configuration for PtG systems, as identified in the literature review.

3.2.2.1. Business offering and drivers

PtG systems respond to the same challenges and needs than WSES (section 3.2.1.1). However, their reach is much greater, as PtG systems can play a key role in the transformation and decarbonisation of the entire energy and industrial system (IEA 2019).

Batteries alone used in WSES are unlikely to support long-term renewable energy storage because they suffer from self-discharge and a vast number of batteries would be needed for large-scale storage (Dowling et al. 2020, IEA 2019). The temporal and spatial fluctuations of renewable electricity production, demand both high-capacity distribution systems and intermittent energy storage solutions to provide seasonal flexibility (Lehner et al. 2014, Grueger et al. 2017, Wind Europe 2018, IRENA 2019c).

Green hydrogen production is at the heart of PtG systems (Table 5), which is considered a crucial requirement to decarbonise both easier-to-abate sectors (including power generation, light-duty transport, pulp and paper, aluminium, buildings, and agriculture) (Wind Europe 2019b) and harder-to-abate sectors, such as the heavy industry (e.g. cement, steel and chemicals) and long-haul transportation (e.g. maritime shipping, heavy transport and aviation) (see section 3.2.3) (SGRE 2021a).

Considering that hydrogen is an energy carrier and base chemical, it can be used for a wide range of different applications; in its pure form as a combustible gas in internal combustion o fuel cell vehicles to support clean transportation, blended into existing natural gas networks for high-temperature process heat and steam generation through direct combustion (e.g. through hydrogen boilers or fuel cells) in the industry and residential and commercial areas, used as industrial raw material to produce polymers and resins, or employed as a feedstock to produce liquid fuels for heavy-duty transport (section 3.2.3) (Lux and Pfluger 2020, Grueger et al. 2017, Wind Europe 2019b, IEA 2019, Hydrogen Europe 2021, Siemens Energy 2021).

However, nowadays, hydrogen is primarily used for hydrocarbon cracking in oil refineries and the synthesis of methanol and ammonia as feedstock to produce fertilisers and other chemicals (Siemens Energy 2021, IEA 2019). The current global hydrogen production accounts for 90 Mt (70 Mt used as pure hydrogen and 20 Mt mixed with carbon-containing gases in methanol production and steel manufacturing) (IEA 2022). The industry consumes around 56% (≈ 51 Mt) of the global hydrogen production with the chemical industry alone using about 46 Mt; three quarters to produce ammonia and one quarter to produce methanol. The remaining 5 Mt is mostly used in steelmaking (direct reduced iron process) (IEA 2022).

Table 5. Power-to-Gas (PtG) business model configurations. Acronyms: DSO – distribution system operator, NRA – national regulatory authorities, PPA – power purchase agreement, PV – photovoltaics, TSO – transmission system operation, VRE – variable renewable energy, WTs – wind turbines.

PtG systems	Technological alternatives	a) Power-to-Hydrogen, b) Power-to-Methane, c) Power-to-Power
Value proposition	Problems addressed	Climate change impacts, local air pollution, renewable power curtailment, fluctuating renewable energy production and consumption, renewable energy access, addressing hard-to-electrify sectors.
	Business offering	Converting electricity to hydrogen in times of high VRE electricity generation, matching of renewable energy supply and demand both temporally and geographically, facilitating the integration of high levels of VRE into the energy system, mitigation of GHG emissions through indirect electrification and sector coupling, energy security.
	Products & Services	Green electricity (production and supply), and green hydrogen and methane delivery for use as combustible gases. Hydrogen and methane can be stored and become a source of seasonal flexibility.
Value creation	Key activities	Power-to-Hydrogen: wind energy conversion to electricity, splitting water into hydrogen and oxygen using electrolysers, adapting WTs to integrate electrolysers (optional). Power-to-Methane: CO_2 capture and catalytic (thermochemical) methanation via the Sabatier process. Hydrogen and methane storage and distribution. Power-to-Power: re-electrification (gas to electricity, if required).
	Key resources	Power-to-Hydrogen: power grids, WTs, PV panels, electrolysers, batteries and/or fuel cells, pressurised hydrogen storage facilities (e.g. natural salt caverns or hydrogen tanks), and distribution equipment and infrastructure (e.g. high-capacity hydrogen trailers, pipelines, and refuelling stations). Power-to-Methane: same plus carbon capture technologies, methanation facilities, blending equipment, and heat pumps or electric boilers. Power-to-Power: gas turbine reciprocating engine or fuel cells. Other: digital solutions and specialised technicians.
	Key partners	Wind and solar farm owners and operators, technology and equipment suppliers, renewable energy managers, TSOs, DSOs and NRAs, oil and gas utility companies, water treatment specialists, wholesalers, software developers, private investors, engineering firms, local and national governments (and permits) other specialised actors from industry and academia.
Value delivery	Customer segments	Wind power plant owners with expiring feed-in tariffs or operating in an electricity market characterised by price and demand volatility, renewable power suppliers (electricity and peaking plants), transport companies (light-weight road vehicles), industries (oil refining, steel, cement, paper, food, aluminium, glass, electronics), building managers (residential and commercial).
	Channels	On- and off-shore green electricity distribution network, hydrogen and methane delivery infrastructure
	Customer relationships	PPA linked to Guarantees of Origin certificates to demonstrate that green hydrogen and methane have been produced using renewable energy, international harmonisation of regulations, codes and standards for transport and storage, and integrated servicing and maintenance contracts, including well-defined safety standards.
Value capture	Cost structure	Mostly renewable electricity (30% to 60% of the total hydrogen production costs) and electrolysers (800 to 1950 Euro/kW). Green hydrogen costs from 2.4 to 10 Euro/kg. Production and injection of green methane is more expensive than injecting pure hydrogen to form a blend.
	Revenue streams	Increased green electricity production and delivery (surplus) and selling of hydrogen and methane, helping to avoid power curtailment which improves the return on investment and generates incremental revenues for VRE asset owners, reducing their exposure to price volatility.

Current hydrogen production processes determine around 6% the global natural gas consumption and 2% the global coal consumption, as 80% to 95% of hydrogen production relies on fossil fuel use (steam methane reforming and coal gasification) (SGRE 2021a, Wind Europe 2019b, IEA 2019, ETIPWind 2021). Consequently, around 900 Mt of CO_2eq./year are released to the environment (IEA 2022b).

According to the Net Zero Emissions 2050 Scenario developed by the IEA (2022b), total hydrogen demand from industry by 2030 is expected to increase up to 44%, where green hydrogen must amount at least 21 Mt. However, less than 0.1% of global hydrogen production today comes from water electrolysis. Producing all current hydrogen requirements from electricity would result in an electricity demand of 3,600 TWh, which is higher than the total annual EU electricity generation (IEA 2019).

Thus, for green hydrogen (produced by using renewable energy) to contribute to a sustainable energy transition, it is critical to develop low-carbon hydrogen production routes that can replace conventional grey hydrogen (produced by using fossil fuels), while expanding production capacity to meet new demands (IEA 2022).

3.2.2.2. Value creation and delivery

Surplus wind and solar energy can be used to feed electrolysers to split water into hydrogen (H_2) and oxygen (O_2) (Balan et al., 2016; IRENA 2019c, Rasmussen et al., 2020, Hydrogen Europe 2021) (Power-to-Hydrogen, Figure 3).

There are various types of electrolysers than can be used to produce green hydrogen, including alkaline electrolysers (AE), polymer electrolyte membrane (PEM) electrolysers, anion exchange membrane (AEM) electrolysers or solid oxide electrolyser cells (SOECs) (Wassermann et al. 2022, Hydrogen Europe 2021). However, they are at different stages of development, being the most mature AE and PEM (IEA 2022b).

As electrolysers can be fed with freshwater or desalinated seawater, they can be implemented in both onshore and offshore wind farms. However, the latter requires the implementation of seawater reverse osmosis desalination equipment (Fasihi et al., 2017).

Within wind farms, electrolysers can be directly connected to the WTs (SGRE 2022b) and/or be powered by the renewable electricity stored in batteries (section 3.2.1.) (Kristensen, 2020). By integrating electrolysers in offshore WTs, the array cables, offshore substation, export cable and onshore substation can be replaced with hydrogen transmission pipelines, which reduces significantly the power losses, resulting in higher hydrogen output per kWh of electricity produced at the rotor level (SGRE 2021a). Nevertheless, the use of batteries can ensure excess wind energy is used to support a constant production of green hydrogen (security of supply) in moments of wind and solar energy underproduction, which increases the wind farm capacity factor (Wind Europe 2018).

Additionally, when the PtG system is connected to the grid, the batteries can act as a stabilising power source and offtaker, supporting the grid with ancillary services. The batteries can also extend the lifetime of the electrolyser by ensuring a stable and high-quality power supply, increasing the value of the component (Papadopoulos et al. 2018, SGRE 2021b).

As hydrogen has a low energy density by volume, it requires high pressure (combined with low temperatures) to be transported or stored in either gaseous or liquid form

(McDonagh et al. 2020, SGRE 2021a). Accordingly, green hydrogen can be directly injected into the existing natural gas networks (by blending it with natural gas) or new gas infrastructure (only hydrogen), and transported for large distances in pipelines (GWEC 2021). The volume of hydrogen that can be injected into the existing natural gas grid infrastructure without causing major changes or refurbishment requirements on the pipeline infrastructure ranges from 5% to 20%, although hydrogen injection up to 10% in volume is considered safer in some countries (Hydrogen Europe 2021).

Alternatively, green hydrogen stored in natural geological underground deposits (e.g. salt caverns) or compressed in gas cylinders or cryogenic pressurised liquid tankers for distribution to end customers by maritime vessels or tanker trucks (Balan et al., 2016; Rasmussen et al., 2020, Hydrogen Europe 2021); the latter is considered one of the most economical ways to provide hydrogen for refuelling stations (Wind Europe 2018). Likewise, salt caverns are the best choice for the underground storage of pure hydrogen because of their tightness and low risk of contamination (IEA 2019).

Once produced, green hydrogen can be used to produce synthetic methane (e-methane) (CH4) (Power-to-Methane, Figure 3) via de Sabatier procedure. This requires additional industrial processes, such as hydrogen compression, direct CO_2 capture from air and catalytic methanation, which incurs efficiency losses and increases investment and maintenance costs (Balan et al., 2016). Unlike hydrogen, methane could be directly injected into the existing gas network at any volumes without the need to refurbish and/or develop new distribution infrastructure, including pipelines and storage facilities (Siemens-Energy 2021).

Green hydrogen and methane can be converted back into electricity (re-electrification) using conventional modern gas turbines (simple cycle and combined cycle) and fuel cells (Grueger et al. 2017, Siemens-Energy 2021, Hydrogen Europe 2021) and feed into the electricity grid or, as suggested in Figure 3, be used to support the energy requirements of other processes taking place in hybrid wind farms (Fasihi et al., 2017).

As applies for WSES (section 3.2.1.2), digitalisation is a crucial requirement for monitoring and controlling PtG energy generation and delivery for a more effective match between supply and demand, while maximising system efficiency through optimal operation of the assets thanks to preventive maintenance (Wind Europe 2018).

Potential customer segments for green hydrogen and methane are mobility companies, industries and buildings, as described in Table 5. In terms of partnership, collaborative and joined-up approach between industries, governments and public authorities, private investors and the wider research and innovation community (GWEC 2022) is crucial to overcome the challenges of scaling up production by booting investments in technology and infrastructure to build a cost-efficient and resilient supply chain (IEA 2019), as discussed in section 3.4. Further information on the value creation mechanisms for PtG systems is provided in section S6.2 (SF).

3.2.2.3. Value capture

The average cost of green hydrogen production through onshore PtG systems ranges from €2.8/kg up to €12.2/kg, depending on the renewable electricity costs, and the CAPEX, location, efficiency and operating times of the electrolysers (IEA 2019, Hydrogen TCP 2020, Hydrogen TCP 2021).

These costs are substantially higher than the costs for grey hydrogen production through conventional steam methane reforming (€0.47/kg to less than €3.1/kg) or coal (€1.1/kg to €2.1/kg) (IEA 2019, IEA 2022b). Nevertheless, in countries with favourable renewable resources, but dependent on natural gas imports, producing green hydrogen may be cheaper than producing grey hydrogen from natural gas (Nauen 2021).

For instance, green hydrogen production using offshore wind electricity can account for only €1.90/kg in some regions, which is equivalent to the cost of producing hydrogen from natural gas with carbon capture and storage (CCS) and lower than the cost of producing hydrogen from coal with CCS (≈ €2.4-2.7/kg) (Hydrogen TCP 2021). GWEC (2022) also indicates that green hydrogen costs could be reduced to €0.95/kg in just one decade due to combined effects of reduced renewable electricity and electrolyser costs, and higher CO_2 emission taxes for fossil fuel consumption (Nauen 2021).

Renewable electricity to produce green hydrogen determines 30% to 60% of the total costs. Nevertheless, the levelised cost of hydrogen (LCOH) (Euro/kgH_2) is directly proportional to electrolyser load factors (Lux and Pfluger 2020); the higher the load factor, the lower would be the share of fixed cost and the higher the share of electricity cost (IRENA 2019c).

According to Enevoldsen and Eichmann (2018), the turnkey price of electrolysers can range from €9.6M to almost €149M plus additional €175K to €12.4M of O&M, depending on the electrolyser chemistry (AE vs PEM), the average system efficiency (60% to 80%) during their lifetime (20-25 years) and the plant size (10 MW vs 100 MW).

Nevertheless, electrolyser costs could halve from €799/kW to €357/kW between now and 2050 (IRENA 2019d), while other estimates indicate that hydrogen parity (moment where the price of green hydrogen equals that of grey hydrogen) can be achievable by 2030 for onshore wind-based hydrogen generation and by 2035 for offshore wind-based hydrogen generation (SGRE 2021a). The price of electricity, however, should fall to below €28/MWh or the electrolyser costs decline significantly (IRENA 2019c). At low natural gas prices, renewable electricity must reach a cost range below €9.5/MWh for electrolysis to become cost-competitive (IEA 2019).

Focusing on green methane production, current average production costs account for about €247/MWh, which is mostly determined by the electricity costs, followed by the CO_2 feedstock costs and the CAPEX (IEA 2019). Nevertheless, long-term production costs could be reduced to €114/MWh (- 54%) due to economies of scale (IEA 2019).

Likewise, when electrolysers are integrated within WTs (decentralised solutions), CAPEX can be reduced by replacing expensive high-voltage infrastructure with pipes network and increase system efficiency due to lower high-voltage electrical losses (Nauen 2021). Besides, adding electrolysers into existing wind farms can generate relevant economic benefits, especially in wind farms with expiring feed-in tariffs and/or incentives and/or wind farms located in regions with decreasing electricity prices and/or high price volatility.

Wind farms can diversify revenue streams by selling green hydrogen along with wind electricity, while the WTs lifetime could be extended leading to a reduced LCOH (Nauen 2021). Furthermore, the oxygen produced during water electrolysis could be sold for industrial purposes, (e.g. electronics industry, oxy-fuel processing in the steel industry, or high-tech medical applications in hospitals (Fasihi et al., 2017; Hank et al., 2018), generating further revenues. Likewise, hybrid wind farms are able to support grid stability through ancillary services when requested by the TSO, making wind farm assets more profitable (Rasmussen et al., 2020). According to HyBalance (2021), grid balancing services derived from PtG systems could generate revenues equivalent to 15% to 25% of the electricity costs on average

Thus, a multimodal PtG operation is frequently suggested to improve profitability. Nevertheless, since green hydrogen and methane production depend on the wind farm's forecast of surplus energy generation, the relationship between the wind farm and its customers should be based on agreements where gas demand is defined in advance (Rasmussen et al. 2020, Balan et al. 2016).

3.2.3. Power-to-Liquid (PtL)

In PtL systems, green hydrogen is reacted with carbon dioxide to produce liquid fuels (gasoline, diesel and jet fuel), and chemicals (methanol and ammonia, although both can be also used as liquid fuels as well) (IRENA 2019b) (Table 3). Table 6 provides an overview of the business model configurations for PtL systems, as identified in the literature review.

3.2.3.1. Business drivers and needs

As it applies for PtG (section 3.2.2), PtL systems can improve the flexibility of hybrid wind farms through a strategic use of the energy surplus. Likewise, PtL solutions also represent a suitable strategy for long-term renewable energy storage to overcome the weekly and seasonal variability of wind (and renewable) energy systems (Wind Europe 2018).

Although electro-mobility is currently being promoted and deployed in countries worldwide, current technology solutions (e.g. battery electric vehicles) are mainly oriented to support low-carbon light vehicle passenger mobility (Picatoste et al. 2022). However, long-haul heavy road transportation, marine shipping and aviation represent hard-to-electrify and hard-to-decarbonise transportation modes.

The second European Renewable Energy Directive (European Commission 2021a) also highlights that the minimal share of renewable energy sources in fuels has to grow from 5% today to 14% in 2030. Whereas a quarter of this increase is expected to come from direct electrification (e.g. electro-mobility), bio-fuels must contribute a minimum 3.5% but they must be produced from non-food relevant sources (second biofuel generation). Thus, the so-called electric fuels (e-fuels) produced by using renewable energy and captured CO_2 (either from air or from unavoidable emissions from industries and power plants) are required to achieve the remaining share (Wassermann et al. 2022, Siemens Energy 2021).

E-fuels are similar to, and can be mixed with, conventional fuels to reduce the carbon content of the mixture, without the need to change the current vehicles engines or the existing fuel logistic infrastructure. Likewise, e-fuels have the potential to outperform biofuels in terms of production and CO_2 avoidance costs (Siemens Energy 2021). Accordingly, the use of e-fuels represent an instrumental strategy to mitigate fossil fuel consumption in the hard-to-electrified and hard-to-decarbonise transportation sectors (GWEC 2021).

Table 6. Power-to-Liquid (PtL) business model configurations. Acronyms: CAPEX – capital expenditure, GHG – greenhouse gases, PtG – power to gas.

PtL systems	Technological alternatives	a) Power-to-Methanol (e-methanol), b) Power-to-Hydrocarbons (e-fuels), c) Power-to-Ammonia (e-ammonia and e-chemicals)
Value proposition	Problems addressed	Same as PtG plus fossil fuels consumption and GHG emissions by industrial production processes and long-haul transportation activities
	Business offering	Managing renewable energy demand by providing seasonal storage and supplying clean liquid energy and intermediary products to end-users
	Products & Services	Green methanol, e-fuels (gasoline, diesel, kerosene, jet fuel), ammonia and high-value chemicals (fertilisers, polymers, resins).
Value creation	Key activities	Same as PtG (Power-to-Hydrogen) plus hydrogen compression (liquefied hydrogen) and/or cooling (cryogenic hydrogen) for transportation and further conversion into hydrogen-based fuels or feedstocks, such as e-methanol and e-fuels, which entail CO_2 capture and conversion to CO with the subsequent catalytic hydrogenation of carbon monoxide (e-methanol), or the conversion of the synthesis gas to raw liquid fuels and further upgrading into diesel and kerosene via the Fischer-Tropsch process (e-fuels). E-ammonia: Haber-Bosch process, including onsite nitrogen capture from atmospheric air using pressure swing adsorption units and (if required) further conversion into solid fertilizer salts or, after catalytic oxidation, into nitric acid and nitrates. Other: cleaning of green hydrogen, treatment and deionization of water, upgrading of industrial processes, design of integrated control systems.
	Key resources	Same as PtG (Power-to-Hydrogen) plus compressed gas cylinders or cryogenic liquid tankers, and maritime vessels (for liquid hydrogen transportation), chemical technologies and facilities (e.g. carbon capture solvents or fuel cell membranes), precision-engineered products (e.g. storage tanks), and refuelling stations for e-fuels. Sea and freshwater facilities for e-ammonia production, including large steel storage tanks.
	Key partners	Same as PtG plus industrial companies (e.g. car manufacturers), trade associations and technology platforms.
Value delivery	Customer segments	Hard-to-electrify sectors, such as transport companies (heavy-duty trucks, aviation and maritime shipping), chemical industries (base chemicals, fertilizers, fuel refining, and plastics) and heavy industry (e.g. cement production).
	Channels	Land and ocean green energy delivery infrastructure
	Customer relationships	Same as PtG
Value capture	Cost structure	Same as PtG plus the CO_2 feedstock costs and synthesis processes for the production of e-fuels and e-ammonia. Whereas CAPEX determine 30%-40% of the total production costs for e-fuels and e-ammonia, electricity accounts for 40%-70%. E-fuels (e.g. e-kerosene for aviation) are very expensive: €3,000/tonne (six times higher cost than fossil kerosene).
	Revenue streams	Selling of multiple green energy carriers and products.

Likewise, green methanol and green ammonia can be used as feedstock for fertiliser production (e.g. ammonia phosphates and urea), synthetising other chemicals and products, such as plastics, nylon and acrylics, and/or potentially produce other e-fuels (e.g. for the shipping industry) (Wind Europe 2019b). Ammonia can be also used as refrigerant gas and, as every tonne of ammonia contains about 175 kg of hydrogen, it is a suitable carrier of hydrogen for long distance transportation using existing infrastructures (ETIPWind 2021, Siemens-Energy 2021).

3.2.3.2. Value creation and delivery

The PtL technology pathways add two additional processes to those mentioned for PtG systems (section 3.2.2): the conversion of a gas into a liquid and the subsequent product upgrading according to the end-use applications (Dieterich et al., 2020).

Methanol (CH_3OH) can be produced using green hydrogen and CO_2 captured directly from the air (Power-to-Methanol, Figure 3). According to ETIPWind (2021), the production of 1 tonne of e-methanol involves the sourcing of 875 kg of carbon monoxide and the use of 125 kg of hydrogen. A conversion and upgrading process (hydrocracking) then converts the methanol into, for example, diesel, gasoline, jet fuel (kerosene) and olefins or waxes (CXH_y) via Fischer-Tropsch processes (Wassermann et al. 2022, Fasihi et al. 2017, Siemens Energy 2021).

Focusing on e-fuels production (Power-to-Hydrocarbons, Figure 3), the captured CO_2 must be first converted into CO through a reverse water-gas shift, and subsequently the Fischer-Tropsch process converts the resulting syngas into synthetic crude hydrocarbons or syncrude (Fasihi et al. 2017). From this highly exothermic reaction the water produced can be reclaimed and reused to feed the electrolyser. In the same way, the heat released can be used in the CO_2 capture process through a heat exchanger (Figure 3). As applies for methanol production, the syncrude could be treated with the addition of hydrogen (hydrocracking of the long-chain syncrude) resulting in renewable naphtha, diesel or jet fuel (Fasihi et al., 2017).

Ammonia (NH_3) can be also produced from green hydrogen and nitrogen uptake from an air separation unit via the Haber-Bosch process (Siemens-Energy 2021), which is a process particularly well-suited to locations with fresh or sea water sources (Figure 3). Indeed, ETIPWind (2021) suggests that this is one major reason why green ammonia is considered crucial to potentially decarbonising maritime shipping.

Green e-methanol, e-fuels and e-ammonia can be distributed using existing fuel logistics infrastructures, contributing to save material and economic resources compared to pure hydrogen distribution, which requires significant infrastructure investments (Siemens Energy 2021). On the other hand, Bos et al. (2020) suggest that the air capture installation, electrolysis equipment and methanol reactor can be installed in the base tower of WTs, contributing to save material resources further.

As applies for WSES and PtG systems, digitalization is an important component and enabling technology for the realisation of any of PtL solutions along the whole value chain (Siemens Energy 2021).

3.2.3.3. Value capture

Whereas the average conventional diesel and gasoline costs account for €25/MWh and €30/MWh, respectively (IEA 2019), the average cost for conventional methanol production is equivalent to €30-70/MWh (Siemens Energy 2021). However, the current average production costs for e-methanol accounts for €115/MWh (IRENA 2019d), whereas average e-fuel production cost ranges from €100/MWh to €135/MWh (Siemens-Energy 2021). Likewise, studies suggest that e-fuel costs can increase up to €285/MWh, due to CAPEX and electricity and CO_2 feedstock costs (IEA 2019).

Nevertheless, although e-fuels are more expensive than conventional diesel, gasoline and methanol, they could be cheaper, or have a similar cost, than the current production costs of biofuels, ranging from €80/MWh to €130-€150/MWh for first and second generation bio-ethanol, respectively (Siemens Energy 2021).

Focusing on green ammonia production, current costs account for almost €140/MWh, which is significantly higher than current conventional ammonia costs (≈ €60/MWh). However, green ammonia costs can be reduced up to €62/MWh in the near future, reaching price parity (IEA 2019).

As PtL systems represent an extension of PtG systems (section 3.2.2, Figure 3), the largest cost component is the electricity consumption, accounting for 40% to 70% of the production cost of different hydrogen-based products (IEA 2019). Focusing on green methanol, about 45% of the production costs are determined by the electrolysers, 50% by the CO_2 capture installation and 5% for the methanol synthesis, including purification (considering a 100 MW plant) (Bos et al. 2020).

The CO_2 feedstock costs are also an important cost component in the case of e-fuels, as it can vary significantly, depending on the availability of suitable CO_2 sources. CO_2 feedstock costs of €29-96/t CO_2 translate for synthetic diesel into a cost of €12-40/bbl. Thus, reducing the cost of electricity together with increasing the overall efficiency of the conversion chain is crucial.

For instance, air capture costs may be low if pure CO_2 is readily available as a by-product from an industrial production process, such as the manufacture of bioethanol. Nevertheless, it would depend on the prevailing CO_2 emissions price or the competing financial benefits for sending the CO_2 to long-term geological storage (IEA 2019).

Likewise, e-fuel production can benefit from the existing vehicle combustion engines (e.g. jet turbines), the conventional fuel distribution infrastructure (requiring only minimal to no modifications or refurbishments) and the large number of available end users (transport operators), which reduces investment requirements and, ultimately, the costs of supplying e-fuels (IEA 2019, ETIPWind 2021).

Besides, selling multiple green energy products by hybrid wind farm owners and operators can increase revenues significantly. For instance, the production and sale of green methanol can increase the wind farm's revenues by 33% compared with selling only renewable electricity (González-Aparicio et al. 2018).

Hank et al. (2018) also concludes that although the cost of methanol production supplied by a wind farm (ranging between €1,028-1,067/tonne) can be higher than the methanol produced with grid electricity (€608-1,453/tonne), CO_2 avoidance costs between €365-430/tonne could be achieved in Germany. Thus, the country could reach market parity by 2030 to 2035 and the price for CO_2 avoidance turning from a cost to a benefit at the same time. Further information on alternative solutions to reduce the production costs of PtL systems is presented in section S6.3 (SF).

3.3. Potential sustainability benefits of wind farm hybridisation pathways

Table 7 provides an overview of the potential sustainability benefits derived from the HWF through the implementation of WSES, PtG and PtL systems.

3.3.1. Sustainability performance of WSES systems

Off-grid WTs coupled with PV panels and batteries are suitable for locations without access to the main power grid, such as remote rural areas or islands. Thus, WSES can accelerate rural electrification and ensure energy security (Wind Europe 2019a).

In the case of islands, WSES can also reduce the dependence over fossil fuel imports and the economic vulnerability to international fluctuations in fuel prices (Tariq, 2020). As diesel-based power generators can be eliminated, WSES can also facilitate the decarbonisation of the energy mix (Solomin et al., 2019), while improving health indicators (e.g. reduction in respiratory illnesses due to particulate matter emissions).

For instance, in some islands, WSES can lower the share diesel-based power generation from 66% to 0.5% (Tariq 2020) and the implementation of WSES in Tonga, where 90% of the power generation is based on imported diesel, can increase renewable energy penetration up to 50% and avoiding the annual emission of 13,000 tons of CO_2 eq. Besides, WSES can increase clean energy access of marginalised populations in Tonga by 3% (Global Opportunity Explorer 2022b).

When WSES are grid-integrated, they can reduce network use tariffs paid by green electricity end-users thanks to having a single WTs and PV panels grid connection point. Accordingly, the finances of companies and citizens using electricity can be improved; the latter being especially relevant for low-income social groups (Wind Europe 2019a).

Focusing on ETES, as a particular WSES alternative (section 3.2.1.2. and section S6.1 of the SF), these systems can help increasing the share of renewable electricity and reduce carbon footprint of industrial processes by supplying emission-free process heat or steam, which can attract sustainability investors and customers (SGRE 2022b). Likewise, the transformation of conventional fossil power plants into renewable energy storage systems by implementing ETES, can ensure a second use life of existing infrastructure and assets, contributing to keeping resources in use for longer (SGRE 2022c).

3.3.2. Sustainability performance of PtG systems

According to IEA (2019), whereas the CO_2 intensity of hydrogen production from hard coal and natural gas (with or without CCS) can range from 2 kg CO_2/kgH_2 to over 20 kgCO_2/kgH_2, the CO_2 intensity of hydrogen production through water electrolysis using electricity from the world average electricity mix can account for over 25 kgCO_2/kgH_2.

However, using wind power for green hydrogen production (< 5g CO_2 eq./MJ) results in over 95% GHG emission reductions compared to grey hydrogen production (≈ 100-135 g CO_2 eq./MJ) (HyBalance 2021). Likewise, hydrogen has higher energy density (≈ 120 MJ/kg) on a mass basis compared to coal (≈ 24 MJ/kg), natural gas (≈ 55 MJ/kg), diesel (≈ 45.5 MJ/kg) and gasoline (45.8 MJ/kg) (Hydrogen Europe 2021). Thus, using green hydrogen to substitute fossil energy consumption in the transportation and industrial sectors can lead to relevant energy and GHG savings.

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Table 7. Potential sustainability benefits related to WSES, PtG and PtL systems, as identified in the literature review (section 2.1-2.3). Acronyms: WSES – wind and solar energy systems, PtX – Power-to-X, WT – wind turbines, PV – photovoltaic, B – batteries, PtG – Power-to-Gas, PtL – Power-to-Liquid, AEP – annual energy production, R&D – research and development, O&M – operation and maintenance, GHG – greenhouse gases.

CBMs for the HWF		**Sustainability performance**		
		People	**Profit**	**Planet**
WSES	**WT-PV-B**	• Acceleration of rural electrification • Investments in local grid infrastructure • New markets in developing countries. • Increased energy access and security. • People upskilling and job creation.	• Power curtailment reduction • Increased AEP • More efficient use of the land and grid infrastructure • Optimisation of O&M services	• Efficient use of the land • Reduction in fossil fuel consumption • Mitigation of GHG emissions
PtX	**PtG**	• Energy supply to regions with energy deficits or limited (or lack of) access to the main electricity grid • Energy security. • Hydrogen is less toxic and safer than conventional fuels. • Hydrogen and methane can be used to store energy for weeks to months to address seasonal variability in supply and demand and differences in heating and/or cooling requirements between seasons.	• Increase in the wind farm flexibility and productivity • Storage of renewable electricity to decoupling generation from demand and increase consumption of renewable energy • Hydrogen has the highest energy content of any common fuel by weight (three times higher than liquid hydrocarbons) • Creation of local markets for the use of clean gases	• No direct GHG emission through hydrogen combustion • Green hydrogen can mitigate GHG emissions in energy- and carbon-intensive sectors. • The required CO_2 to produce methane (and e-methanol and e-fuels) from could be sourced from industries or biogas plants to reduce GHG emissions further • CO_2 emissions of hydrogen-fuelled vehicles could be 75% lower than for equivalent diesel vehicles
	PtL	• Job creation • Promotion of new local value chains boosting the local economy • Facilitate energy access in remote locations requiring longer-term energy storage, • Displace of fossil fuel use to power houses or local businesses. • Reduced human toxicity due to less pollutant (e.g. fine particles) emissions in combustion	• Creation of new markets • Enhance renewable energy integration in nations • E-fuels can replace fossil fuels without the need to change end-use technologies.	• Decarbonisation of transportation, industrial and agricultural activities. • Reduction in local air pollution, improving the health of citizens. • Reduction GHG emissions by ammonia and fertiliser production up to 2.5 Mt/year.

For instance, whereas the use of 1 ton of green hydrogen for light-weight vehicle mobility can abate the emission of about 7 tons of CO_2 eq., using the same amount of green hydrogen for steel production can abate 26 tons of CO_2 (IEA Hydrogen TCP 2021). Siemens Energy (2021) also suggest that the combined effect of reducing the CO_2 intensity of conventional fuels, while replacing grey hydrogen with green hydrogen production, can help reducing by 10% the GHG emissions by the transport sector in the short term.

However, water electrolysis to produce green hydrogen, and subsequently converting it to methane, is an energy-intensive process. Also, the liquefaction and transport of the oxygen resulting from water electrolysis (if managed as a marketable by-product) requires a considerable amount of energy (Hank et al. 2018). Thus the production of PtG products requires the installation of new wind energy capacity complemented with other renewable energy technologies, facing several sustainability challenges, such as the management of wind blades composites and the REEs (e.g. Dysprosium, Neodymium and Praseodymium) used in the WT generators (Mendoza et al. 2022a). REEs, such as nickel and zirconium, are also used in the manufacture of the electrolysers (GWEC 2022), which further increase the concerns related to supply chain disruptions and the corresponding life cycle environmental impacts. The environmental impacts of green hydrogen and methane transportation can be also relevant (Balan et al. 2016; Fasihi et al. 2017; González-Aparicio et al. 2018).

Consequently, the resource efficiency of PtG processes must be optimised for a sustainable energy transition. For instance, besides eco-designing technologies and improving their operation efficiency and end-of-life management, the co-location of the electrolysis and methanation plants within or close to the wind farms and/or the final consumer (Rasmussen et al. 2020), would reduce transportation costs and allow a more efficient use of the land (Bos et al. 2020; Fasihi et al. 2017).

Likewise, the waste heat from electrolysis and methanation could be used to satisfy the heat demand of the CO_2 capture process, which would increase the efficiency of the PtG systems (Figure 3). Similarly, surplus water from subsequent synthesis (e.g. methanation or methanol production) could be recycled to feed the electrolyser (Bos et al. 2020; Fasihi et al. 2017). Using hydrogen and oxygen locally, or in nearby energy or chemical plants, is also important to reduce costs and environmental impacts further (Hank et al. 2018).

According to the IEA (2022b), the impact of green hydrogen production and consumption should be tracked through the consideration of three main indicators: i) the extent to which it replaces conventional hydrogen use in existing industrial applications and meets demand for new applications, ii) the rate of demand growth in new sectors (e.g. specific transport and industrial applications), and iii) the potential cost reductions and improvements (e.g. efficiency, lifetime or process integration) of scaling up cross-cutting technologies, such as the electrolysers.

3.3.3. Sustainability performance of PtL systems

Same as PtG systems (section 3.2.2), PtL solutions contribute to eliminate power curtailment, which enables to operate the grid more efficiently. This can help reducing renewable electricity prices for end-use customers, including local businesses, organisations and citizens. Nevertheless, the bidding strategy of hybrid wind farms is dependent on the market prices for fossil-based energy resources. Thus, the higher the fossil fuel prices, the more cost-efficient PtL products could be (Balan et al., 2016).

Likewise, PtL solutions can create new employment, training and business opportunities in the value chain as the PtL-based HWF is labour intensive and demands new skills and market actors (e.g. new emerging technologies and industrial operations coupled with smart control, maintenance and management systems) (Balan et al. 2016).

PtL solutions can be also useful to supply clean energy in far-off places (e.g. rural areas and islands) relying on the importation of fossil fuels (Siemens Energy 2021), contributing to increase energy security, while reducing energy-related environmental impacts, including harms to human health (e.g. respiratory illnesses) due to the emission of pollutants and particles (IEA 2019).

Focusing on environmental sustainability, PtL products can help decarbonising energy-intensive industrial processes, such as cement or chemicals production and long-haul heavy transportation (Balan et al., 2016). Green methanol, e-fuels and ammonia production have no net direct CO_2 emissions, instead indirect GHG emissions derive from the equipment and infrastructure life cycle management requirements are released (IEA 2019). Thus, e-fuels can emit from 5 g to less than 15 g CO_2 eq./MJ, which represent 83%-95% lower GHG emissions than gasoline (≈ 90-100 g CO_2 eq./MJ) and 40%-93% lower GHG emissions than bio-ethanol (≈ 25-70 g CO_2 eq./MJ) (Siemens-Energy 2021).

Accordingly, GHG emissions avoidance costs for e-fuels can range from less than €200/tCO_2 up to €450/tCO_2, whereas it can account up to €700/tCO_2 for bio-ethanol. Likewise, land use and water requirements by e-fuels are similar, or even lower than those of bio-fuels. However, the conflict between land use for food production versus energy production does not applies to e-fuels (Siemens Energy 2021).

Nevertheless, PtL systems face the same environmental challenges than PtG systems because significant amounts of renewable electricity and generation capacity are required for the production of e-methanol, e-fuels and e-ammonia due to the low overall efficiency of production processes. For instance, between 700 TWh to 1,000 TWh would be needed for e-fuel production to supply just 1% of current global gas and oil consumption, respectively. This would be equivalent to the installation of 230 GW and 340 GW of onshore wind technologies with a capacity factor of 35% (IEA 2019).

3.4. Challenges for the implementation and upscaling of WSES, PtG and PtL systems

The HWF can be complex, costly and time consuming due to the sizing requirements for the plants, including the energy production, conversion, storage and distribution equipment and infrastructure, the land location restrictions (e.g. PV panels cannot be installed on farm lands), the permitting, connection, metering and taxation needs for system operation, and the development of certifications and energy labels to support the traceability of renewable energy (Wind Europe 2019a).

System integration (sector coupling) and system flexibility (generation and consumption) are also key aspects to be addressed for the effective management of the variability from power demand and supply at different time scales (Wind Europe 2018). Consequently, excellent renewable energy production planning through forecasting is needed to maximise the resource efficiency and possible revenues from grid balancing processes (HyBalance 2021).

According to IEA (2022b), the uptake of green hydrogen must be achieved at triple the speed of renewable energy to achieve the global net zero-carbon targets. By 2050, the global demand for hydrogen it is expected to reach 500 Mt, requiring between 3,000 and 6,000 GW of new installed renewable capacity (having 2,800 GW today) for green hydrogen production. Also, installed EU electrolyser capacity should increase from less than 1 GW today to 40 GW by 2030 and 500 GW by 2050 (SGRE 2021). Finally, whereas the total length of hydrogen pipelines globally will need to quadruple (> 20,000 km) by 2030, hydrogen storage requirements could amount 50 Mt by 2050 (IEA 2022b).

As green hydrogen production is at the core of PtG and PtL systems, developing cost-effective solutions to produce, store, distribute and transport hydrogen, whether in gaseous or liquid form, including the use of existing natural gas infrastructure, is crucial for the market uptake of green PtX products (Schnuelle et al. 2020, Dieterich et al. 2020. However, a number of relevant technical challenges should be properly addressed first.

For instance, if green hydrogen is transported using existing gas infrastructures to reduce investment costs, the appropriate blend may vary significantly between natural gas compositions and pipeline networks (IRENA 2019c). Thus, this must be assessed on a case-by-case basis, including the consideration of end-user applications (e.g. gas vehicles, compressors, gas turbines and aquifer storage) that may impose further technical constraints (Balan et al., 2016).

Focusing on the latter, e-fuels are considered suitable for decarbonising aviation and deep-sea shipping because planes and cargo ships require energy-dense fuels (such as e-kerosene or e-ammonia, respectively), to move heavy loads over long distances that cannot be supported by the use of batteries (Hydrogen Europe 2021). Nevertheless, the use of e-fuels to meet exclusively the aviation’s growing fuel demand by 2050 would require 95% of the EU current renewable electricity generation (ETIPWind 2021, based on European Federation for Transport and Environment AISBL 2018). Focusing on ammonia, its current use is limited to its application as a feedstock in the chemical industry. Thus, value chains for using green ammonia as fuel in the transportation sector are non-existent today (IEA 2019).

Consequently, the creation of an appropriate demand-side market of green hydrogen-based products by developing the entire supply chain is a pre-requisite for the market uptake of PtX products with the subsequent reduction in the equipment (e.g. renewable energy technologies and electrolysers), infrastructure (e.g. liquefying and storage units and pipeline transmission system), and management costs and environmental impacts, due to economies of scale (Hydrogen TCP 2021).

In this regard, the IEA (2019) recommends making industrial ports the nerve centres for scaling up the use of cost-effective green hydrogen because much of the refining and chemical industries using hydrogen today are concentrated in coastal industrial areas. Likewise, large sources of green hydrogen could be used to fuel trucks and ships serving the ports and power other nearby industrial facilities, such as steelmaking plants. However, for green hydrogen to be used at a large scale in the transportation sector, the hydrogen refuelling infrastructure needs to be developed across the globe (Wind Europe 2018).

Nevertheless, although it is expected that that e-fuels will cover 30% of the EU transport fuel demand by 2050 (European Union 2016), ETIPWind (2021) highlights that the use of e-fuels in light-weight transportation is not a suitable energy efficient solution compared to battery electric vehicles (BEV). Whereas only 5% of energy is lost during electricity distribution, around 56% of energy is lost during green hydrogen production (water electrolysis), CO_2 air-capture and Fischer-Tropsch synthesis for e-fuel production, leading to a final well to wheel energy efficiency as low as 13%, the total energy efficiency for BEV accounts for 77% (ETIPWind 2021).

Thus, the process of converting electricity through water electrolysis into hydrogen and/or methane (after a methanation process), and then converting hydrogen or methane back into electricity (re-electrification) suffer from low round-trip efficiency (ETIPWind 2021). For this reason, Wind Europe (2019b) and ETIPWind (2021) consider than green hydrogen should be prioritised to decarbonise hard-to-abate sectors only, where direct electrification is not viable.

Accordingly, minimising the number of conversions between energy carriers and addressing energy losses during both renewable energy production and energy conversion, including storage and transportation, is a key area for innovation to improve the efficiency of PtG and PtL systems (IEA 2022b).

Focusing on policy development, the elimination of unnecessary regulatory barriers, the harmonisation of technical and safety standards, the development of green certifications (Balan et al., 2016), the creation of incentives to displace fossil fuel use (e.g. shifting energy taxes from renewable electricity to gas and oil, providing start-up subsidies and setting up strict CO_2-certificate price and emission reduction quotas) (Schnuelle et al. 2020, Wind Europe 2018), and supporting investment and sector innovation, is crucial for the deployment of WSES, PtG and PtL systems (IRENA 2019c).

For example, the IEA (2019) indicates that if e-diesel could be produced at a cost of 145 Euro/bbl, a CO_2 emission price of 173 Euro/tCO_2 would be needed for e-diesel to become competitive with fossil diesel having an average cost of 72 Euro/bbl. Thus, a combination of low renewable electricity production costs and high CO_2 emission taxes is required to make e-fuels competitive and represents an important instrument to develop more circular and sustainable production and consumption systems (Balan et al. 2016).

Nevertheless, whereas car manufacturers were forced to reduce their average fleet emissions to 95 gCO_2/km in 2020, other transportation modes, such as shipping or aviation, do not suffer from such GHG emission restrictions (Schnuelle et al., 2020), although the United States and the EU have started the process of developing standards and revising directives on airplane GHG emissions (EPA 2021, European Commision 2021b).

In this process, the development of a standardised methodology to calculate the carbon footprint of hydrogen-based products production and consumption is recognised as a critical priority for the development of PtX markets (green hydrogen, methane, e-methanol, e-fuels, e-ammonia) by ensuring that green hydrogen production is 100% based on the use of renewable energy (IEA 2022b).

Guarantees of Origin certificates can represent a suitable mechanism to certify the origin of hydrogen production, while providing energy consumers a proof of origin IRENA (2020). These certificates can also serve to stimulate final customers demand for renewable energy (Wind Europe 2019b).

In any case, the use of robust sustainability assessment tools, including LCA, to analyse the technical, economic, social and environmental suitability of alternative business cases for WSES, PtG and PtG through the HWF (and other renewable energy production systems) is crucial to support well-informed decision-making processes, considering the potential implications that the upscaling of these systems can have in the entire economy. Particular attention should be placed on the analysis of the resource-efficiency and sustainability performance of the production and consumption of green hydrogen and hydrogen-based products at different scales, including on-site, semi-centralised, centralised and intercontinental systems, requiring different levels of infrastructure investment and management (IRENA 2018, IRENA 2019bd).

4. Conclusions

A systematic literature review of 82 academic papers and industrial reports supported the categorisation and characterisation of three major circular business models (CBM) typologies and nice technology pathways or business model solutions for the hybridisation of wind farms (HWF).

The HWF can be driven through the implementation of wind and solar energy systems (WSES) business models (integrated wind and solar energy production, wind and solar energy production and energy storage, wind energy production and energy storage), Power-to-Gas (PtG) business models (Power-to-Hydrogen, Power-to-Methane and Power-to-Power) and Power-to-Liquid (PtL) business models (Power-to-Methanol, Power-to-Ammonia and Power-to-Hydrocarbons).

Consequently, the HWF can be addressed at stages, starting first with the integration of solar and wind energy technologies and subsequently extending the system further through the integration of PtG and PtL systems. However, the development of PtL systems are dependent on the previous implementation of PtG solutions, which are also dependent on the precedent implementation of integrated wind and solar systems to optimise green energy production. Thus, the HWF should be carefully planned upfront and one system influences and/or conditions the other.

In any case, energy storage systems (batteries) and hydrogen production technologies (electrolysers) are the most relevant resource requirements for the successful HWF and production and delivery of green energy products, including electricity, hydrogen, methane, methanol, ammonia and e-fuels (diesel, gasoline, kerosene) for use in the energy, industrial, transport and residential sectors.

On the one hand, batteries are essential technology solutions to avoid power curtailment and optimise the energy system efficiency and performance by ensuring a constant supply of green electricity can be delivered to the grid and/or used to support the energy conversion activities taking place in the Power-to-X (PtX) systems.

On the other hand, hydrogen produced in hybrid wind farms (or hybrid renewable energy plants) represents a central energy vector to produce green energy products and materials (e.g. polymers and fertilisers). Accordingly, electrolysers are a crucial technology requirement for the successful implementation and upscaling of PtX systems.

Indeed, both batteries and electrolyser, with the cost of the renewable electricity itself, highly determine the production costs of PtG and PtL products, and therefore the economic viability of hybrid wind farms and PtX systems. Likewise, these technologies also highly determine the life cycle environmental performance of the renewable energy products, due to the environmental burden associated with the resource requirements (e.g. fossil energy and critical materials) in manufacture and the challenges faced in material recycling and recovery at the end of life.

Nevertheless, the sustainability performance of hybrid wind farms, and the corresponding WSES, PtG and PtL systems, is not only determined by the electricity, the batteries and the electrolysers, but also by the scale (size) and scope (end goals) of these innovative green energy production systems (e.g. local, regional or continental). The scale and scope of the WSES, PtG and PtL systems determine the requirements in terms of facilities (e.g. methane, methanol, ammonia and e-fuels plants), equipment (e.g. water treatment and air capture technologies and storage systems), infrastructure (e.g. pipelines and tank trucks or ships) and labour (e.g. engineers and technicians). Thus, the HWF should be carefully analysed on a case-by-case bases by comparing multiple scenarios from a system-level perspective.

This includes analysing how these innovative systems could be deployed from a producer (green energy supplier) versus a consumer (end-user) perspective, as the market and resource requirements extend far beyond the hybrid wind farms (or hybrid renewable energy plants) and the energy sector. For instance, the local consumption of green hydrogen in the industry through onsite production systems requires a technological configuration, economic investment and labour requirements that differ substantially from the centralised green hydrogen production and distribution to intermediate energy conversion partners to produce hydrogen-based products or to end-users to consume green hydrogen as-is in industrial processes. Likewise, the use of green hydrogen in the industry can affect the quality of the manufactured products, such as aluminium and steel, while using e-fuels in mobility (e.g. engine combustion) or e-methane in residences (e.g. heating) can add further technical, economic and environmental challenges.

Consequently, although the deployment of WSES, PtG and PtL systems through the HWF represent a promising circular and enviornmental strategy that is being actively promoted worldwide to support the sustainable energy transition by displacing the use of fossil fuels, it should be carefully planned and managed by analysing all the potential supply chain disruptions and negative impacts these innovative green energy systems can generate compared to conventional production systems. This calls for the use of holistic analytical tools, such as life cycle assessment (LCA), to demonstrate the full resource decoupling potential and net economic, environmental and social sustainability benefits of these alternative green energy production systems.

Indeed, this research paper has been focused on analysing literature resources that explicitly focus on the HWF from a business or business models perspective. Accordingly, the research outcomes could be expanded further by analysing wider sustainability focussed studies on both the HWF and other hybrid renewable energy systems (e.g. combination of biomass with solar and wind energy), including focused LCA studies, which could lead to the identification, categorisation and characterisation of additional CBMs, challenges and opportunities for the implementation and upscaling of these systems. This entails a careful analysis of the inter-dependencies and trade-offs between green and conventional energy production systems by applying a business ecosystem approach.

The deployment of WSES, PtG and PtL must be also accompanied with the implementation of energy efficiency solutions to substantially cut energy consumption in end-use applications in order to avoid the contribution to rebound effects and/or environmental burden shifts, while facilitating the implementation of these alternative green energy production systems. This requires, as happens in the implementation of other complex eco-innovations, an active and close collaboration between industry actors, business associations, policymakers, researchers and social bodies to co-create effective solutions for the short-, medium- and long-term.

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Supporting Information file

Further information and data is presented in the supplementary file of the paper, including: S1) the list of keywords used in the literature review search, S2) the list of keywords used in business-oriented academic studies on the hybridisation of wind farms, S3) the list of predefined circular economy keywords used to analyse the content of the academic and grey literature, S4) the CBM canvas with the list of documents analysed and the resulting categorisation and characterisation of CBM solutions, S5) the list of keywords identified in the bibliometric analysis, and S6) additional analysis of CBM typologies and solutions for the hybridisation of wind farms.

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