Chapter 4
Circularity and Sustainability Performance of Hybrid Renewable Energy Systems: Exploring the Benefits and Challenges Behind the Hybridization of Wind Farms

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Abstract Accelerated deployment of renewable energy production technologies is instrumental in supporting a sustainable energy transition to mitigate greenhouse gas (GHG) emissions worldwide. However, renewable energy production imposes relevant economic, technical and environmental challenges that must be overcome for clean energy systems' resource-efficient and sustainable development. Some of these challenges include a high levelized cost of electricity (due to the large capital and operational expenditures), intermittency in renewable electricity production (leading to a lack or excess of energy supply that cannot be fully utilized to displace fossil-based energy sources) and high consumption of resources, including the critical raw materials, to manufacture technology components (which can be difficult to recycle for material recovery). Based on a systematic literature review combined with a bibliometric analysis and content analysis, this chapter provides an overview of all the potential technological pathways, business model solutions and circular economy strategies for the hybridization of wind farms to produce multiple clean energy carriers (e.g. hydrogen, methane, methanol, carbon-free fuels), to optimize the technical and economic efficiency of wind energy systems, while contributing to decarbonizing high energy and carbon-intensive sectors (e.g. heavy transportation, aviation, steel, cement, plastic, chemical industry). The results include a conceptual framework of three technological pathways, nine business model solutions and ten circular economy strategies for the sustainable hybridization of wind farms, including a discussion of related industrial and policy challenges.

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S. A. Bandh et al. (eds.), *Renewable Energy in Circular Economy*, Circular Economy and Sustainability, https://doi.org/10.1007/978-3-031-42220-1_4

Keywords Circular economy · Wind farm · e-fuels · Green hydrogen · Hybrid renewable energy systems · Bibliometric analysis

4.1 Introduction

Accelerated deployment of renewable energy production technologies is instrumental to support a sustainable energy transition worldwide. The strategies of the European Union for the decarbonization of industry and mitigation of greenhouse gas (GHG) emissions seek an increase in renewable energy to at least 32% of total consumption and an improvement in energy efficiency to at least 32.5% by 2030 (Lux and Pfluger 2020). However, the efficient and sustainable development of clean energy system resources requires overcoming significant economic, technical, and environmental challenges.

The widespread adoption of renewable sources such as wind and solar poses intermittency and uncontrollability for reliable integration into the power grid (Buonomano et al. 2018; Xu et al. 2021). In addition, fluctuating feed-in from renewables is leading some countries to face excess energy production that cannot be harnessed (e.g., Denmark supplies 130% of the load in 24 h) (Dieterich et al. 2020). Moreover, grid congestion and power curtailments lead to high costs to compensate for the temporary mismatch between energy supply and demand (Balan et al. 2016; Schnuelle et al. 2020a, b).

Other economic challenges include the end of feed-in tariffs, which affects the profit generation of wind farms older than 20 years (Council of European Energy Regulators 2020). As repowering wind farms are costly, some wind farm owners opt for decommissioning wind farms (Kristensen 2020) even though the technical lifetime of wind turbines could be extended to 25–35 years (Rasmussen et al. 2020) through remanufacturing or refurbishment (Mendoza et al. 2022).

One promising solution to these challenges increasingly highlighted by academics and professionals is the hybridization of wind farms (HWF). HWF refers to the integration and management of multiple renewable energy generation and storage technologies (Carvalho et al. 2019) to increase the flexibility of electricity supply and use while producing multiple clean energy carriers (e.g., hydrogen, methane, methanol, carbon-free fuels) (Mendoza et al. 2022).

HWFs have significant advantages compared to pure renewable and storage power plants (Wind Europe 2019): Optimizing grid utilization (maximizing the use of the existing grid and solving bottleneck problems), reducing Levelized Cost of Electricity (LCOE) and infrastructure investment costs, eliminating wind and solar intermittency problems, providing a more stable power output or using land more efficiently. In addition, HFW's should be based on circular economy (CE) strategies and business models (BMs) that strive to minimize waste generation and emissions through efficient use of resources to optimize energy system efficiency and sustainability performance (Mendoza et al. 2022).

Several studies can be found exploring the environmental and economic challenges of HWF. Some authors provide frameworks and feasibility analyses of hybrid energy systems combining photovoltaics, wind turbines and storage systems on small-scale solutions and off-grid locations such as micro-grids (Zhang et al. 2016), residential buildings (Alhashmi et al. 2021), energy hubs (Eladl et al. 2020) or rural and remote communities (Olabode et al. 2021). Other studies explore the financial viability of producing green hydrogen from renewables (Lux and Pfluger 2020; McDonagh et al. 2020). Some reviews (Dieterich et al. 2020) can be found exploring the technological developments and pilot plants for the conversion of power to liquid fuels (e.g., methanol, DME and Fischer–Tropsch-fuels).

However, none of these studies offers an integrative view of potential technological pathways, BM solutions and CE strategies for HWF. The only study that comes close to this approach is the one developed by Mendoza et al. (2022), who characterized three circular BMs for HWF: (1) photovoltaic panels, WT and batteries, (2) Power-to-gas, and (3) Power-to-Liquid. However, the authors did not exhaustively discuss the possible combinations between technologies and circular economy strategies in the context of HFW.

In response, this paper aims to systematically identify and categorize technology pathways, BM solutions and CE strategies that can potentially drive HWF. To this end, three research questions (RQ) were defined:

RQ1: What are the main technological pathways and BM solutions in HWF?
RQ2: What are the main CE strategies addressed in HWF?
RQ3: How are BM solutions and CE strategies related in HWF?

A methodology comprising a systematic literature review (SLR) based on bibliometric analysis and content analysis was applied to answer these research questions. The following lines detail the methodology applied and describe the results and conclusions of the study.

4.2 Methodology

A SLR is a structured method for identifying, evaluating and interpreting available evidence relevant to a particular research domain in a rigorous, transparent and reproducible manner (Tranfield et al. 2003). SLR involves a series of steps, including defining the topic area, the inclusion criteria and the search keywords and collecting, analysing and synthesizing the literature (Chakraborty et al. 2021). Supporting SLR analysis and synthesis procedures with bibliometric analysis and content analysis can improve the rigour of the review and enable systematic evaluation of the main research topics (Chakraborty et al. 2021; Koberg and Longoni 2019; Lode et al. 2022). The bibliometric analysis allows for systematically evaluating scientific data using statistical methods to gain an overview of selected publications' main research themes and trends (Lode et al. 2022). Content analysis, in turn, supports the classification of large amounts of textual data into content categories for subsequent quantification and

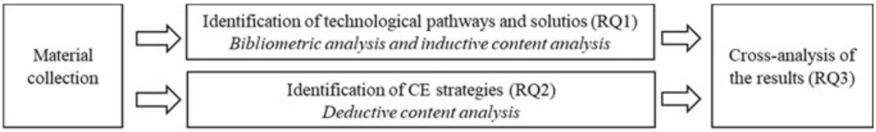

Fig. 4.1 Methodological steps followed in the present research

qualitative description (Bryant et al. 2018; Downe-Wamboldt 1992; Weber 1990). Content analysis can be deductive, using theoretical concepts to define the data coding system before the literature review, inductive, codes are developed from data and refined throughout the process during the review, or both (Elo and Kyngäs 2008; Horne et al. 2020; Hsieh and Shannon 2005). As Koberg and Longoni (2019) and Seuring and Gold (2012) recommended, the present study follows an iterative process combining deductive and inductive approaches. Figure 4.1 shows the applied methodology.

First, the material to be evaluated was searched, selected and collected. Then, a bibliometric analysis (deductive approach) combined with inductive content analysis was applied to identify the main technological pathways and solutions in HFW (RQ1). Next, a deductive content analysis identified CE strategies addressed in HWF (RQ2). Finally, the bibliometric analysis and content analysis results were cross-checked to explore the relationships between technological solutions and CE strategies in HWF (RQ3).

4.2.1 Material Collection

In March 2022, English articles and review papers on business models for HWF were located using the SCOPUS database. The following search string combining keywords on (1) wind energy, (2) business models and (3) hybrid energy systems was used in titles, keywords and abstract:

(1) TITLE-ABS-KEY (“wind technology*” OR “wind turbine*” OR “wind farm*” OR “wind park*” OR “wind energy*” OR “wind power” OR “wind energy technology*” OR “wind power technology” OR “wind sector” OR “wind energy sector”) AND
(2) TITLE-ABS-KEY(“business” OR “business model*” OR “value proposition” OR “value creation” OR “value delivery” OR “value capture” OR “value recovery” OR “value opportunit*” OR “value offering*” OR “value generation” OR “value configuration*” OR “value network*” OR “value chain*” OR “supply chain management” OR “revenue model*” OR “revenue stream*” OR “financial model” OR “customer relationship*” OR “distribution channel*” OR “customer segment*” OR “cost structure*” OR “revenue stream*” OR “revenue

model" OR "revenue mechanism*" OR "financial architecture*" OR "partnership*" OR "partner network" OR "infrastructure management" OR "financial mechanism*") AND

(3) TITLE-ABS-KEY (hybrid* OR "hybrid wind farm*" OR "hybrid wind park" OR "wind farm hybridization" OR "wind farm hybridization" OR "wind park hybridization" OR "wind park hybridization" OR "renewable hybrid power plant*" OR "renewable hybrid wind power plant*" OR "renewable hybrid wind farm*" OR "hybrid renewable energy" OR "hybrid renewable*" OR "power to" OR "power-to*").

Eighty-one articles were collected, and after a first quick content check of titles and abstracts, 35 were removed as out-of-scope. The remaining 46 articles were carefully read. 13 articles that did not explicitly focus on hybridization or business models were excluded. And 11 papers focused on remote communities, islands, residential buildings and microgrids rather than wind farms were discarded. As a result of this process, 22 potential studies and paper gathered through snowballing (Mourão et al. 2020) remained, resulting in a final sample of 23 academic papers.

In line with prior research (Bocken et al. 2014; Kristoffersen et al. 2020), the analysis was extended with a grey literature review to complement and enrich scientific data with additional real-life business cases. Industrial practices in HFW were analyzed by exploring the websites of 2 European wind original equipment manufacturers (OEM) and 6 International renewable energy associations:

- Vestas (https://www.vestas.com/): 9 documents
- Siemens Gamesa Renewable Energy (https://www.siemensgamesa.com/): 12 documents Wind Europe (https://windeurope.org/): 4 documents
- The European Technology Platform on Wind Energy (https://etipwind.eu/): 2 documents
- The Global Wind Energy Council (https://gwec.net/): 3 documents
- The International Renewable Energy Agency (https://www.irena.org/): 4 documents
- The International Energy Agency (https://www.iea.org/): 6 documents
- Hydrogen Europe (https://hydrogeneurope.eu/): 5 documents.

Thus, the final sample of documents to be analyzed consisted of 23 academic articles and 45 grey documents.

4.2.2 *Identification of Technological Pathways and Solutions in HWF*

A bibliometric analysis was conducted to evaluate the characteristics of the published scientific articles and provide some background for the subsequent evaluation of the content of each article. The bibliometric analysis involved examining authors' keywords in the 23 papers reviewed. Three different analyses were conducted using the R-package Bibliometrix v. 3.1.4, operated under the Biblioshiny web interface (Aria and Cuccurullo 2017): (1) most frequent words (to identify the most usually addressed topics), (2) word dynamics (applied to explore the evolution of keywords over time to identify main research trends), and (3) co-occurrence analysis (used to map and cluster related keywords together to identify main research themes).

The results of the analyses identified three main categories describing technological pathways and two sub-categories suggesting potential technological solutions for HFW. These initial categories and sub-categories were refined inductively throughout the academic and grey literature content analysis. The results are presented in Sect. 4.3.1.

4.2.3 Identification of CE Strategies in HWF

To identify potential CE strategies in HWF, predefined keywords drawn from the Circular Strategies Scanner developed by Blomsma et al. (2019) were defined. This scanner presents 30 CE strategies organized into four main categories that support CE innovations within manufacturing firms: (1) Recirculate, (2) Reinvent, (3) Rethink and Reconfigure and (4) Restore, Reduce and Avoid. The analysis was performed using the qualitative data analysis software QDA Miner Lite v2.0.9 (Lewis and Maas 2007). Table 4.1 shows the nomenclature and descriptions of the CE strategies (divided into categories and subcategories) adapted from Blomsma et al. (2019) and 33 related keywords used in the present study. The quantitative analysis of the results is presented in Sect. 4.3.2.

4.2.4 Cross-Analysis of the Results

In the last step, text was extracted from academic and grey literature and classified into technological pathways and CE strategies based on the results achieved in prior steps. The data was then cross-checked to explore the relationships between technological solutions and their circularity potential. The results are collected in a conceptual framework and discussed in Sect. 4.3.3.

Table 4.1 Categorization and definition of CE strategies adapted from Blomsma et al. (2019)

Category	Sub-categories/definitions		Keywords
Circular economy	An economic system that targets zero waste and pollution generation by using resources efficiently while relying on clean and renewable energy sources		*circular economy; circularity*
Recirculate	Extending use cycles of parts and products and managing end-of-life of materials to capture (residual) value or to reduce value loss from continued use of parts, products and materials		*recirculat**
	Upgrade	Extend existing use cycle by adding value or enhancing the function of a product in respect to previous versions	*upgrad**
	Repair and maintenance	Extend existing use cycle by countering wear and tear and correcting faulty components of a defective product/part to return it to its original functionality	*repair*; reparation; maintenance*
	Reuse	Extend the new use cycle by reusing a part/product (discarded/not in use) that is still in good condition and can fulfil its original function in a different context (new customer/user)	*reus**
	Refurbish and retrofit	Extend to new use cycles by returning a part/product (discarded/not in use) to a satisfactory working condition that may be inferior to the original specification	*refurbish*; retrofit**
	Remanufacture	Extend to new use cycles by returning a product (discarded/not used) to at least original equipment manufacturer (OEM) performance specification and quality	*remanufactur**
	Repurpose	Extend to new use cycles by using a product (discarded/not in use) or its parts for different functions	*repurpos**
	Recycle	Extend material lifespan by processing them in order to obtain the same or comparable quality	*recycl**
	Cascade	A subsequent use that significantly transforms the chemical or physical nature of the material	*cascad**
	Recover	Recover energy or nutrients from composting or processing materials	*recover**
Reinvent	Enable smarter business concepts through striving for full decoupling		*reinvent**

(continued)

Table 4.1 (continued)

Category	Sub-categories/definitions		Keywords
Rethink and reconfigure	Enable smarter business concepts through business model innovation for circularity. Products tend to not radically change, although the technology can evolve		*rethink*; reconfigur**
	Multi-flow offering	Extend the life of materials or products in a manner that exploits their residual value and becomes a significant part of the offering of the business. May involve providing new forms of value	*"multi-flow"*
	Long life products	Extend the life of products through offering support during their lifetime	*"long life"*
	Access or availability	Satisfying user needs without transferring ownership of physical products. Instead, user or consumer pays for access to the product for a certain period of time	*Sharing; "product share"*
Restore, reduce and avoid	Improve circularity potential and efficiency, prevent excess and aim for "gentani" (i.e., the absolute minimum input required to run a process)		*restor**
	Raw and materials sourcing	In the sourcing process	*"restorative sourcing"; "secondary sources"; "secondary materials"*
	Manufacturing	In product manufacture through consuming fewer natural resources or energy, aim for 'gentani'	*rework*; cascad*; recycle*; "lean manufacturing"; "cleaner production"*
	Product use and operation	In product use and operation through wiser use and operation of products (e.g., using digital technologies) and aim for 'gentani'	*"product longevity"; Longevity*

4.3 Results

4.3.1 Technological Pathways and Solutions in HWF

The bibliometric analysis was exploratory and aimed to provide an overview of the main research themes and trends based on the keywords most frequently used by the researchers in the 23 papers reviewed. Authors' keywords were analyzed by exploring keywords' frequency, dynamics and co-occurrence. Before the analyses, keywords were manually scanned to avoid typos and to homogenize spelling (Henry et al. 2021). Table 4.2 shows the 23 original keywords manually replaced by eight generic ones.

Table 4.3 presents the top-10 most frequent keywords out of the total of 79 authors' keywords comprised in the 23 articles. In line with the central theme of the study, the Keyword with the highest number of occurrences per article is "wind energy" (39,1% occurrences per article). The next most frequent keywords are "power-to-gas", "hydrogen", and "electrolysis", with 34,8%, 26,1% and 21,7% of the articles targeting these solutions, respectively. "Hybrid system", "solar energy", "energy storage", and "power-to-liquid" follow the ranking with the representativeness of 17,14%, 17,14%, 13% and 13% per article, respectively. Among the less frequent keywords are "methanol" and "offshore wind", each with 8,7% occurrences per article.

Exploring the dynamics of the top-10 keywords over time (Fig. 4.2), it can be observed that until 2015, "wind energy" research was closely aligned with research

Table 4.2 Manually corrected keywords

No	Authors' original keyword	Revised keyword
1	Hydrogen	Hydrogen
2	Cost of hydrogen	
3	Power-to-gas	Power-to-gas
4	Power-to-gas (ptg)	
5	Power to gas	
6	Power-to-gas technologies	
7	Power-to-liquids (ptl)	Power-to-liquid
8	Power-to-liquid	
9	Electrolysis	Electrolysis
10	Electrolyzer	
11	Pem electrolysis	
12	Wind energy	Wind energy
13	Wind power	
14	Wind farm	
15	Wind turbine	
16	Wind power cooperatives	
17	Hybrid energy systems	Hybrid system
18	Hybrid renewable energy	
19	Hybrid pv-wind	
20	Solar energy	Solar energy
21	Pv park	
22	Methanol	Methanol
23	Methanol production	

Table 4.3 Top-10 most frequent authors' keywords

Author's keywords	Occurrences	% Occurrences	% Per article
Wind energy	9	11,4	39,1
Power-to-gas	8	10,1	34,8
Hydrogen	6	7,6	26,1
Electrolysis	5	6,3	21,7
Hybrid system	4	5,1	17,4
Solar energy	4	5,1	17,4
Energy storage	3	3,8	13,0
Power-to-liquid	3	3,8	13,0
Methanol	2	2,5	8,7
Offshore wind	2	2,5	8,7

on "hydrogen" and "electrolysis" solutions, while the remaining keywords started to be used from 2015 onwards. Thus, the keywords "power-to-gas", "hybrid system", "solar energy", "energy storage", power-to-liquid", and "methanol" are gaining relevance; moreover, since 2020, the frequency of these keywords has doubled, suggesting a growing interest in hybrid solutions for wind farms in academia. On the other hand, "offshore wind" keyword seems to start to be used from 2020 onwards, which could indicate a recent interest for the hybridization of offshore wind farms. These results are consistent with the first circular economy action plan adopted by the European Commission in 2015 and the introduction of the first climate action initiatives under the European Green Deal in 2020.

For keywords' co-occurrence analysis, the Louvain clustering algorithm and association normalization were used (Bretas and Alon 2021). Co-occurrence analysis allows keywords used together by the authors to be clustered, suggesting key topics

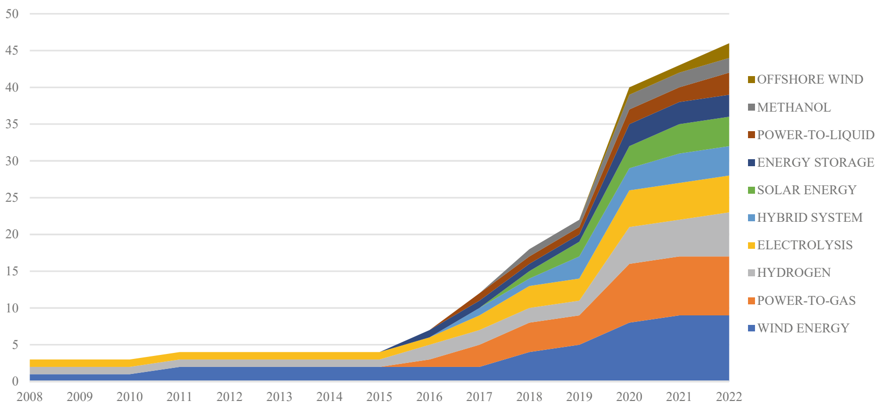

Fig. 4.2 Evolution of authors' keywords over time

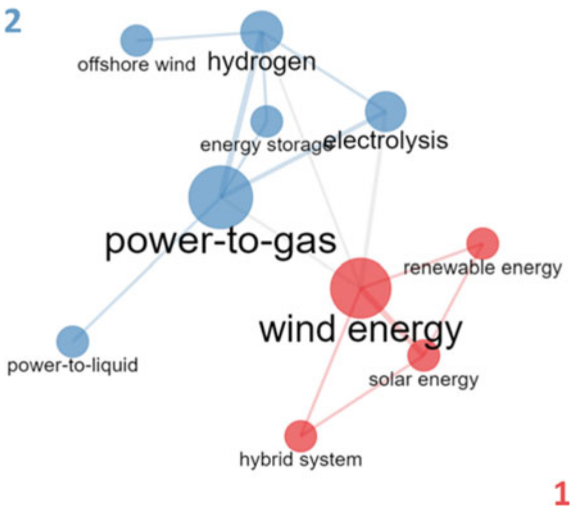

Fig. 4.3 Keyword co-occurrence analysis. Cluster 1 (red): wind and solar energy systems, Cluster 2 (blue): power-to-X solutions

within a research area (Aria et al. 2022). Figure 4.3 shows the keywords network indicating two main clusters: Cluster 1 (Wind and Solar Energy Systems) and Cluster 2 (Power-to-X solutions). Keywords are represented in nodes, where the size of the circle and text indicate the relevance of the Keyword in the network. The nodes are linked by ties, the thickness of the tie representing the closeness between keywords.

In cluster 1, "wind energy" is the most representative Keyword, having the closest link to "solar energy". Both keywords also bridge the keywords "hybrid systems" and "renewable energy". These results are consistent with the trend observed in the academic literature, where the concept of hybrid systems is often used to refer to the integration of PV in wind farms (Carvalho et al. 2019; Diemuodeke et al. 2019; Fasihi et al. 2017; Xu et al. 2021).

In cluster 2, the keywords "Power-to-Gas", "Hydrogen", and "Electrolysis" are the most representative of the cluster, being the links between "Power-to-Gas" and both "Hydrogen" and "Electrolysis" are the closest ones. Moreover, these three keywords link the blue cluster to the red cluster by linking to the keyword "wind energy". Therefore, cluster 2 seems to be related to the so-called Power-to-X technologies, which extend the value chain of wind farms by converting renewable energy into gaseous or liquid energy carriers. In line with the results, hydrogen is obtained via water electrolysis at the core of Power-to-Gas technologies (Lux and Pfluger 2020). Hydrogen can be further synthesized into liquid energy carriers such as methanol (González-Aparicio et al. 2018), usually known as Power-to-Liquid (linked to Power-to-Gas in the network). "Energy storage", linked in the network with both "Hydrogen" and "Power-to-Gas", may stress the potential of Power-to-Hydrogen solutions to facilitate the storage and transport of intermittent energy sources such as wind and solar (Balan et al. 2016). Finally, the tie between offshore wind and hydrogen could represent a research stream in the field of Power-to-Hydrogen solutions in the marine domain (McDonagh et al. 2020).

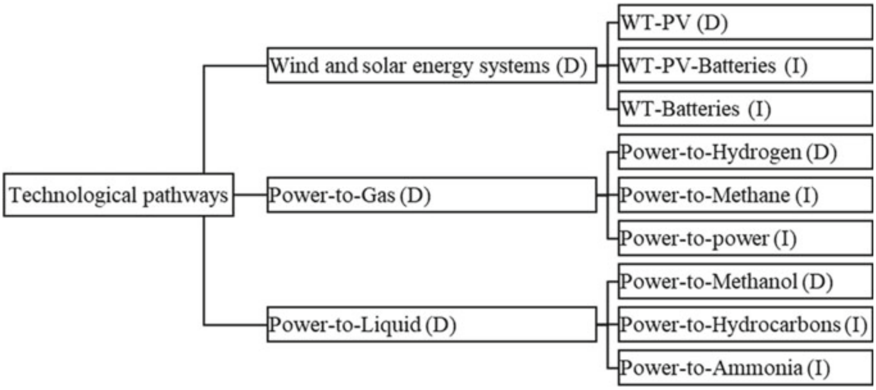

Fig. 4.4 Technological pathways and BM solutions in HWF. *WT* wind turbine, *PV* photovoltaics, *D* deductive, *I* inductive

Figure 4.4 presents the three technological pathways and two BM solutions for HWF deductively derived from the bibliometric analyses (indicated by a D in the figure). These preliminary categories were validated by further reviewing the academic and grey literature. Moreover, six new BM solutions were inductively identified, two for each technological pathway (indicated by a I in the figure). Therefore, the final framework consists of three technological pathways and nine BM solutions (three for each pathway) for HWF.

The simplest form of HWF (Wind and Solar Energy Systems, Fig. 4.2) is the integration of photovoltaics (PV) and/or batteries at the wind farm site. PVs produce more electricity during daytime/summer, while WTs produce more electricity during night-time/winter (Buonomano et al. 2018). Thus, the daily and seasonal complementarity of the two technologies can reduce intermittency impacts and produce power constantly (Carvalho et al. 2019). By adding batteries to WT or WT-PV solutions, energy can be stored and shifted to another time of the day or year, adding flexibility and efficiency to the energy system, improving the balance between energy demand and production and increasing asset revenues (Buonomano et al. 2018).

In Power-to-Gas technological pathway, renewable energy is used to power an electrolyzer and produce green hydrogen (Power-to-Hydrogen). Hydrogen can be stored, traded (e.g., industrial or transport sector) or converted into methane (Power-to-Methane) through CO_2 capture and a methanation process (Balan et al. 2016). Moreover, the stored hydrogen can be reconverted into electricity (Power-to-Power) using fuel cells (Scolaro and Kittner 2022) and gas turbines (Fasihi et al. 2017). Power-to-gas are potential solutions for long-term energy storage and transportation (Dieterich et al. 2020). The sale of hydrogen and methane allows market diversification of wind farms to sectors such as mobility, industry (e.g., chemical, fertilizer production), or heating (Balan et al. 2016; Schnuelle et al. 2020a, b).

In Power-to-Liquid technological pathway, hydrogen can be synthesized into liquid energy carriers such as methanol (Power-to-Methanol) and Fischer–Tropsch-fuels (e.g., diesel, kerosene and olefins) (Power-to-FT fuels). Two additional processes are required: gas-to-liquid synthesis (based on CO_2 capture) and product upgrading (Dieterich et al. 2020). Power-to-Liquid is a promising pathway to substitute fossil-based fuels in the chemical industry and hard-to-electrify sectors, e.g., aviation, shipping, and heavy transportation (Fasihi et al., 2017). Hydrogen can also be converted into ammonia as a feedstock in industrial processes (Power-to-Ammonia).

For a more detailed description of the technological pathways and BM solutions in HWF presented in this paper, see Mendoza and Ibarra (2022).

4.3.2 Deductive Content Analysis of CE Strategies

Of the 33 keywords defined to analyze the textual content of the 23 academic articles and 45 grey documents (i.e., company websites, industrial reports and business cases), a total of 13 CE strategies (39,4%) were recorded (Table 4.4).

Table 4.4 CE strategies reported in academic and grey literature

Category/Sub-category	Keywords defined	Academic literature	Grey literature	% Academic literature	% Grey literature
CIRCULAR ECONOMY	circular economy	0	2	0,0%	4,4%
	circularity	0	3	0,0%	6,7%
RECIRCULATE	recirculat*	0	1	0,0%	2,2%
- Upgrade	upgrad*	6	11	26,1%	24,4%
- Repair & maintenance	repair*	1	1	4,3%	2,2%
	reparation	0	0	0,0%	0,0%
	maintenance	14	13	60,9%	28,9%
- Reuse	reus*	1	4	4,3%	8,9%
- Refurbish & retrofit	refurbish*	1	2	4,3%	4,4%
	retrofit*	1	7	4,3%	15,6%
- Remanufacture	remanufactur*	0	0	0,0%	0,0%
- Repurpose	repurpos*	0	7	0,0%	15,6%
- Recycle	recycl*	0	4	0,0%	8,9%
- Cascade	cascad*	0	0	0,0%	0,0%
- Recover	recover*	4	9	17,4%	20,0%
REINVENT	reinvent*	0	0	0,0%	0,0%
RETHINK AND RECONFIGURE	rethink*	1	0	4,3%	0,0%
	reconfigur*	0	0	0,0%	0,0%
- Multi-flow offering	"multi-flow"	0	0	0,0%	0,0%
- Long life products	"long life"	0	0	0,0%	0,0%
- Access or availability	Sharing	0	0	0,0%	0,0%
	"product share"	0	0	0,0%	0,0%
RESTORE, REDUCE & AVOID	restor*	0	1	0,0%	2,2%
- Raw & materials sourcing	"restorative sourcing"	0	0	0,0%	0,0%
	"secondary sources"	0	0	0,0%	0,0%
	"secondary materials"	0	0	0,0%	0,0%
- Manufacturing	rework*	0	0	0,0%	0,0%
	cascad*	0	0	0,0%	0,0%
	recycl*	5	3	21,7%	6,7%
	"lean manufacturing"	0	0	0,0%	0,0%
	"cleaner production"	0	1	0,0%	2,2%
- Product use & operation	"product longevity"	0	0	0,0%	0,0%
	Longevity	0	0	0,0%	0,0%

The percentages have been calculated based on the total number of publications in the academic and grey literature (23 and 45 documents, respectively)

The most frequently addressed CE strategies in the HWF correspond to the RECIRCULATE category. Extending the existing use cycle of parts and products through *maintenance* and *upgrading* strategies and end-of-life material *recovery* represent 60,9%, 26,1% and 17,4% of academic literature and 28,9%, 24,4% and 20% of grey literature, respectively. In addition, the grey literature also emphasizes the extension of parts and products to new use cycles through *retrofitting* (15,6%) and *repurposing* (15,6%).

The second category that encompasses the most referenced CE strategies is RESTORE, REDUCE and AVOID; being *recycling* of materials (e.g., CO_2 or water) during the production processes of Power-to-Gas, and Power-to-Liquid solutions is the most relevant approach (21,7% of the academic literature and 6,7% of the grey literature). Additionally, one industrial report refers to the generic term *restore* (2,2%), highlighting the use of grid converters and batteries in offshore wind farms to reduce the restoration time of power plants and potentially avoid blackouts. Another report mentions a *clean production* strategy (2,2%) to refer to power-to-gas solutions, which involve cleaner production methods for hydrogen generation.

The following most used keywords fall under the general category of CIRCULAR ECONOMY. Interestingly, only the grey literature refers to a *circular economy* (4,4% of the documents) and *circularity* (6,7% of the documents).

The categories REINVENT and RETHINK AND RECONFIGURE are barely addressed. There were no results for the search of "reinvent", while in the RETHINK AND RECONFIGURE category, none of the keywords was found, except for the generic term "rethink", which appears only once in the academic article referring to the hybridization of wind farms to integrate Power-to-Gas solutions (Rasmussen et al. 2020).

4.3.3 Cross-Analysis of the Results

The cross-analysis analysis of the results allowed us to explore the relationship between the technological pathways and the CE strategies as summarised in Fig. 4.5. In terms of recirculating products, parts and materials, five CE strategies appear to cut across all technology pathways: Upgrade, Repair and Maintenance, Repurpose, Recycling and Recover.

As HWF is based on integrating new assets and technologies in new or existing plants, all BM solutions require infrastructure, equipment, and grid connection upgrades (Papadopoulos et al. 2018; Rasmussen et al. 2020). Similarly, these new BMs require skills and training to repurpose the workforce (GWEC 2022).

Maintenance of installations and equipment is also a key activity in all BM solutions. One of the challenges related to this CE strategy is optimising maintenance costs, as the new assets needed for converting energy into gas and liquids entail higher maintenance costs (Balan et al. 2016). In response, digitalization and artificial intelligence can help reduce costs through predictive maintenance, which allows optimization of the detection of possible failures before they occur (GWEC 2022). In

	Technologycal pathways	WSES			Power-to-Gas			Power-to-Liquid		
		WT-PV	WT-PV-Battery	WT-Battery	Power-to-Hydrogen	Power-to-Methane	Power-to-power	Power-to-Methanol	Power-to-FT fuels	Power-to-Ammonia
RECIRCULATE parts & products	Upgrade	Infrastructure & equipment upgrades. Grid upgrades								
					Product upgrading					
	Repair & maintenance	Facilities & equipment maintenance								
	Reuse							Reuse of chemicals		
	Refurbish				Plant refurbishment. Retrofitting pipelines					
	Repurpose	Skills and training repurpose. Repurposing wind blades. Repurposing grids.								
					Repurpose of infrastructure and pipelines					
RECIRCULATE materials	Recycle	Wind blades recycling								
	Recover	Recovery of composite materials								
			Energy recovery		Heat and CO_2 recovery					
RESTORE, REDUCE, AVOID	Clean production				Replacement of fossil fuel-powered processes with clean production methods to create clean gas and fuels					
	Recycling (pre-user)				Recycling of CO_2 and water					
RETHINK & RECONFIGURE	Multi-offering	New value propositions and revenue streams (ancillary services, electricity, gas and fuels)								

Fig. 4.5 Framework of technological pathways, BM solutions and CE strategies for HFW

offshore farms, applying remote sensing, robotic inspection and repair methods could increase the availability of wind turbines and reduce risk and human interventions (Fraile et al. 2021).

Moreover, recycling wind blades and the recovery of composite material used in their production (glass or carbon fibres and a polymer matrix) is another major challenge for the circularity of wind energy and, consequently, HWF. Approximately 90% of wind turbine materials and components can be commercially recycled (GWEC 2022). Advancing recycling technologies for composite materials (the remaining 10%) would further reduce wind technology's ecological footprint and the sector's dependence on critical raw materials. They would promote new business opportunities, such as secondary materials markets (Fraile et al. 2021).

Focusing on the Wind and Solar Energy Systems pathway, in WT-battery and WT-PV-Battery solutions, energy recovery is the main CE strategy, as batteries allow the storage of energy that would otherwise be lost (Malakar et al. 2014).

Power-to-Gas solutions require refurbishment and retrofit of existing gas pipelines and infrastructures for hydrogen and methane injection (Balan et al. 2016). Compatibility with repurposed pipelines and existing sites is already facilitating the establishment of green hydrogen as a mainstream energy source (Gamesa 2021).

In both, Power-to-Gas and Power-to-Liquid, various CE strategies such as the reuse of chemicals (Bos et al. 2020), heat (Balan et al. 2016) and CO_2 recovery (Wassermann et al. 2022) and CO_2 and water recycling (Bos et al. 2020; Fasihi et al. 2017) can lead to the optimization and efficiency of hybrid plants. For instance, since the production of methane or methanol requires CO_2 capture, locating hybrid plants close to high CO_2 emitters (e.g., power plants, cement or steel industries, and refineries) can facilitate recovering CO_2 while generating environmental benefits (Balan et al. 2016). Furthermore, the heat output from conversion processes, such as electrolysis and methanation, can be recovered and used in subsequent processes (e.g., Capture of CO_2). In addition, surplus water from methane or methanol could be recycled and reused in the electrolysis process electrolyzer (Bos et al. 2020; Fasihi et al. 2017).

Finally, the nine BM solutions represent circular business model strategies (multi-flow offering typology) since they involve new value creation, delivery, and capture (Blomsma et al. 2019). By adding new assets and technologies, they extend the life of wind farms by creating multiple energy products (electricity, ancillary services, hydrogen, methane, methanol, fuels, etc.), which in turn generate new revenue streams for wind farm owners.

4.4 Conclusions

This chapter provides an overview of all the potential technological pathways, business model solutions and circular economy strategies for the hybridization of wind farms based on a systematic literature review combined with a bibliometric analysis and content analysis of 23 academic articles and 45 grey papers.

The results of the bibliometric analysis showed a growing interest in the academic field in technological approaches to HFW, specifically in Wind and Solar hybrid systems, Power-to-Gas and Power-to-Hydrogen, Hydrogen storage and Power-to-liquid solutions, such as Power-to-Methanol. The detailed analysis of technological pathways and BM solutions resulted in 3 pathways (wind and solar energy systems, Power-to-Gas and Power-to Liquid) and 9 BM solutions (3 for each technological pathway) that support the technical and economic optimization and efficiency of wind energy systems, and the decarbonization of high energy- and carbon-intensive sectors (e.g., heavy transportation, aviation, steel, cement, plastic or chemical industry).

The quantitative content analysis on CE strategies addressed in both academic and grey literature shows that the main circular approaches adopted in HFW relate to extending the existing use of hybrid plants through recirculating strategies such as maintenance, upgrading, retrofitting, repurposing and material recovery. However, there is a gap in research and practice on strategies to reinvent, rethink and reconfigure current business strategies and business models for HWF. Moreover, only a few industry reports address concepts relating to a circular economy with HWF. Thus, more research is needed to understand what circular business model typologies can contribute to hybrid energy systems' economic viability and sustainability.

The cross-analysis of BM solutions and CE strategies for HWF resulted in a conceptual framework that serves as a professional guide and a basis for future research. The framework suggests that recirculate strategies (Upgrade, Repair and Maintenance, Repurpose, Recycling, and Recover) span all BM solutions. At the same time, Power-to-Gas and Power-to-Liquid pathways promote recycling and material recovery of heat, water and $CO_{2,}$ leading to the optimization and efficiency of hybrid plants.

The nine BM solutions represent potential BMs aiming to extend the life of wind farms by increasing the efficiency of their assets, diversifying their value propositions, and creating new revenue streams. However, the identified CE strategies should be complemented with appropriate approaches for cost-effective decommissioning, disassembly and recovery of components and materials at the end-of-life of hybrid plants.

In addition, further research should address the impact of digitalization and related technological developments such as artificial intelligence or robotics on HWF since they can bring new opportunities to increase the efficiency of hybrid plants and create new business opportunities (e.g., servitization capabilities and product-service system BMs).

Finally, progress towards circularity solutions for the HWF will require public–private partnerships (aligning innovation programmes with industry investments) and cross-sectoral collaborations to address common challenges such as composite material recycling (GWEC 2022). To make Power-to-Gas and -Liquid BMs economically viable, further technological development and reduction of investment costs are still needed regarding electrolyzer efficiency, "low carbon" CO_2 procurement and synthetic fuels production.

Acknowledgements This work has received financial support from the CISTE ("circularity and sustainability of wind energy technologies") project (2020-CIEN-000052-01) funded by the Department of Economic Development, Tourism and Rural Environment of the Gipuzkoa Provincial Council from the Basque Country, Spain.

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