

State of the art of Windthermal Turbines: A Systematic Scoping Review of Direct Wind-to-Heat Conversion Technologies

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Windthermal turbines convert wind directly into thermal energy. Albeit it is an uncharted field of research, the overall system efficiency and costs of fully developed windthermal turbines are promising; since they can contribute to a sustainable energy transition. We identify the current state of the art of windthermal conversion principles, technology maturity, applications, substitutes, advantages, and disadvantages. To scope relevant literature, we follow the Joanna Briggs Institutes selection and screening process resulting in 61 relevant publications from which we identified three main conversion types, namely, compression-, friction-, and induction-based windthermal devices. These devices can directly supply thermal energy for space heating or industrial processes, work as a component of wind-powered thermal energy systems, short windthermal energy system (WTES), or can substitute any conventional or renewable heat device. Although heat is the lowest form of energy, windthermal applications could provide cheap renewable energy that can be stored easily enhancing security of supply. However, these technologies are currently on laboratory scale, and we suggest scaling up the existing prototypes to engineering scale. Finally, due to a missing general terminology, we propose to establish one of the terms windthermal energy, vento-thermal energy, or anemo-thermal energy to distinguish these specific wind energy conversion technologies. [DOI: 10.1115/1.4052616]

Keywords: systematic scoping review, direct wind-to-heat conversion, windthermal energy, wind-powered thermal energy system, Joule machine, multi-cylinder Taylor-Couette system, hydrodynamic retarder, heat pump, hydraulic pump, permanent eddy current magnet converter, alternative energy sources, energy conversion/systems, heat energy generation/storage/transfer, renewable energy

1 Introduction

Climate change is indisputable; and the transition to sustainable energy systems is indispensable to mitigate global warming [1]. This transition is one of the main challenges facing the energy sector and is expressed very well by the energy trilemma of balancing the three dimensions of energy sustainability: energy security, energy equity (accessibility and affordability of energy), and environmental sustainability of energy systems [2]. Renewable heat production and sector coupling—power-to-heat applications, for instance, convert renewable electricity into heat—can boost system flexibility and contribute to sustainable energy solutions [3] and therefore act as a game changer balancing at least the two dimensions energy security and environmental sustainability of the energy sustainability trilemma.

Many current power-to-heat projects and research approaches use excess wind generation [4–8]. But, converting the wind turbines' mechanical energy directly into heat (Fig. 1) could save one conversion step and therefore be more cost-effective [9] and efficient [10,11]. Hence, the development of windthermal converters could make renewable heat more affordable and consequently provide the last of the three pillars of energy sustainability.

The idea to convert wind directly into heat is not new [12]. However, this promising field plays only a marginal role in the scientific discourse, lacks of coherent terminology, and has not

yet been reviewed comprehensively, which justifies a scoping review [13]. Systematic scoping reviews intend to “extract as much relevant data from each piece of literature ... to provide an overview of the existing evidence base regardless of quality” [14]. This review aims to scope windthermal energy applications systematically by synthesizing previous research, identifying effective techniques and possible gaps, and setting conceptual boundaries to electrical wind generation. We focus on windthermal conversion principles, technology maturity, and possible applications and follow the methodologies from Joanna Briggs Institute [15], the most-cited systematic scoping review methodology.

In Sec. 2, we set our research scope and describe the applied methodology. Then, we present a bibliometric analysis in Sec. 3 and a summary of the different conversion principles in Sec. 4. In Sec. 5, the technology maturity of these conversion principles is

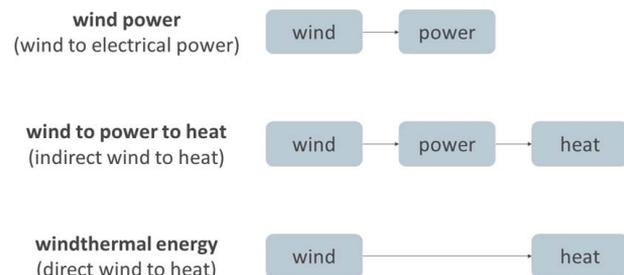


Fig. 1 Distinction of “wind power,” “wind to power to heat,” and “windthermal energy”

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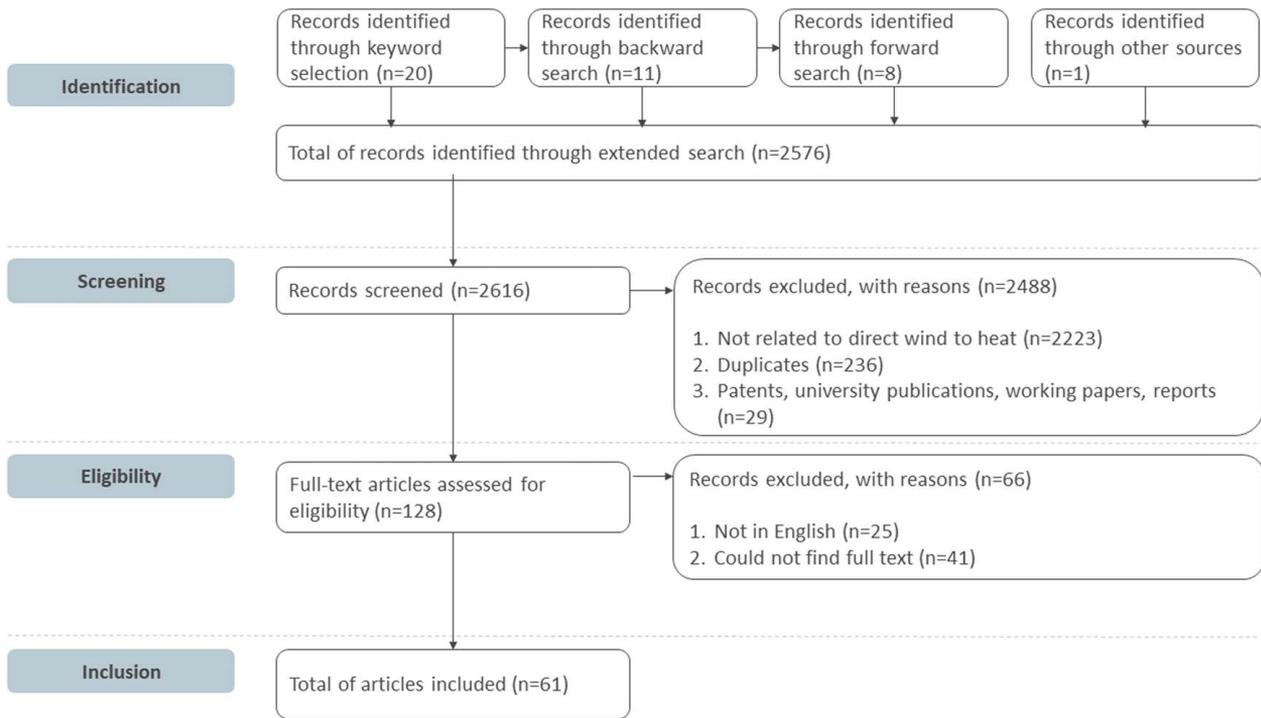


Fig. 2 Selection and screening process

analyzed, and Sec. 6 focuses on possible application scenarios. Finally, Sec. 7 is devoted to a summary of our main conclusions.

2 Search Methodology

We followed an eight-step systematic literature search process [14,16] resulting in only 61 publications (Fig. 2), which underlines the reason to systematically investigate this research field. Each of these eight steps is described as follows:

Step 1 (Formulate the problem): We aim to answer the following research questions:

- (1) Which are the relevant academic windthermal energy publications?
- (2) Does any specific terminology exist to distinguish windthermal energy from other wind energy technologies?
- (3) Which windthermal conversion principles does the literature propose?
- (4) How mature are these technologies?
- (5) Which windthermal applications does the literature propose?
- (6) Which are the competing technologies that can be substituted by these applications?
- (7) What are the advantages and disadvantages of windthermal energy?

Therefore, we consider all academic publications (conference proceedings and journal articles) regarding windthermal energy. This includes every concept where wind is converted directly into heat; no matter whether this heat is directly consumed by the end-user or stored in thermal energy storage. Due to the scoping approach, we also consider articles that are not peer reviewed, but do not consider non-English literature, books, patents, university publications, and working papers.

Step 2 (Develop the review protocol): We developed a review protocol to improve the quality and reliability and train the team. This protocol comprises the search methodology presented in this section and two Microsoft[®] Excel files: One to record each step of the literature search and another to catalog the identified literature.

Steps 3 and 4 (Select and screen for inclusion): We searched and screened the literature based on the methodology proposed

by Levy and Ellis [17] and refined by Schumann et al. [18]. This methodology comprises a three-step approach—keyword selection, forward search, and backward search. In a fourth step, we expanded this search process by repeated forward and backward searches with less stringent criteria to identify additional literature.

- The keyword selection aims to query relevant literature with keywords that are related to our scope. To get a first overview into windthermal energy, we used the Google[®] search engine to identify relevant websites and documents. We compared 224 combinations of keywords from the domains “wind,” “heat,” “possible devices,” and “others” that we obtained from already identified windthermal publications. We selected 11 of these terms due to their relevance and number of hits. For this selection, we screened the results of the first two search result pages of each of these combinations for academic literature regarding windthermal energy. In a first step to prefilter these publications, we screened their abstracts and titles for the keywords “heat,” “thermal,” and “wind.” In a second step, we excluded further publications when their abstracts were not relevant for this review. Since we found very few academic literature, we considered in this step also patents, theses, and working papers.
- The backward search aims to identify additional literature that is referenced in the already identified relevant literature. We applied a three-step filtering process to all references: eliminating duplicates, considering all publications that were cited twice or more, and screening for inclusion (described in search-step “keyword selection”).
- The forward search aims to identify additional literature that cites the literature. We used Google Scholar’s “cited by” function and then screened for inclusion (described in search-step “keyword selection”).
- The expanded search aims to widen the literature base. We applied another forward and backward search to all relevant literature and repeated this process until no additional literature was found. Within this step, also publications, which were cited at least once, were considered.

Table 1 Definition of publication categories

Category	Category definition
Applications (applic.)	Publications that propose a specific application of windthermal turbines. They may also contain in some extent assessments or proofs of concept (see below). The brief description specifies application cases, turbine type, windthermal converter, and article focus.
Assessments (assmt.)	Publications that aim to provide a technical and/or economic assessment of two or more different windthermal conversion technologies or both. The brief description specifies the type of assessment and assessed windthermal converters.
Field trials (f. trial)	Publications that discuss outcomes, measured during the operation of a windthermal prototype. The brief description specifies windthermal converter and study focus.
Laboratory trials (lab. trial)	Publications that discuss outcomes, measured during the dry running of incomplete windthermal prototypes, where a motor replaces the rotor. The brief description specifies windthermal converter and study focus.
Proofs of concept (pf of concept)	Publications that prove the concept of windthermal converters or a specific component. The brief description specifies the respective windthermal converter, study focus and methodology.

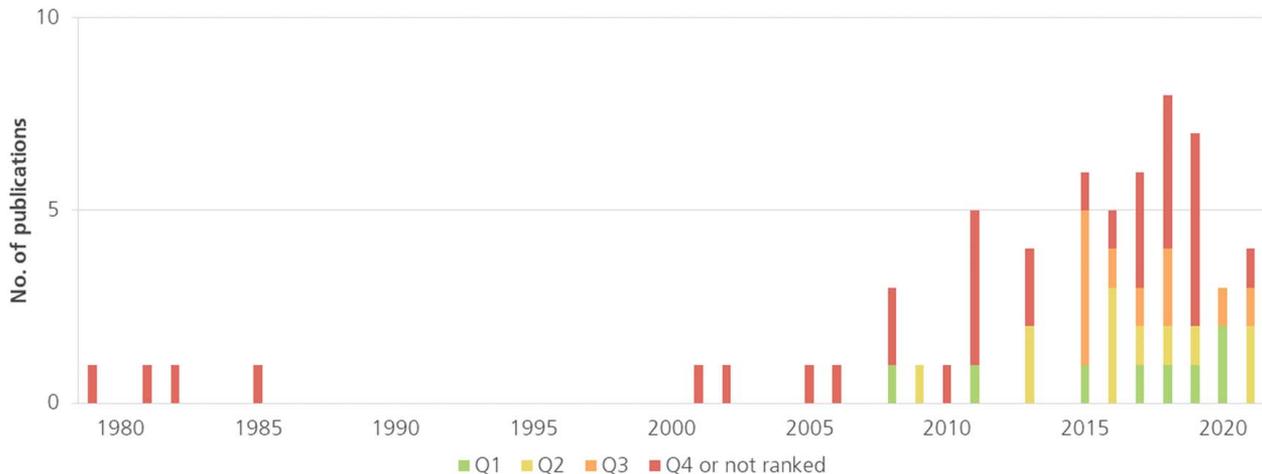


Fig. 3 Number of publications by year of publication, indicating the SCImago[®] quartiles as quality indicators of the publishing journals (Q1 = best 25%, Q4 = less 25%). Conference proceedings and journals where the SCImago[®] quartile is not yet assigned are indicated as “not ranked.”

Step 5 (Assess quality): A bibliometric analysis answered the first research question and also assessed the quality of the identified literature. Therefore, we cataloged the relevant literature and carried out a bibliometric analysis identifying the publication type and the SCImago[®] quartiles [19] of the subdiscipline (renewable) energy in the year the respective article was published. All citations among the relevant publications were organized in an edge list and mapped with YED [15], an open source graph editor software. The relevant publications were also classified by category (definitions in Table 1) and conversion principle, and their contents are described briefly. To identify common terms, the frequency of words used in abstracts and titles was analyzed with WordCloud Generator [20]. Doing this, we spelled out acronyms and eliminated empty phrases like “in this paper.”

Steps 6 and 7 (Extract, analyze, and synthesize data): An in-depth analysis of the relevant literature answered the remaining research questions presented in Step 1. In addition, we assessed the technology maturity according to the nine-point scale of technology readiness levels (TRLs) defined by the United States Department of Energy (DOE) [21]. We also identified strengths, weaknesses, opportunities, and threats (SWOT) of the proposed applications.

Step 8 (Report findings).

²The SCImago[®] Journal & Country Rank is a portal that includes the journals and country scientific indicators based on Scopus[®] data (Elsevier B.V.). SCImago[®] divides the journals into categories. The Q1 quartile comprises the top 25% of journals in the category and so on.

3 Bibliometric Analysis

We found 61 relevant publications but we could not identify any specific terminology to distinguish windthermal energy from other wind energy technologies.

3.1 Relevant Literature. It is likely that these 61 publications comprise all English academic literature about windthermal energy. (Unfortunately, we cannot be certain due to the inconsistent terminology.) Most of the publications were published within the last decade, and over time the number of publications in journals with higher SCImago[®] rankings increased (Fig. 3).

To understand the relations among these publications, we grouped their authors by repeated co-authorship or when they work at the same institution. These groups are as follows: Firețeanu, Nebi, and Tudorache from the Politechnical University of Bucharest; Jwo and Ting from the National Taipei University; Černečienė and Ždankus from the Kaunas University of Technology; Garvey and Swinfen-Styles from the University of Nottingham; Miskiv, Mamonov, and Serov from the Kutateladze Institute of Thermophysics; Matsuo and Okazaki from the Kyoto University; Bostan and Sobor from the Technical University of Moldova; Katawaluwa and Chakirov that both co-authored Vagapov (on a side note, Chakirov and Katawaluwa presented the same findings twice). We observed that the identified author groups rather self-cite themselves instead of citing publications from author groups and that many articles have not been cited in any relevant publication yet. Apparently, research networks and the general attention for the windthermal research discourse are underdeveloped.

The identified literature covers a wide range of different subtopics. This makes it difficult to point out the most relevant literature. It rather depends on the specific research question. To make it easier to identify pertinent literature, we provide a brief description of every paper classified by category and conversion principle (Table 2). We recommend the articles from Jwo et al. [11] and Żdankus et al. [48] to familiarize with compression-based windthermal energy, the articles from Liu et al. [57] and Serov et al. [54] to familiarize with friction-based windthermal energy, and the article from Chen et al. [62] to familiarize with induction-based windthermal energy. The proposed application of a windthermal energy system from Okazaki et al. [38] is by far the most-cited article and is worth reading.

3.2 Windthermal-Specific Terminology. We struggled to identify relevant literature and dedicate this section to windthermal-specific terminology, which could help to identify future publications. Earlier, we introduced the term “windthermal,” but we want to emphasize that, so far, the search term “direct wind heat” works better to search for relevant literature.

Apparently, there exists no specific term to distinguish windthermal energy from other forms of wind energy usage. The terms used in the abstracts and titles of the relevant literature (the ten most frequent terms are “thermal energy,” “wind turbine,” “wind energy,” “rotor,” “heat pump,” “wind power,” “heat generator,” “permanent magnet,” “heating system,” and “mechanical energy”) are generic and could be used for other forms of wind energy conversion or any type of thermal application. This underlines the fact that searching with these terms in Google Scholar and Scopus resulted in a fraction of articles dealing with windthermal energy.

For future literature reviews, we recommend to combine keywords from the domains “wind,” “thermal,” and “possible devices” and add the keyword “direct”—by chance we found out that this inconspicuous word refines the literature search substantially and its infrequent use in abstracts and keywords of the relevant literature (13 times in total) is remarkable.

It is obvious that a specific term is necessary to distinguish windthermal energy in future. Most energy technologies are designated by the source of energy in Greek (e.g., “hydropower”), Latin (e.g., “solar power”), or English (e.g., “wind power”) combined with the word “power” in case of electricity generation. To distinguish heat generation, mixed terms like “solar thermal energy,” “aerothermal energy” (air-source heat pump), “geothermal energy” (ground-source heat pump), or “hydrothermal energy” (water-source heat pump) are used. Therefore, we propose to denominate the direct conversion of wind into heat as “anemothermal energy,” “ventothermal energy,” or “windthermal energy” energy, using the respective term for wind in Greek, Latin, and English. In this article, we use “windthermal energy” as it seems better accessible to everyday language.

4 Windthermal Conversion Technologies

There is a broad range of research activities, focusing on the device that converts mechanical energy into heat. Please notice that our goal is to outline these technologies by presenting authors’ opinions.

We found three different concepts to convert wind energy directly into heat: compression, friction, and induction; or a combination of two concepts [9]. In all proposed devices, wind energy is converted into rotational energy by the rotor of the wind turbine. Rotational energy is subsequently transferred into heat by increasing the temperature of a working fluid (gas or liquid, e.g., water, oil, sodium chloride) that circulates in a closed circuit. This circuit is either connected directly to the consumer or the heat is transferred through a heat exchanger to a secondary circuit, which delivers the heat to its respective consumer.

Similar to wind to power converters, direct drive [27,42,46] and gearbox-type [43] windthermal converters are proposed for both vertical- [31,48,67] and horizontal-axis [9,38,42,43] wind turbines.

We also present details about the compression-, friction-, and induction-based concepts. We describe the different applied heat conversion technologies and their nomenclature. Furthermore, we provide available research findings focusing on the working fluid temperature and the system efficiencies. Two types of efficiencies are presented as authors considered different system boundaries: The wind-to-heat efficiency is the coefficient of generated thermal power (output) and available kinetic wind power (input); the turbine-to-heat efficiency is the coefficient of generated thermal power (output) and available rotational power from the turbine or its replacement (input). We decided to focus on the temperatures and efficiencies. In our understanding, they are relevant parameters to assess the technical potential of windthermal converters.

We noticed that the measured efficiencies and output temperatures vary significantly and assume that this results from the diverse experimental designs. If you are interested in more details, please refer to the cited references.

4.1 Compression-Based Windthermal Conversion. The general concept of compression-based windthermal conversion uses the rotational energy of the wind turbine blades to drive a pump or compressor, e.g., reciprocating compressor (Fig. 4). The compression of the working fluid increases its pressure, and, assuming an ideal gas as working fluid, its temperature will increase as a consequence. This effect can be observed in compressed air systems [35,36], but it is used in particular for heat pumps [11,22–24,42–44].

In the case of a liquid, the pump will accelerate the working fluid within the pipe system. Friction losses increase by the fluid’s velocity raised to the power of two, converting kinetic energy into heat. The installation of an orifice or throttle valve within the pipe system further increases heat generation [27,46–48]. We assume that this application is called “liquid extrusion” [28,40] or “liquid squeezing” [40] despite that the terms were neither elaborated within the provided literature nor found in further research.

Taiwanese researchers investigated a wind-powered refrigeration system. The prototype was an eight-vane horizontal-axis wind turbine, where the shaft was coupled directly to a compressor. Under different wind conditions, 6 liters of water were cooled down from 24 to 16 °C and from 23 to 10 °C [43]. The prototype was upgraded with an electric generator to provide continuous cooling. The only wind-powered refrigeration process cooled 30 liters of water down from 20 to 14 °C and from 15 to 6 °C within 55 min [44]. The same research institute investigated a similar project with a three-vane horizontal-axis wind turbine for cooling (refrigeration) and heating (heat pump) application. Results are presented for average wind speeds from 3 to 6 m/s after a total operational time of 60 min. Cooling was provided from 25 to 23 °C and from 23 to 3 °C; heating from 10 to 13 °C and from 10 to 25 °C, respectively [11].

For liquid squeezing, the analysis shows that hydraulic oil reaches temperatures up to 122 °C, but its change in viscosity limits heat transfer [27]. In the case of compressed dry air, coupling various windthermal converters in series heats the dry air up to ~600 °C [36].

The wind-to-heat efficiencies for the eight-vane wind-powered refrigeration system was reported from 10% to 33%, with increasing efficiency due to increasing outdoor temperatures [43]. In the second experiment, wind-to-heat efficiencies started from 45% to 60% [44]. In the case of the three-vane combined cooling and heating system, wind-to-heat efficiencies of the cooling processes started from 49% to 61%. The heating processes showed wind-to-heat efficiencies from 45% to 61% [43,44].

One experimental study in liquid squeezing presents turbine-to-heat efficiencies from 91% to 95% [46]. A long-distance heat transmission system is proposed for which the assessment evaluated a wind-to-heat efficiency of 40% [27]. Another study presented that a well designed compressed dry air windthermal

Table 2 Academic publications about windthermal energy sorted by category and then by brief description/conversion principle for applications/all others, respectively

Source	Pub. type	Category	Conv. princ.	Brief description
Tapiador and Chua (2018) [22]	J. (Q4)	Applic.	Comp.	Cooling system (cold storage room), small-scale horizontal-axis turbine driving a compression heat pump, conceptual system proposal
Klueter and Liljedahl (1981) [23]	J. (n.a.)	Applic.	Comp.	Heat supply (dairy) including ice storage, small-scale vertical-axis turbine driving a compressor, design, and performance analysis
Gunkel et al. (1985) [24]	J. (n.a.)	Applic.	Comp.	Heat supply (dairy), small-scale vertical-axis turbine driving a compressor, performance analysis, and simulation of energy supply
Kim et al. (2001) [25]	Conf.	Applic.	Frict.	Heat supply (greenhouse) including heat storage, small-scale vertical-axis turbine driving a Joule machine, conceptual system proposal, and proof of concept
Ma (2019) [26]	Conf.	Applic.	Frict.	Heat supply (greenhouse), small-scale horizontal-axis turbine driving a Joule machine, conceptual system proposal
Cheng et al. (2017) [27]	J. (Q1)	Applic.	Comp.	Heat supply (long-distance pipelines for district heating), large-scale horizontal-axis turbine driving a hydraulic pump, model building, and thermodynamic analysis
Zheng et al. (2017) [28]	J. (Q3)	Applic.	n.a.	Heat supply (oilfields), small-scale vertical-axis turbine (conversion principle not specified), analysis, and comparison of wind profile and heat demand (North China)
Yamaki et al. (2020) [29]	J. (Q1)	Applic.	Ind.	Heat supply (paper mill), large-scale horizontal-axis turbine driving a permanent eddy current magnet (standalone and integrated in wind-thermal energy systems), mathematical simulation of lifecycle greenhouse gas emissions
Chen et al. (2013) [30]	Conf.	Applic.	Friction	Heat supply (seawater desalination), small-scale vertical-axis turbine driving a Joule machine, conceptual system proposal
Hu et al. (2017) [31]	Conf.	Applic.	Frict.	Heat supply (seawater desalination), small-scale vertical-axis turbine driving a Joule machine, feasibility study
Addo-Binney et al. (2022) [32]	J. (Q2)	Assmt.	Comp.	Heat supply (space heating), small-scale horizontal-axis turbine driving a compression heat pump, conceptual system proposal, energy exergy analysis
Černeckienė and Ždankus (2015) [33]	J. (n.a.)	Applic.	Comp.	Heat supply (space heating), small-scale vertical-axis turbine driving a hydraulic pump, analysis and comparison of wind profile and heat demand (Lithuania)
Chen et al. (2019) [34]	Conf.	Applic.	n.a.	Heat supply (thermochemical storage, transported in containers), large-scale horizontal-axis offshore turbines (conversion principle not specified), conceptual system proposal
Swinfen-Styles et al. (2019) [35]	Conf.	Applic.	Comp.	Wind-powered thermal energy system including heat and compressed air storage, large-scale horizontal-axis turbine driving a compressor, conceptual system proposal
Garvey et al. (2015) [36]	J. (Q3)	Applic.	Comp.	Wind-powered thermal energy system, large-scale horizontal-axis turbine driving a compressor, concept study, and energy/exergy analysis
Sami (2013) [37]	J. (Q2)	Applic.	Frict.	Wind-powered thermal energy system, large-scale horizontal-axis turbine driving a hydrodynamic retarder, concept study, and energy/exergy analysis
Okazaki et al. (2015) [38]	J. (Q1)	Applic.	Ind.	Wind-powered thermal energy system, large-scale horizontal-axis turbine driving a permanent eddy current magnet, concept study
Karasu and Dincer (2018) [39]	J. (Q2)	Applic.	Ind.	Wind-powered thermal energy system, large-scale horizontal-axis turbine driving a permanent eddy current magnet, energy/exergy analysis
Cao et al. (2018) [9]	J. (Q1)	Assmt.	Comp., frict.	Techno-economic assessment of generic models of 5 different wind-powered thermal energy system configurations (heat pump, hydrodynamic retarder, combination of heat pump and hydrodynamic retarder, electrical boiler, electrical heat pump)
Su (2017) [40]	Conf.	Assmt.	Comp., frict., ind.	Economic assessment of 2 windthermal converters and 1 wind power converter (wind to power to heat)
Sobor et al. (2011) [10]	J. (n.a.)	Assmt.	Ind.	Technical assessment of windthermal converters versus wind power converters, comparison of heat/power output
Gunkel et al. (1979) [41]	Conf.	f. trial	Comp.	Small-scale vertical-axis turbine driving a heat pump, economic assessment and determination of optimal system design
Braymer et al. (1982) [42]	Conf.	f. trial	Comp.	Small-scale vertical-axis turbine driving a heat pump, design, and performance test
Ting et al. (2008) [43]	J. (Q1)	f. trial	Comp.	Small-scale vertical-axis turbine driving a heat pump (setup allows direct coupling to a heat pump or electricity generator), efficiency comparison of direct and indirect heat pump operation

Table 2 Continued

Source	Pub. type	Category	Conv. princ.	Brief description
Ting et al. (2011) [44]	J. (Q1)	f. trial	Comp.	Small-scale vertical-axis turbine driving a heat pump (set-up allows direct coupling to a heat pump or electricity generator), determination of cut-in windspeed
Jwo et al. (2013) [11]	J. (Q2)	f. trial	Comp.	Small-scale vertical-axis turbine driving a heat pump (setup allows direct coupling to a heat pump or electricity generator), efficiency validation for specific indoor and outdoor temperatures
Kim et al. (2005) [45]	J. (n.a.)	f. trial	Frict.	Joule machine (motor emulated wind turbine), performance test by varying rotational speed
Ždankus et al. (2016) [46]	J. (Q2)	Lab. trial	Comp.	hydraulic pump (motor emulated wind turbine), determination of optimal work regime
Ždankus et al. (2019) [47]	J. (n.a.)	Lab. trial	Comp.	hydraulic pump (motor emulated wind turbine), determination of optimal work regime, and opening degree of valve; determined heat energy
Ždankus et al. (2020) [48]	J. (Q1)	Lab. trial	Comp.	Hydraulic pump (motor emulated wind turbine), performance test by varying rotational speed
Kim et al. (2002) [49]	Conf.	Lab. trial	Frict.	Joule machine (motor emulated wind turbine), performance test by varying rotational speed, working fluid, and volume
Hamakawa et al. (2008) [50]	J. (Q4)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (motor emulated wind turbine), examination of cavitation effects
Mamonov et al. (2016) [51]	J. (Q3)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (two motors emulated wind turbine), examination of output temperatures by varying rotational speed
Saffar et al. (2016) [52]	J. (Q2)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (motor emulated wind turbine), investigation of design, material, fluid properties and efficiency, assisted with computational fluid dynamics
Yang et al. (2018) [53]	Conf.	Lab. trial	Frict.	Joule machine (motor emulated wind turbine), performance test by varying working fluids (water, hydraulic oil, sodium chloride solutions)
Serov et al. (2019) [54]	J. (Q1)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (two motors emulated wind turbine), performance test by varying working fluid viscosity and rotational speed
Mamonov et al. (2019) [55]	J. (Q2)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (two motors emulated wind turbine), examination of drag torque and heat output
Miskiv et al. (2020) [56]	J. (Q3)	Lab. trial	Frict.	Multi-cylinder Taylor-Couette system (two motors emulated wind turbine), analysis of flow structure
Liu et al. (2021) [57]	J. (Q2)	Lab. trial	Frict.	Joule machine (motor emulated wind turbine), performance analysis by varying layer number and working fluid, assisted with computational fluid dynamics
Chen et al. (2021) [58]	Conf.	Lab. trial	Frict.	Joule machine (motor emulated wind turbine), test of torque behavior by varying angular acceleration
Liu et al. (2011) [59]	J. (n.a.)	Lab. trial	Ind.	Permanent eddy current magnets (motor emulated wind turbine), examination of output temperatures by varying rotational speed
Sobor et al. (2013) [60]	J. (n.a.)	Lab. trial	Ind.	Permanent eddy current magnets (motor emulated wind turbine), examination of output temperatures and efficiency by varying input power and rotational speed
Makarchuk (2015) [61]	J. (Q3)	Lab. trial	Frict.	Permanent eddy current magnets (motor emulated wind turbine), examination of thermal power by varying rotational speed
Chen et al. (2016) [62]	J. (Q2)	Lab. trial	Ind.	Permanent eddy current magnets (motor emulated wind turbine), examination of output temperatures and eddy current distribution, finite element method
Bostan et al. (2018) [63]	Conf.	Lab. trial	Ind.	Permanent eddy current magnets, component testing and proposal of integration in small-scale horizontal-axis wind turbines to supply rural areas in Moldova
Shchur et al. (2021) [64]	J. (Q3)	Lab. trial	Ind.	Permanent eddy current magnet synchronous generator for a vertical-axis heat and power cogeneration turbine (motor emulated wind turbine), comparison of experimental results with MATLAB/SIMULINK simulation
Mujtaba et al. (2018) [65]	J. (n.a.)	Pf of concept	Comp.	Hydraulic pump for a small-scale vertical-axis turbine, calculation of heat output, MATLAB simulation
Katawaluwa et al. (2006) [66]	Conf.	Pf of concept	Frict.	Joule machine for a small-scale vertical-axis turbine, determination of optimal system design, MATLAB simulation
Chakirov and Vagapov (2011) [67]	Conf.	Pf of concept	Frict.	Joule machine for a small-scale vertical-axis turbine, determination of optimal system design, MATLAB/SIMULINK simulation
Fireteanu and Nebi (2008) [68]	J. (Q4)	Pf of concept	Ind.	Permanent eddy current magnets, analysis of dependences of induced power on rotor speed and on number of poles, finite element method
Tudorache and Popescu (2009) [69]	J. (Q2)	Pf of concept	Ind.	Permanent eddy current magnets, determination of optimal design, finite element method

Table 2 Continued

Source	Pub. type	Category	Conv. princ.	Brief description
Nebi and Fireţeanu (2010) [70]	Conf.	Pf of concept	Ind.	Permanent eddy current magnets for a small-scale vertical-axis turbine, analysis of electromagnetic fields, finite element method
Dirba and Kleperis (2011) [71]	Conf.	Pf of concept	Ind.	Permanent eddy current magnets for a small-scale vertical-axis turbine, determination of optimal design, finite element method versus analytical analysis
Makarchuk (2015) [72]	J. (Q3)	Pf of concept	Ind.	Permanent eddy current magnets for a small-scale vertical-axis turbine, calculation of electric and magnetic fields, finite element method
Tudorache et al. (2015) [73]	J. (Q3)	Pf of concept	Ind.	Permanent eddy current magnets, analysis of electromagnetic and heat transfer, finite element method
Tudorache and Melcescu (2016) [74]	J. (n.a.)	Pf of concept	Ind.	Permanent eddy current magnets; analysis of demagnetization level, rotor speed and electromagnetic torque; finite element method
Tudorache et al. (2017) [75]	Conf.	Pf of concept	Ind.	Permanent eddy current magnet synchronous generator for a horizontal-axis heat and power cogeneration turbine, electromagnetic field analysis, finite element method
Matsuo and Okazaki (2017) [76]	J. (Q2)	Pf of concept	Ind.	Permanent eddy current magnets for a large-scale horizontal-axis turbine, calculation of heat generation, finite element method
Tudorache et al. (2018) [77]	J. (Q3)	Pf of concept	Ind.	Permanent eddy current magnet synchronous generator for a horizontal-axis heat and power cogeneration turbine, analysis of performance and operation characteristics, finite element method
Grigorash et al. (2019) [78]	Conf.	Pf of concept	Ind.	Permanent eddy current magnets, determination of optimal design, numerical analysis
Cao et al. (2018) [79]	J. (Q3)	Pf of concept	n.a.	Windthermal Darrieus turbine (conversion principle not specified), assessment of turbine characteristics and mechanical energy output

Note: For journal articles, the SCImago® quartiles (Q1–Q4) indicate the quality of the publishing journals (Q1 = best 25%, Q4 = least 25%, n.a. = not assessed by SCImago®).

energy system with storage could reach an overall system efficiency above 85% [36].

4.2 Friction-Based Windthermal Conversion. Friction-based windthermal conversion uses the rotational energy of the

shaft to mechanically rotate an impeller submerged in a working fluid. The rotation of the submerged impeller generates heat due to friction losses among the working fluid's molecules.

The simplest application is an impeller directly coupled to a wind turbine that stirs a working fluid in a tank, which is equipped with baffles (Fig. 5). Most of the authors refer to this concept as “Joule

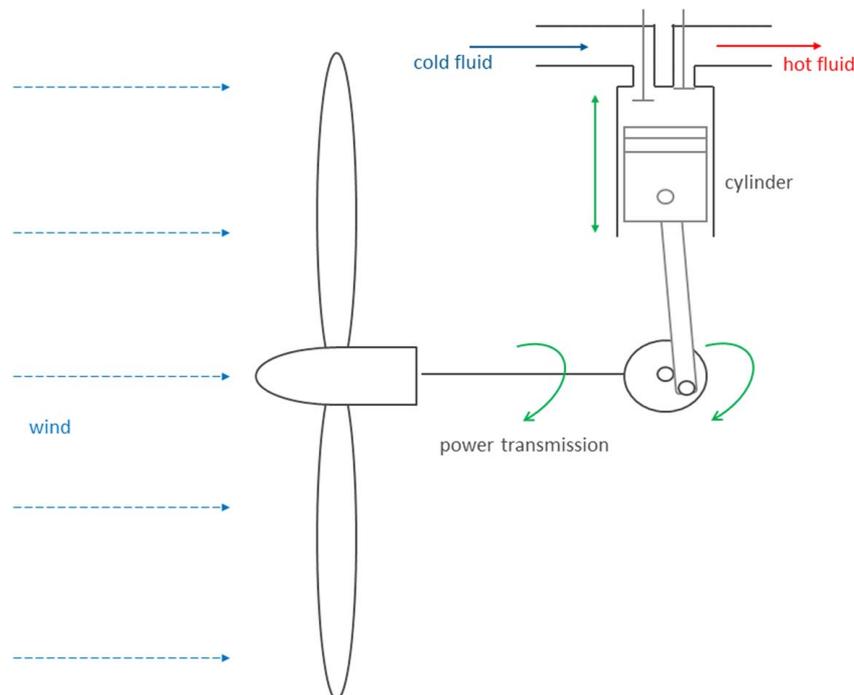


Fig. 4 Reciprocating compression-based windthermal converter

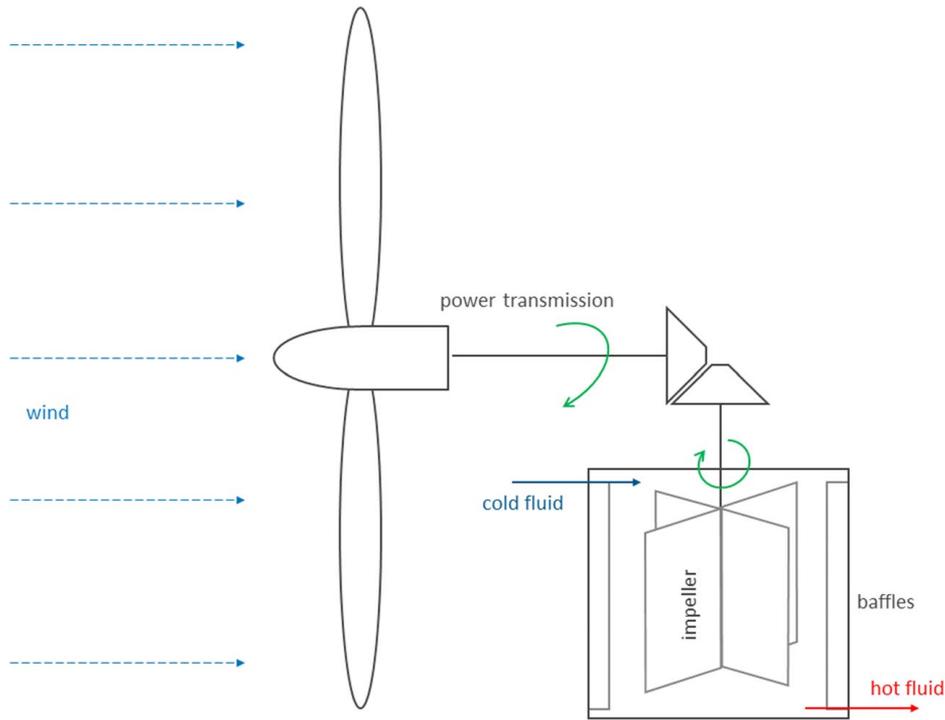


Fig. 5 Joule machine (friction-based windthermal converter)

machine” [10,63,66,67]; further terms are “agitation of fluid” [38], “liquid mixing and heating” [40], “liquid stirring” [31], “retarder” [9], “stirring heating device” [26], or “wind stirring machine” [53].

A more sophisticated application is a “hydrodynamic retarder” (Fig. 6), where the working fluid circulates inside a toroidal chamber formed by a rotor and a stator, both equipped with vanes. By rotating the blades, the clearance between the rotating and fixed parts of the chamber can be controlled. Since the fluid

needs to run through the space between the rotating and fixed part of the retarder, a braking torque is generated by viscous drag of the fluid [9,37].

A “multi-cylinder Taylor-Couette system” (Fig. 7) composed of two vertical-axis wind turbines that rotate in opposite directions and drive two coaxial rotating cylinders; these transfer heat to a fluid that flows in the gap between them [54]. A further term for this concept is “viscous heating” [52].

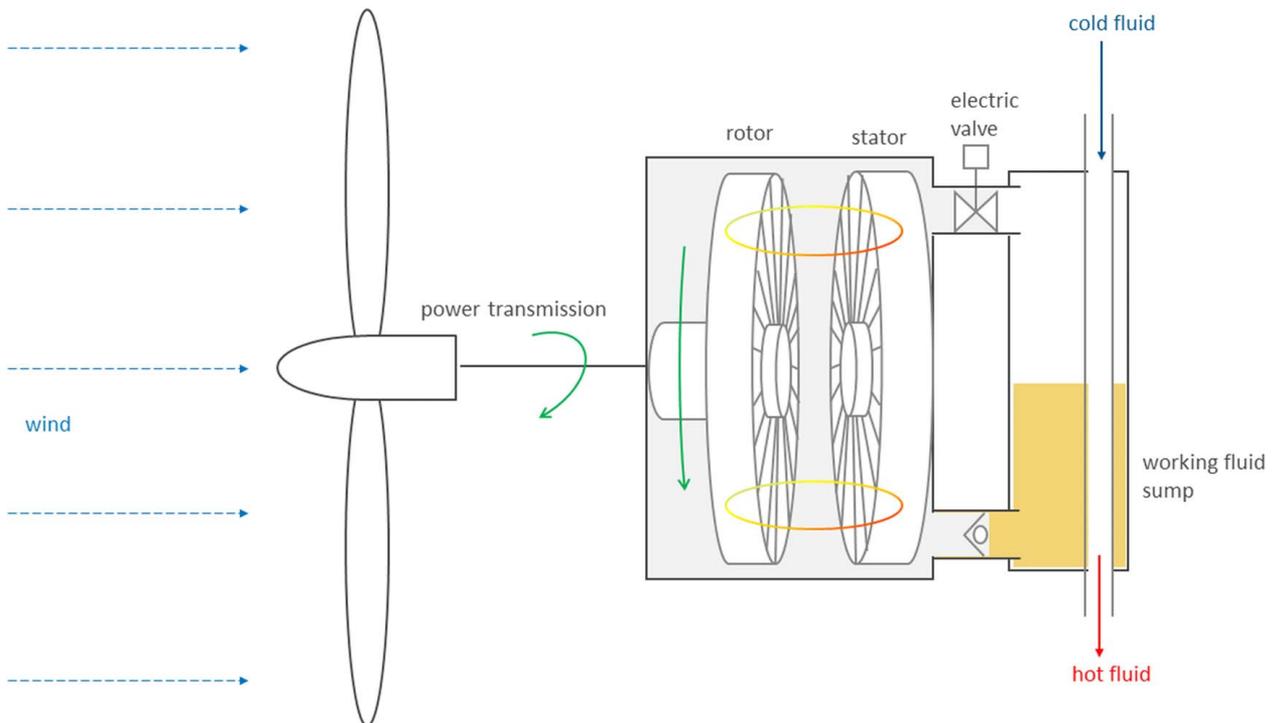


Fig. 6 Hydrodynamic retarder (friction-based windthermal converter)

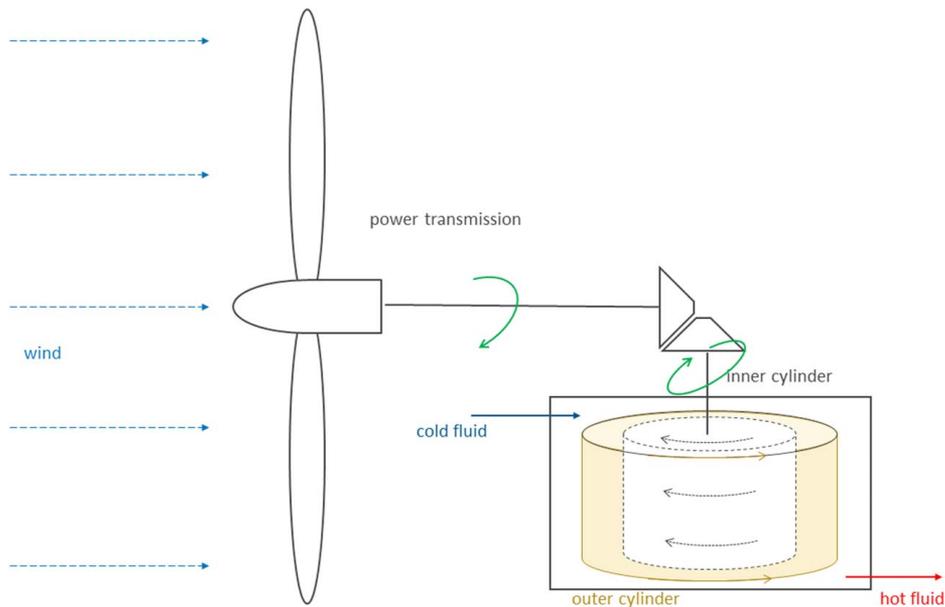


Fig. 7 Multi-cylinder Taylor-Couette system (friction-based windthermal converter)

For the sake of completeness, we mention “friction of solids” [28,38] as it is mentioned in the literature, but not further elucidated.

Researchers investigated the absorbed heat and the resulting temperature increase for different working fluids. Experiments with a Joule machine demonstrated that 70 liters of water and thermal oil were heated up to 78 and 87 °C, respectively, after 40 min (under constant rotational speed) [25]. In another laboratory trial, 20 liters of water, hydraulic oil, and saturated sodium chloride solution temperatures increased by 18, 25, and 28 K, respectively, within 1 h (under constant rotational speed) [53]. Similar research activities show that the temperature of 3 liters water (starting at 20 °C) increased within 1 h by 8 or 17 K when the rotor is rotating at 300 or 400 rpm [26]. In a computational analysis, the temperature of the outer cylinder of a Taylor-Couette system results in 62 °C [52].

In a field trial, thermal oil’s temperature (starting at 16 °C) increased by 6 K using a vertical-axis wind turbine. For this field trial, the author concluded that the size of turbine and gear system was not proper for heat generation at the installed wind site [45].

The authors reported several efficiencies for Joule machines. For 300–500 rpm and working fluids like oil, water, and sodium chloride, turbine-to-heat efficiencies for highest rpm are 27%, 40%, and 45%, respectively [53]. In a different setup, the turbine-to-heat efficiencies using water were reported to be 62% [25] and 68% [49]. One experiment investigated the turbine-to-heat efficiency for three different rotor structures. Results show that an optimized rotor structure increases the turbine-to-heat efficiency from 81 to 91% [57]. For a multi-cylinder Taylor-Couette system, the turbine-to-heat efficiency is close to 100% [50].

The authors point out that higher rotational speeds [25,26,52,53], high-viscous working fluids [25,52], high-density fluids [57], and maximum filling of the tank [49,57] will generate more heat.

A torque limiting coupling decreases the starting torque of a Joule machine from 2.2, 4.0, and 7.2 Nm to 0.68, 0.9, and 1.46 Nm, respectively [58].

4.3 Induction-Based Windthermal Conversion. Induction-based windthermal conversion (Fig. 8) uses the rotational energy of the wind turbine blades to mechanically rotate a conductor loop within a magnetic field. The conductor perceives the permanent magnetic field as alternating magnetic field due to its rotation. The alternating magnetic field induces a voltage, which leads to the

flow of eddy currents in the conducting material and as a result to the dissipation of heat. Magnetic conductors dissipate additional heat through the effect of magnetic hysteresis [78]. Alternatively, the permanent magnets can be rotated around a static conductor, resulting in the same induction heating effect.

Most of the authors refer to this concept as “eddy currents” [10,59,69–71,76]. Further denominations are “induction heater” [78], “induction retarder” [9], “electromagnetic induction” [34,38,39], and “magnetic vortex” [28].

Literature suggests that induction-based windthermal converters can achieve temperatures up to 560 or 600 °C for wind thermal energy storage or induction retarder, respectively [38]. In the case of a paper mill application, an induction-based converter is considered to provide steam at 500 °C [29]. Experimental results show that the water was heated from 10 to 16 °C for a 1.2 kW motor-simulated prototype [62] and from 26 to 40 °C with a maximum eddy current power of almost 3.8 kW [60].

The turbine-to-heat efficiency for induction heating is from 70% to 91% [60] and from 96% to 99% [62]. In the case of a cogeneration induction system, the turbine-to-heat efficiency considering electricity and heat generation was calculated as 90% [77]. Furthermore, it was concluded that windthermal energy supplies from 6% to 18% more energy than conventional wind power in warm and in cold season, respectively [10].

Another study developed the optimal designs of induction-based windthermal converters up to 10 kW [61].

5 Technology Maturity of Windthermal Converters

We found that windthermal energy conversion is still an immature technology. According to the DOE technology readiness levels, we assessed that most windthermal converters reach TRL 3 and only compression-based converters reach TRL 6 (Table 3). Nevertheless, the concept is promising, and most of the system components are commercially available. In a next step, a full-scale prototype of a windthermal converter will level this technology up to TRL 7. All validated concepts have in common that the heat generation is on the ground; hence, a full-scale prototype with a heat converter in the nacelle of a vertical-axis wind turbine should be build and evaluated.

Proofs of concept, applications, and assessments reach TRL 2; hence, they are still limited to analytic studies. The laboratory

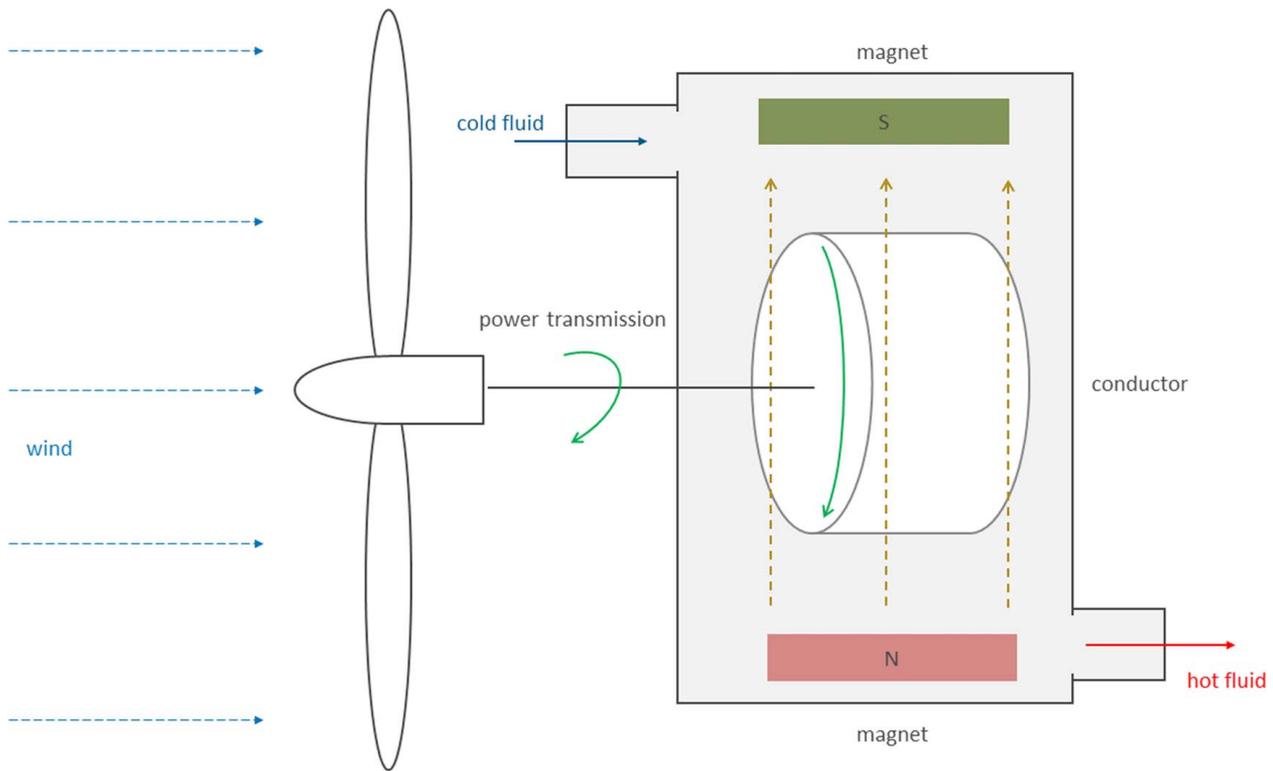


Fig. 8 Induction-based windthermal converter

trials reach TRL 3; hence, a motor simulates the rotor. The field trials reach TRL 6; hence, pilot-scale windthermal prototypes were tested in a relevant environment. TRL 1 does not appear in this list; hence, the basic principle, the conversion of rotational energy into heat, is a well-known effect. TRL 4 and TRL 5 do not appear; hence, a laboratory-scale wind turbine—a crucial system component—is unreasonable.

Proofs of concept (TRL 2) were conducted for induction and friction. Apparently, three researcher groups independently analyzed permanent eddy current magnets applying the finite element method [60,69,70,72–74,76]. The optimal design of small-scale vertical-axis induction-based [78] and friction-based [66,67] windthermal converters were determined. It is important to note that the windthermal converter shall match the wind turbine's torque-speed characteristic.

Laboratory trials (TRL 3) were conducted for all three conversion principles. The experiments proofed the concepts and demonstrate that the heat generation is positively correlated with viscosity [48,52,53] and temperature [46] of the working fluid, and with rotational speed of the wind turbine [46,52,59]; the experiments also

demonstrate that the heat generation is negatively correlated with the volumetric flow rate of the working fluid [46,62].

All field trials (TRL 6) that are described in the identified literature that were only conducted with compression-based windthermal converters. Two researcher groups coupled mechanical heat pumps directly with a wind energy turbine [11,42–44]. They showed that the direct wind-driven mechanical heat pump is 10% more efficient than an electrical wind-driven heat pump [11] and that the compressor powers up at a wind velocity of 6 m/s [44]. Nevertheless, some friction-based windthermal prototypes, which are not mentioned in the literature, were running in the 1970s in Denmark [80].

6 Windthermal Application Scenarios

We found several applications of windthermal turbines in the literature, which we primarily categorized into medium- and low-temperature applications. On the one hand, large-scale windthermal converters could supply heat for industrial processes (up to 600 °C), including district heating and demand-oriented generation of

Table 3 Technology readiness of windthermal converters

TRL		Conversion principle		
TRL	TRL definition [17]	Compression	Friction	Induction
TRL 9	Actual system operated over the full range of expected mission conditions			
TRL 8	Actual system completed and qualified through test and demonstration			
TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment			
TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	X		
TRL 5	Laboratory scale, similar system validation in relevant environment			
TRL 4	Component and/or system validation in laboratory environment			
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	X	X	X
TRL 2	Technology concept and/or application formulated	X	X	X
TRL 1	Basic principles observed and reported			

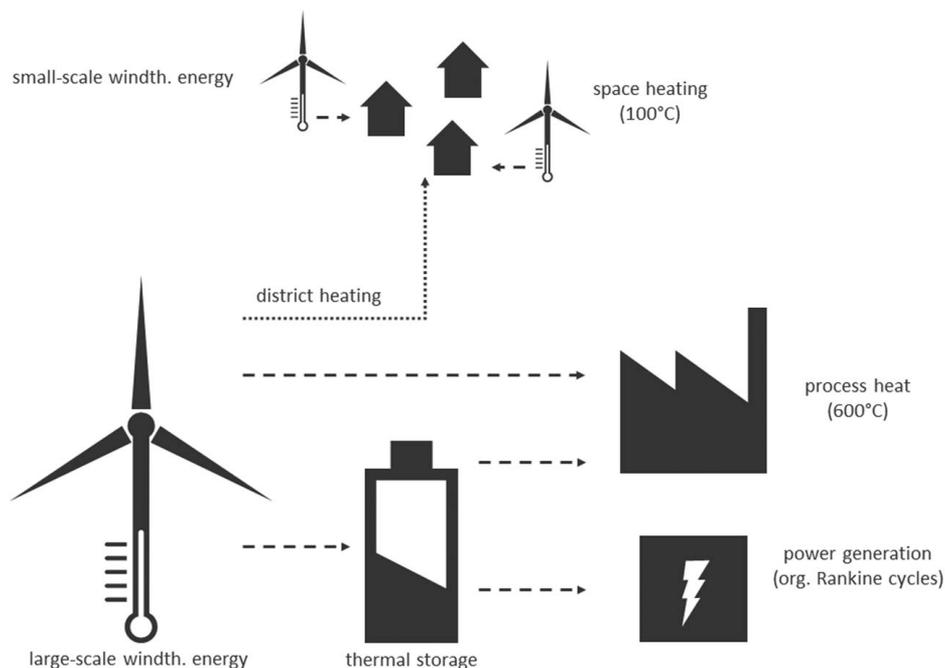


Fig. 9 Windthermal energy applications

electricity via multimegawatt-scale heat storages (Fig. 9), and on the other hand, small-scale windthermal converters could supply space heat (up to 100 °C) on-site. We start with a more detailed description of these applications, consider then possible technological substitutes, and conclude this section with a SWOT analysis where we point out positive and negative factors of both technologies. A summary of these factors is given in a SWOT matrix (Table 4). We further introduce the findings of the technology's economic potential.

Large-scale windthermal turbines and windthermal parks are recommended for industrial purposes since they can theoretically provide output temperatures up to 500/600 °C [36,38]. In most of these applications, a central multimegawatt heat storage is proposed

to stabilize the heat supply. The heat can be distributed via district heating or directly used as process heat for different industries, e.g., paper mills [29], greenhouses [26], breweries/distilleries [9], seawater desalination [31], oil fields [28], wine making, cattle farms, and tea processing [78]. Wind-powered thermal energy systems can also supply electricity to the grid when compromising a thermal engine (e.g., an organic Rankine cycle) to generate electricity.

Small-scale windthermal turbines are recommended for commercial and residential space heating: Considering the wind profile of Lithuania, a 2 kW windthermal turbine can cover up to 76% of a residential building's heat consumption [33], and in cold regions like Canada, a windthermal turbine is the best option to improve

Table 4 Strengths, weaknesses, opportunities, and threats for windthermal turbines

Strengths	Opportunities
Heat demand and supply correlate	Decarbonize the heating sector
Residential sector consumes more heat than electricity	Grid-independent operation
Location-independent and cost-effective storage solutions	Potential market for renewable heating solutions
Generator and other electric components are dispensable	Dispensability of gearboxes
Conversion of kinetic to mechanical energy does not differ to conventional wind turbines	Operation at a wider range of wind speeds
	Less noises and fewer vibrations
	Lower costs
	Lower nacelle weight
	Easier maintenance/smaller breakdown possibility
	Governmental support
	Simpler construction ^a
	Higher acceptance in society ^a
	Built closer to houses ^a
	Integrate in existing fluid systems ^a
	Improvement of the local air quality ^a
Weaknesses	Threats
Heat is a low-grade energy	Availability of the heat supply
Technical immaturity	Realization uncertainties and efficiency issues regarding the heat transport and storage solutions
	Possibly too low efficiencies and thus noncompetitiveness
	Shrinking acceptance for wind turbines/parks

Note: Due to the technical immaturity, many advantages and disadvantages are not yet proven and therefore listed as opportunities and threats.

^aValid only for small-scale applications.

the efficiency of residential space heating systems [32]. A 5 kW windthermal turbine can cover up to 42% of a dairy farm's heat consumption [24]. Most of the proposed applications are friction based and convince with technical simplicity. The researcher's goal is mainly to provide cost-effective renewable technologies in the heating sector [46,48,67]. Some articles also focus on autonomous households in secluded areas [9], while other focus on heating applications for smart homes [46].

6.1 Technological Substitutes. *Large-scale* windthermal turbines provide process heat for temperatures up to 600 °C. Hence, they could supply 40% to 70% of European member states' industrial heat demand [81], which is currently based on process heating technologies like furnaces, boilers, and cogeneration [82]. Worldwide, process heat is provided predominantly by fossil fuel combustion [83]: 80% of the sold heating technologies in 2019 were either fossil fuel-based or conventional electric equipment [84] and renewable heat is not even on the radar of the US Department of Energy [85]. Fully developed windthermal turbines could be a main driver of the renewable transition of the heating sector balancing the three dimensions of energy sustainability. Nevertheless, the leveled cost of energy must be competitive not only in comparison with the mentioned fossil technologies but also with other renewable heating solutions. Especially wind-powered thermal energy systems must show that they can compete for space and resources with other wind energy storage applications (e.g., pumped hydro, compressed air, flywheels, batteries, superconducting magnets, or super capacitors [86]) and other innovative concepts like wind turbines with compressed air storage [87]. Further competing technologies are concentrated solar power, large-scale geothermal energy, and biomass [38].

Small-scale windthermal turbines provide space heating and must compete with other technologies that provide temperatures up to 100 °C. Currently, the market is based on fossil fuels: In Germany, for example, gas and oil boilers share 50% and 25% of the market, respectively [88]. It is foreseen that these will be replaced with power-to-heat applications like electrical heat pumps or boilers [46] or other renewable technologies like solar thermal energy.

6.2 SWOT Analysis. *Strengths:* In 2018, about 50% of the global final energy consumption were used for heating and cooling, which in turn split up into process heating (50%), space and water heating (46%), and lastly for cooking and agriculture [89], and only 22% of the total energy used for heating and cooling were produced from renewable sources [90], which indicates that there is a potential market for renewable heating solutions [48]. In particular for the residential sector, there is a correlation of demand and (hypothetical) supply by windthermal turbines [32,42,46,48,91] because of higher average wind speeds in Europe and Canada in winter [32,92]. Another aspect regarding this sector is that more heat than electricity is consumed [48]: 78% of the total energy consumption by European households accounts for space and water heating [93]. Currently, the wind's unsteady nature and thus variations in the energy supply result in the two problems of supply availability and cost-generating excess generation. Energy storages can solve these problems by enhancing grid flexibility and controllability [86], but they face the problems of either being location dependent (e.g., pumped-hydro storage plants or compressed air reservoirs) or having high capital costs (e.g., lithium-ion or redox flow batteries) [9]. Molten salt storages and thermal storages are proposed as location-independent and cost-effective storage solutions that can be charged by windthermal converters [38,39]. Economically and technically relevant is also that the generator and other electric components are dispensable [9,34,40,60]. The basic principle to convert the wind's kinetic energy into mechanical energy does not differ from conventional wind turbines. Hence, the research and development of wind turbines benefit windthermal energy systems. Examples of ongoing research activities for wind power are: wind farm

layout design [94,95], turbine power output optimization [94,96], resource mapping [97], and utilizing wind turbines to reach net zero energy facilities [98].

Weaknesses: The most crucial weakness is the immaturity of wind thermal energy applications; hence, price and performance today and in the future are uncertain [99]; appropriate algorithms and control laws need to be developed [64]. Until now, only horizontal-axis wind turbines reached marketability, but most of the considered solutions convert the heat on the ground. Furthermore, heat is low-grade energy: Electricity can be converted to 100% into heat, but vice versa the conversion efficiency is low [34,38,66]. Additionally, the community acceptance for wind projects [38,46], which is strongly tied to noise, visual and socio-economic impacts [100], is of importance as well.

Opportunities: As a technology which uses the renewable energy source wind, windthermal energy could decarbonize the heating sector [29,46], thus being part of many countries' strategy to a zero carbon society; in particular with the option of location-independent and cost-effective (thermal) storage systems.

Many opportunities result from the dispensability of the generator and other electric components. They make up to 15% of the total costs and up to 6% of the total weight of wind power converters [101]. In the absence of these requirements and conditions resulting from the use of generators, the following opportunities for windthermal turbines are identified: grid-independent operation [27,39,48], dispensability of gearboxes [54,76,102], operation at a wider range of wind speeds [27,31,38,46,48,53,78,91,102], less noises and fewer vibrations than conventional wind turbines due to lower turbine speeds [54,102], lower costs [9,34,60,102], lower nacelle weight [9,38,76,102], easier maintenance, and smaller breakdown possibility [76,102]. A novel transmission system can tenfold the transmission distance of district heating pipelines [27]. Windthermal offshore turbines in combination with storage applications in containers that can be transported on ships to the shore, instead of installing submarine cables, which could reduce the capital the costs of offshore wind parks, especially if they are far away from the shore [34].

For small-scale turbines, further opportunities are simpler construction [31,40,53,60] with less noises [31,78] as well as a higher acceptance in society [46]. It is suggested that small-scale windthermal converters can be built closer to the load [46,78] and are easier to integrate in the existing fluid systems [48]. As many researchers aim to provide a cost-effective and environmental-friendly alternative to heating with fossil fuels or wood [40,46,53,54,60,67,78], additional opportunities are an improvement of the local air quality, partly due to the reduction of haze and soot particles in the air [27] and also governmental support for transiting to environmental-friendly technologies [46,91].

Threats: The most severe threats are the availability of the heat supply of windthermal energy due to fluctuations of the wind energy [38,91], realization uncertainties [9,27,34], and efficiency issues [39] regarding the heat transport and storage solutions. Furthermore, efficiencies of these technologies could be lower than the technological substitutes [34,39,91,103], resulting in noncompetitiveness of windthermal energy.

6.3 Economic Potential of Windthermal Converters. So far, only a few authors provided an economic evaluation of the technology, but it is likely that windthermal energy can compete with current gas prices (in 2020 European households paid around 0.07 EUR/kWh) [104].

One study presents a simplified (excluding finance and maintenance costs) leveled cost of energy for a windthermal system including heat storage, also referred as wind-powered thermal energy system. Assuming a lifetime of 20 years, the leveled cost of energy results in less than 5.00 JPY/kWh (~0.05 USD/kWh) [38].

In addition, one comprehensive study analyzing the economic potentials of wind-powered thermal energy systems states that

multimegawatt wind energy converters using either heat pumps (compression) or retarder (friction) yields an average levelized cost of energy of 0.08 EUR/kWh (~ 0.10 USD/kWh) with a standard deviation of 0.03 EUR/kWh (~ 0.03 USD/kWh) [9].

Furthermore, the utilization of windthermal converters as partial load for cooling application is an economically feasible technology within a payback period of seven years [22].

Another problem is the transport of energy from remote windy areas to the consumers. Two different concepts for long-distance heat transmission and their feasibility are proposed. One concept encompasses the use of ammonium-sulfate solution, which will be pumped from the windthermal converter to the heat demand site, possibly industries or residential areas. The study concludes that the levelized cost of energy for that system is at 0.06 USD/kWh [27]. The other concept suggests using heat storage containers in remote offshore heat farms. The financial advantage results from using cheaper transport vessels than installing expensive offshore transmission cables, making the transmission concept feasible [34].

7 Conclusion

This systematic literature review answers all research questions raised in Sec. 2.

- (1) Sixty-one publications comprise probably all English academic literature about windthermal energy. The most promising windthermal literature to start are the publications from Jwo et al. [11] (field trial) and Żdankus et al. [48] (laboratory scale) that describe experiments on two different compression-based windthermal applications, the publications from Liu et al. [57] (laboratory scale) and Serov et al. [54] (laboratory scale) that describe experiments on two different friction-based applications, and the publication from Chen et al. [62] (laboratory scale) that describes experiments on an induction-based application. The concept of wind-powered thermal energy systems was introduced by Okazaki et al. [38], and the article is worth reading.
- (2) The term “direct wind heat” is recommended for future literature selection processes.
- (3) Compression (heat pump), friction (Joule machine, hydrodynamic retarder, multi-cylinder Taylor-Couette system), or induction-based (permanent eddy current magnets) conversion principles are identified.
- (4) The overall technology maturity reaches a technology readiness level of 3. The analytical predictions for all conversion principles are validated for laboratory-scale subsystems, where a motor replaces the wind turbine. Only pilot-scale compression-type windthermal converters are validated in relevant environment.
- (5) Possible applications are wind-powered thermal energy systems, heat supply for industrial heat processes (paper mills, greenhouses, seawater desalination, oil fields), space heating (residential buildings, farms), and district heating (pipelines or containers).
- (6) Possible substitutes are any kind of conventional or renewable heating device, or power-to-heat applications. Wind-powered thermal energy systems could substitute any electrical power plant, especially wind parks with storage.
- (7) The main opportunities are potentially lower capital costs and a higher efficiency than electrical wind turbines. The main disadvantage is the immaturity of this technology, and it is uncertain if this new technology will survive market competition.

Windthermal energy could contribute to solve the energy trilemma because it is a renewable heat source (environmental sustainability), decentral, and cost-effective—and therefore affordable and accessible—(energy equity) and nonintermittent in combination with storage (energy security). However, the technology is still on laboratory scale, and it is about time to validate the

techno-economic advantages on a full-scale prototype. A proof of concept lacks for horizontal-axis windthermal converters, where transporting the heat from the nacelle to ground would be a main challenge. The pipes and pumps for the heat transfer could possibly drive the costs and must be further assessed.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. Data provided by a third party listed in Acknowledgment. No data, models, or code were generated or used for this paper.

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