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Energy Savings Analysis in Logistics of a Wind Farm Repowering Process: A Case Study

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Abstract: The process of wind farm operation requires proper logistics services, consisting of the supply of all resources necessary in this process. A critical moment in the operation of wind farms is the implementation of the repowering process, in the form of replacement of the basic elements of wind farms: blades, hub rotors, nacelles or even towers. The replacement of these basic elements of the wind farm relates to the necessity to provide logistics services for heavy and oversized deliveries. Therefore, this article presents a unique analysis of logistics processes related to wind farms. Therefore, the aim of the article is to identify the most energy-saving variant of logistics service of the wind farm repowering process. However, the criterion of selecting the optimal variant is based on the original methodology of energy consumed during logistics services, as opposed to the traditionally used cost-effectiveness criterion. The SolidWorks software with other methods and tools were used for this purpose. As a result of the conducted research, it was found that the differences in individual variants of logistics service implementation may range from 4.7% to even 19.4% in terms of energy savings. Due to the increasingly common need to implement the process of repowering wind farms, the presented original methodology for the analysis and selection of the delivery variant with lowest energy consumption fills the literature gap and formulates a model of business practice, thus constituting both theoretical and practical value.

Keywords: renewable energy; wind farms; energy savings in logistics



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1. Introduction

The main global dilemma is very often the question of what the source of energy will be. Fossil resources will most likely continue to be an important source, but the time of their widespread use is over in favor of renewable energy. Wind power is the second source of renewable energy after the gravitational energy of water (hydropower). It is estimated that in 2020 its production volume amounted to 733 GW, which accounted for 26% of the total production of energy from renewable sources [1]. The importance of wind energy production is increasing. In order not to exceed the average temperature increase of 1.5 °C (2.7 °F) above the average temperature of the pre-industrial period, in line with the Paris Agreement, the amount of renewable energy production in total energy production should increase from 2799 (25% share) to 10,000 GW (90% share) in 2050 [2]. This means that the production of energy from both offshore wind farms and onshore wind farms should also increase significantly from the current 733 GW (2020) to the planned 7 TW (2050), which sets the trend 10-fold increase in the production capacity of wind farms in the next 30 years [2].

The operation of wind farms covers many aspects: political, technological, environmental, economic, including logistical. The economic issues focus primarily on the economics of energy production and consumption, but also energy efficiency, storage, relation to economic growth, policy, etc. One of the basic challenges of energy economics, which is also reflected in this article, is the proper shaping of the relationship between

reducing energy consumption, thus supporting economic development and reduction of CO₂ emissions. In the search for ways to meet this challenge, logistics, understood as supply chain management, responsible for providing all necessary resources for the process of energy production, storage, and distribution, appears to be an important area of improving energy efficiency.

The logistics aspect discussed in this article concerns the issue of providing all the necessary resources in the process of wind farm operation, in particular at a critical moment, i.e., at the end of the 15-year technological life cycle of a wind farm. This moment is inextricably linked with the necessity to decide on the further use of the wind farm, or its utilization [3]. Making a decision about further use implies the process of the so-called repowering, i.e., restoring the farm to full energy production capacity by replacing its main elements; rotor blades, rotor hubs and sometimes also nacelles. From the logistics point of view, the repowering process is a complex undertaking, as it concerns the deliveries of oversized and heavy goods. The rotor blade length can be 49–59 m. The rotor weight is 38 tons, the nacelle 66 tons, and the weight of the tower 275 tons! If producers of these elements in the discussed case are located approx. 1500 km from the target installation site, the logistic problem becomes a serious issue. To deliver the replaced elements of the wind farm a decision on the delivery service conditions, the mode and means of transportation, logistics operator, route, time of the entire process, and many other factors must be considered. Additionally, there is a trade-up problem resulting from the interdependence of both processes, i.e., repowering and logistics. Replacing elements with better ones, with higher parameters, will result in higher logistic costs associated with the delivery of longer and heavier elements, but on the other hand, greater possibilities of electricity production.

Despite the rich publishing achievements in the field of energy economics [4] or logistics management [5], it was found that the problems of logistics in relation to energy are few. There are publications on electric vehicle solutions in urban logistics [6], the use of biomass in supply chains [7,8], minimizing energy consumption in last mile logistics [9,10], optimizing automotive solutions in the context of reducing energy consumption [11,12], reducing logistics costs to minimize cost of energy [13,14], the impact of logistics on the reduction of costs of offshore wind energy [15], the possibility of reducing energy consumption in food logistics [16], or the utilization of logistics capacity to improve its energy efficiency [17].

However, there are no publications directly related to the logistics of oversized and heavy cargo for the wind farm repowering process. As a result, the optimization methods proposed in the above-mentioned literature can be used to a limited extent, especially optimization of the transport route or the use of more energy-efficient logistics infrastructure and superstructure. Few publications extend the issues discussed by the studies on modularity of services as a way to increase the energy efficiency of logistics services [18]; the potential use of Industry 4.0 technology to optimize energy consumption in logistics processes [19]; tools for energy analysis of a synchromodal supply chain [20]; however, their adoption to the delivery of heavy and oversized goods for repowering purposes is also limited.

Therefore, it seems that the area of research aimed at applying logistics to achieve energy savings in the light of literature research is entirely justified. The finding of a research gap implies the following research questions:

- how to organize the logistics of the repowering process?
- how to determine the delivery variants?
- how does logistics contribute to energy savings and production?

Hence, the purpose of this article is to analyze delivery variants of oversized and heavy goods according to the energy consumption criterion for the repowering process on the example of the onshore wind farm located in Treffendel (Brittany, France). The originality of the study results from the applied methodology of assessing and selecting the most energy-saving delivery variant. Contrary to the traditionally used cost-effectiveness criterion, the main criterion in this case is the lowest energy consumption. The presented

methodology for the analysis of various supply options is formulated at a high level of detail, and the energy consumption criterion adopted to identify the right delivery variant is an original solution enriching the theory of energy economics and logistics. The seriousness of the problem results from the repeatability of the repowering processes carried out, not only in Europe, but on a global scale. Developing an appropriate methodology of analysis in the logistics of repowering process may constitute a business practice for many similar undertakings. It can also be a supplement or an alternative to analyses based on traditional cost selection criteria.

The structure of the article consists of theoretical, methodological and research results, followed by a discussion and conclusions. The theoretical part includes two sections, i.e., literature review and theoretical approach, which stands for an introduction to the problem, justification of its importance, and theoretical foundation to the case study. The methodological part describes the case study as a research method followed by the methodology of identification, assessment, and selection of delivery variants with a special focus on the methods, tools and results related to the collection and analysis of data. The next section presents case study results, especially the context and decision situation of the analyzed wind farm in Treffendel; formulation of delivery conditions, identification and assessment of delivery options, and final findings in the form of the most energy-saving delivery variant No. 3. In the discussion section, references were made to the obtained results followed by the comparison of the obtained results with the literature ones. The practical and theoretical contribution of the study is also emphasized. The conclusions refer to the obtained results and indicate further directions of possible research.

2. Literature Review

Publications related to the issue of energy savings in logistics of a wind farm repowering process are falling mainly into two scientific disciplines as economics of energy and logistics, obviously not excluding related research within other disciplines in the field of technical or social sciences.

Literature on energy economics covers a wide range of studies focused on:

- economic efficiency of energy production, storage and consumption;
- energy market;
- energy policy;
- management of energy infrastructure;
- environment and energy sustainability [21].

In a more detailed scope, publications on energy economics in the field of energy policy present for example research results on policy of controlling energy consumption. An example is the original publication of Hartono and Resosudarmo [22], in which, on the basis of Indonesia Energy Social Accounting Matrix, they identified many scenarios of the impact of government decisions on improving energy efficiency on the budgets of different household groups, coming to the conclusions that “a policy improving the efficiency of energy use is relatively better than a policy restricting the use of energy” (p. 1416). In the area of environment and energy sustainability, with political implications a work of Oluoch et al. [23] is worth mentioning. Based on 1020 surveys in Kenya, they found that 73% of Kenyan respondents strongly approve the development of renewable energy, 64% of whom prefer wind energy, right after solar (94%). In the field of the relationship between reducing energy consumption, economic development, and greenhouse gas emissions, an interesting paper related to empirical evidence from China is proposed by Wang et al. [24]. Other studies present detailed results on economic evaluation of energy storage technologies [25]; economic evaluation of energy projects [26]; energy production, transmission and distribution costs [27]; optimization of power equipment and systems according to economic criteria [28]; energy trading [29], energy prices [30], renewable energy sources [31], etc. It can be stated that the main research direction of the above cited studies is the search and application of methods and tools that increase the economic

efficiency of energy, which is basically defined as the ratio of output of energy, to input of energy [32].

The above-mentioned energy efficiency imperative is specific to any objects. One of them are wind farms, which, apart from their basic task of generating electricity from wind energy, are looking for ways to reduce energy consumption for their own operations and, preferably, increase energy production at the same time. This research area is occupied mainly by the literature on the economics of wind farms [33], which focuses above all on the issues of economic drivers for wind energy, wind farm investment costs, operating costs, and levelized cost of energy [34]. The cost aspect dominates in economic analyses at every stage of the wind farm's life cycle, including the decommissioning stage. One of the possible options for decommissioning is a wind farm repowering process, which is aimed at restoring wind energy production after the end of the farm's life cycle [35]. This issue is also widely represented in the literature. In particular, Adedipe and Shafiee [3] have a significant contribution to the study of the cost structure incurred at the repowering stage. The cost aspect is also dominant in Poulsen et al. works [13,15]. Apart from the cost aspect, the repowering process is assessed according to investment [36], environmental [37], or technological criteria [20]. Multi-criteria optimizations [38] are also performed, including scenarios for repowering wind farms [39]. Many works emphasize that the repowering process is complicated and requires a lot of activities [40]. One of them, which significantly determines the economics of wind energy, is logistics.

As stated by Poulsen et al. "logistics may conservatively amount to 18% of the levelized cost of energy for offshore wind farms" [15] (p. 1), thus taking logistics as the object of literature review seems to be justified. Logistics is generally defined as the management of supply chains, and its essence is to deliver goods with related information from point of shipping to the point of destination according to delivery terms [5]. The above understanding of logistics should be actualized by the current aspect of the vulnerability and resilience of supply chains to disruptions caused by the COVID-19 pandemic. In this respect, the work of Ferreira et al. [41] is worth citing. This study found that "small and medium-sized enterprises (SMEs) do not have a codified supply chain and that generally, these companies have a minimal budget, which requires a constant search for new suppliers that represent a reduction in costs" [41] (p. 12).

The above-cited findings also mean that supply chains, including logistics, play an ever-increasing role in relation to the process, which requires delivery of goods and thus formulates delivery terms in relation to logistics activities [42]. For example, logistics can support the repowering process by providing it with all the necessary goods in accordance with repowering delivery requirements. In striving to meet delivery conditions, it is necessary to perform many logistics activities. They are structured within a supply chain, a kind of logistics support system, which, according to the supply chain operations reference model (SCOR), can include the following core processes: plan, source, make, deliver, return, and enable [43]. In particular, logistics of the repowering process covers above all planning activities (determining delivery conditions, identifying and analyzing delivery variants), and executive activities, i.e., delivery, mainly in the form of transport and the transport route security [3]. The logistics literature emphasizes that planning decisions regarding the assessment and selection of a given delivery variant should consider many customer requirements, in particular the type of cargo, quantity, dimensions, weight, distance, delivery time, no damage and cost [44], while practice proves that inexpensive delivery criteria are boundary conditions to be achieved at least cost [45]. This is also confirmed by multi-criteria studies, which show that uneconomical delivery criteria are given less weight, while economic ones, including costs, are given the highest [46]. Perhaps for this reason, there are no publications that would contain the results of the analysis of delivery variants according to the criterion of energy consumption.

In particular, the literature on cross-cutting issues covering the common area of energy and logistics was analyzed. The data records obtained from the search of the database of all MDPI journals from 1996 up to 18 June 2021, 20:22, show that out of 24,132 all publications

in the “Energies” journal, 10 publications contain the category ‘logistics’ and ‘energy’ in the title or in the keywords, plus 13 publications in other MDPI journals. Their content analysis shows that only 12 publications out of 23 deal with the following issues of logistics and energy, which can be grouped into two categories of publications on:

- (a) energy applications for logistics:
 - battery electric logistics vehicles as solutions for urban logistics [6];
 - review of metaheuristics for managing bioenergy supply chain problems with biomass supplies [7];
- (b) logistics applications for energy:
 - evaluating logistics activities for the agricultural pruning-to-energy [8];
 - last-mile logistics scheduling to minimize energy consumption [9];
 - a multi-echelon city collection and distribution system for energy efficiency, sustainability, and emission reduction [10];
 - optimizing electric vehicles routes according to energy consumption constraint, battery capacities and the localization of charging stations [11,12];
 - logistics costs savings for the reduction of levelized cost of energy [13];
 - designing logistics system of shipping electric semi-trucks batteries between the battery energy storage system and electric vehicle charging stations [14];
 - identifying possible logistics opportunities for offshore wind cost reductions [15];
 - designing food supply chain to reduce food losses and waste, thus reducing energy [16];
 - logistics capacity utilization for improving energy efficiency [17].

In particular, three of them [9,10,17] contain proposals for energy reduction in various areas of logistics, but there is no publication directly related to the logistics of repowering process of a wind power plant. As a result of this, the methods mentioned in the above literature on the optimization of logistics scheduling, or transportation routes, or the use of more energy-efficient logistics infrastructure and supra-structure can be used to a limited extent for optimizing deliveries of heavy and oversized goods for repowering process. The literature also includes publications on the optimization of transport or logistics routes [11,12,47]. For example, Yan et al. [47] present multi-stage battery transportation and logistics optimization variants based on full train transport and carpooling routes design that was optimized by the branch-and-bound algorithm and genetic algorithm according to the criterion of the lowest levelized cost of energy that was finally estimated at USD 0.45/kWh on average. Nevertheless, the proposed solutions are intended for standardized and cyclical transport, which limits their suitability for the specific transport of oversized and heavy loads, in addition not according to the cost criterion, but energy consumption.

Extending the literature study with all Web of Science publication databases (Clarivate Analytics, Databases = WOS, BCI, CCC, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO, ZOOREC; Timespan = All years; Search language = Auto) according to the words ‘logistics’ and ‘energy’ in the title or in keywords according to the formula $TI = (\text{logistics AND energy})$ OR $AK = (\text{logistics AND energy})$, 467 publications were obtained as of 27 June 2021, 21:06. Refining the search formula to the WoS categories as environmental sciences/studies, sustainable science, management, transportation, business, and economics, 139 publications were reported. As a result of their content analysis, it can be stated that 136 publications of 139 fit into the set of issues included in the above-mentioned MDPI publications. Only three articles extend the above issues to the following aspects:

- relationship between logistics, economic and environment [48];
- service modularity as a method to increase energy efficiency of logistics services [18];
- potential application of industry 4.0 technologies to optimize energy consumption in logistics processes [19];
- energy analysis tool for synchromodal supply chain [20].

In a more detailed scope, Khan and Qianli [48], based on econometric model examined the relationship between logistics performance indicators, economic and environmental

factors in a time series data of UK for a period of 1981–2016, coming to the conclusions among others that “the results show that the green logistics operations have statistically significant and positive association with renewable energy, while fossil fuel consumption is significantly and negatively correlated with green logistics operations” (p. 11). In a slightly different aspect with usage of different methodological approach, Khan et al. [49] confirmed the significant and positive impact of renewable energy on green logistics, and green logistics on eco-environmental factors, based on structural equations in ASEAN member states as well as in Asian emerging countries [50]. It can be concluded that these three studies clearly prove both the positive role of renewable resources and a strong aim to make logistics more energy effective.

The usefulness of the other publications is limited due to the uniqueness of the logistics of the repowering process, which excludes the possibility of applying the modularity concept assuming standardization of operations. Additionally, the proposal of digitizing logistics processes assumes repeatability of operations, while the optimization methods and tools recommended in the literature require professional expert software and the ability to use it in the daily work of logistics managers, which makes them of little use in logistics practice. The above criticism is not isolated, as other authors also state that the proposed solutions are irrelevant to the case of logistics of wind farm repowering process [17] or for offshore wind cost reductions [15].

In addition, the importance of the cost criterion in the assessment and selection of the delivery variant, which is emphasized in many above cited publications on energy economics and logistics, is not adequate to the current world situation. In the light of the global tendencies to achieve climate neutrality by 2050 by all key sectors of the economy, including energy industry and transportation [51], it is necessary to reevaluate many criteria, including logistics ones, because logistics can be viewed not only in terms of costs, but also in terms of energy as an area of energy consumption, mainly in the form of fuel, electricity, and other operational materials. Therefore, a case study, presented in this paper, on the analysis of delivery variants not according to the cost criterion, but according to the criterion of energy consumption, including the possibility of demonstrating energy savings, is a significant research novelty, which, in the light of the lack of publications in this aspect, can be treated as added value to the literature.

3. Theoretical Approach

Due to the literature limitations in the logistics of wind farm repowering study aspect, it is necessary to propose a theoretical basis for such a study. To address this situation, the following theoretical approach to research the logistics of repowering process according to the energy consumption criterion is applied.

For the need to develop this theory, the concept of the economics of wind farms, especially in the part concerning the repowering process [3], is integrated with the structure of logistics system according to SCOR model [43]. Both of them demonstrate strong logical dependency, because it is necessary to formulate repowering delivery requirements to plan and execute logistics operations, and opposite, the assembly of new items to restore the wind farm full power will not take place without deliveries of the required goods. Therefore, another novelty of the proposed theoretical approach is included in the integration of logistics and the repowering process into the conception of the logistics of the repowering process as an inseparable logical wholeness (system).

Its quintessence in the form of the logistics system structure of the wind farm repowering process at the generic level is presented in Figure 1. The logic of this structure is provided by the modeling notation of economic processes called EPC (Event-driven Process Chain) with the possibility of applying it to business practice in the form of a reference model [52]. Thus, Figure 1 synthetically shows the course of events (purple symbols) that initiate activities (green symbols), which in turn enable the flow of information (gray symbols). The individual activities are carried out by appropriate organizational units on the part of the wind farm and the logistics operator (yellow symbols) with the support of

the IT system (blue symbol). The double (gray) symbols reflect the relationship to one's own and other processes, while the brown symbol represents the supply of goods required for the dismantling and assembly process of the wind farm to restore its energy production capacity. The core elements of the system presented in Figure 1 are the main activities that should be performed within the logistics of wind farm repowering process. Their description is as follows. If a problem with the end of wind farm lifecycle has been raised, then making a decision on possible action should be undertaken. In the case that a decision to consider a wind farm repowering process was taken, then formulating delivery conditions and other repowering conditions should be performed. After the delivery conditions were formulated, the activity named "identifying variants of delivery" should be started. Next, the event "variants of delivery were identified" triggers the activity "assessing delivery variants according to energy consumption". In turn, if delivery variants were assessed according to required criteria, the activity "presenting delivery variants with recommendations" is initiated. After a given delivery variant was accepted, the process of physical delivery takes place, which delivers the required oversized and heavy goods to the process of wind farm disassembly and assembly. Although the description of the above activities is done on relatively high-level of abstraction, it shows their mutual dependencies, thus ensuring the coherence of the entire system.

The logistics system of the wind farm repowering process presented in Figure 1 also allows to deduce that the logistics of the repowering process results in the consumption of energy, and energy production, as well. Thus, logistics has a double impact on the wind farm economics of energy. The first one is direct, because logistics determines its own energy consumption (fuel, electricity, operational materials), and the second one indirectly, when logistics contributes to the restoration of the wind farm's ability to produce energy from wind power, for example, for the next 15 years.

The theoretical approach presented above, especially in the part concerning the method of assessing delivery variants according to the energy consumption criterion, is detailed in the next methodological section.

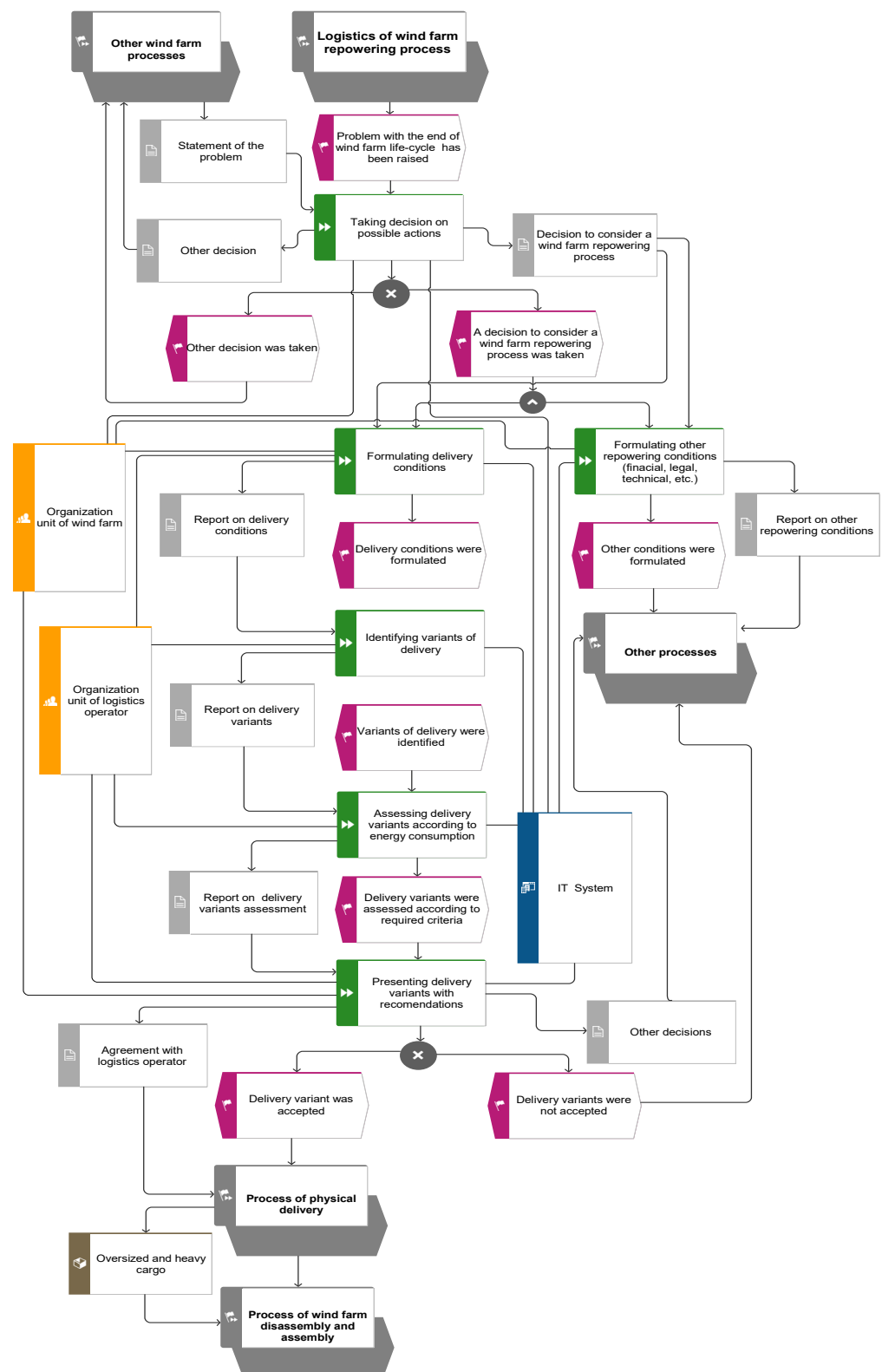


Figure 1. System of the logistics of wind farm repowering. Source: own study based on [3,42], according to EPC notation supported by ARIS Architect&Designer, ver.10.

4. Case Study: Materials and Methods

4.1. Case Study as a Research Method

The research goal formulated in the introduction section is achieved through the following methods and materials. Due to the fact that the subject of the study is a specific case of the problem situation of the Treffendel wind farm (Brittany, France), the basic research method is the case study [53]. Despite the critical opinions about the undemanding nature of the case study as a scientific method, it should be stated that it meets the requirements of methodological rigor, and its results constitute important conclusions that verify, update and supplement, thus enriching the current scientific achievements [54]. The case method is rigorous, complex, robust, and represents strong practical evidence [55,56]. The growing importance of the case study method and its use in various fields should be emphasized, as well as the presentation of research results in the worldwide literature [57,58]. R. Yin states: “There is no formula, but . . . the more that your questions seek to explain some present circumstance (e.g., ‘how’ or ‘why’ some social phenomenon works), the more that case study research will be relevant. The method is also relevant the more that your questions require an extensive and ‘in-depth’ description of some social phenomenon” [57] (p. 4). Three research questions posed in the Introduction section start with the word “how” and the logistics process repowering is also a social phenomenon, what recommends this method for this study.

Therefore, the analysis of this case, including the solution to the problem contained therein, was carried out in the following stages of the research procedure:

- context and problem definition;
- defining the expected solution to the problem;
- defining methods and tools for solving the problem;
- collecting data and applying the adopted methods and tools to solve the problem;
- presentation of the obtained results;
- discussion;
- conclusions.

4.2. Detailed Case Study Methods and Materials

The above research procedure was carried out as follows. The first two stages are based on non-standardized interview materials (interviews) with the management of the Treffendel wind farm (Brittany, France) responsible for the repowering process, plus publications and online sources to present the situational context. Proper definition of the problem and its expected solution was made by the methods of logical reasoning: reduction, induction, and deduction.

The next stage in the form of identifying, criticizing and adopting a set of methods along with supporting tools for solving the problem was carried out using typical methods of literature analysis, in the form of their identification, reduction and assessment of the usefulness of the proposed solutions. MDPI and WOS (Clarivate Analytics) were used as literature databases with the use of the Mendeley Desktop literature research tool. A critical point at this stage is to decide which of the methods and tools proposed in the literature should be adopted for use in the present case, and especially which of them can be modified, applied, partially used, and when it is not possible, to propose new solutions. The basic decision criterion is the properties of the research facility, in particular the specificity of the logistics of oversized and heavy parts in accordance with the requirements of the repowering process of the analyzed wind farm. The specific feature of its uniqueness limits the possibilities of using the methods proposed for repetitive or routine deliveries, in which regularities can be found. Therefore, it was decided to adopt a generally known and commonly used practical methodological approach in the form of identification of delivery options, their analysis and recommendation of the best solutions for decision making purposes.

The steps of collecting and analyzing collected data stage were performed on each logistics activity listed in Figure 1 in the “Theoretical approach” section, therefore in Table 1

the steps are listed in connection with logistics activities and in relation with the methods and tools used, and with the results obtained after individual steps. In addition to the content of Table 1, it should be added that based on the received product specifications and delivery requirements (what to deliver, including dimensions, weight; quantity; point of shipping, point of destination), the authors identified delivery options using Google maps and the HeavyGoods.net application [59] for planning, simulation and optimization of transport means and routes for oversized and heavy cargo transportation, powered by Fraunhofer Institute for Transportation and Infrastructure Systems (Figure 2). Then, expert discussion with two managers professionally engaged with the logistics of these kinds of cargoes was conducted. During these interviews the presented variants of delivery were verified, and specific means of transport were recommended. Then, the data of the verified delivery variants was entered into the SolidWorks software [60]. It is a program, which, among other functionalities, enables the calculation of the energy consumption for a given process of the product life cycle, e.g., transportation process of nacelles, based on the formulas embedded in the algorithms of this program. Since logistics includes not only the transport process, but also additional processes, e.g., route inspection, pilotage, police escort, the energy consumption calculated by SolidWorks was added to the energy caused by these additional logistics activities, thus obtaining the total amount of energy consumption by a given delivery variant. Subsequently, the obtained results were compiled in a descriptive form with graphics (tables and figures) in Section 5 and discussed in Section 6.

Table 1. Steps of collecting and analyzing collected data with relation to other elements.

Logistics Activities (Incl. in Figure 1)	Steps of Collecting and Analyzing Data	Methods	Tools	Results
Formulating delivery conditions	Collecting and analyzing product specifications: nacelles, rotor hubs and rotor blades to be delivered	Received product specifications were carefully read, logically analyzed and cargo parameters were noted	No specific tools were used	Delivery conditions in Table 2 (column “Cargo”)
	Determining other terms of delivery	Received delivery requirement were compiled into delivery conditions	No specific tools were used	Delivery conditions in Table 2 (columns: Quantity, Shipping points, Points of destination)
Identifying variants of delivery	Identification of theoretically possible delivery variants	Spatial analysis	Google maps	List of 12 theoretically possible delivery variants (not presented in the paper)
	Optimization of previously identified delivery variants and verification during discussion	Loading the delivery conditions to HeavyGoods.net application; running the program; recording the results. Discussing the delivery variants with two logistics managers	Optimization application on HeavyGoods.net Interview guide for discussion of the delivery variants with two logistics managers (see Appendix A)	Example of optimization of the long-vehicle route in Figure 2. List of delivery variants in Table 3
Assessing delivery variants according to energy consumption	Assessing the energy consumption of delivery variants provided by SolidWorks software	Loading data from Table 3 to the software; running the software; noting the results	SolidWorks software	Values on energy consumption of delivery variants, e.g., 555,365 MJ for the Variant 1
	Assessing the additional energy consumption caused by additional logistics activities	Calculation of the energy consumption by routes inspection, piloting, and police escort activities	Fuel consumption sheet, e.g., 5.4 L/100 km (VW Golf 1.0 TSI). The Engineering Toolbox on fuels energy content, e.g., 1 of conventional gasoline = 32 MJ	Values on energy consumption of additional logistics activities, e.g., $5.4 \text{ L}/100 \text{ km} \times 4900 \text{ km} \times 32 \text{ MJ} = 8500 \text{ MJ}$ (in round) for inspection of 4900 km; plus 92,100 MJ (piloting) and 72,000 MJ (police escort) give 728,000 MJ (in round) of energy consumption by the delivery variant No. 1
Presenting delivery variants with recommendations	Preparation of the delivery variants presentation	Editing text, tables, figures, recommendations	MS Office	Presentation of the delivery variants in Table 3 and Figure 3
	Presetting and discussing the delivery variants	Visual and oral presentation; active discussion	MS Office	Section 4: Case study: results Section 5: Discussion



Figure 2. Screenshot from optimization of the long-vehicle route on the exit from the N136 road into the N42, which is the Rennes ring road in France. Source: own study based on the application of HeavyGoods.net (accessed on 18 June 2021).

5. Case Study: Results

5.1. Context of the Situation, Defining the Problem

The analyzed wind farm is located in Treffendel (Brittany, France) and is therefore an onshore farm. It is operated by Total Quadran [61]. The wind farm produces energy with a capacity of 8 MW [62]. It consists of four Vestas V100-2.0 MW turbines [63]. The average amount of energy produced during the year is 18.504 GWh [64]. The operation began in September 2016, but its designed life cycle is 15 years. This means that over these years, i.e., until 2031, a real business problem should be solved in the form of not only making a decision regarding its further fate, but also performing specific actions related to the end or extension of the life cycle. In the analyzed case, the extension of the life cycle using the so-called partial repowering, which involves not replacing the whole farm (full repowering), but on replacing selected turbine or plant components to extend the life of the whole wind farm at some cost that is less than full repowering [35]. Due to the wind conditions at the site where the farm is located, the foundations and towers construction, partial repowering is considered by replacing the currently operating four Vestas V100-2.0 MW turbines with Vestas V120-2.2 MW turbines, thus planning to increase the power from 8 to 8.8 MW. The final decision and its implementation are conditioned by many factors of a legal, financial, environmental, human resources, technological and organizational nature, etc. One of them is the logistics of the repowering process of this wind farm, which was expressed in the form of the case decision problem: what are the options for delivering the required parts to the wind farm and how much would it cost? (Unfortunately, although the case presented in this article concerns energy savings in the logistics process, the originally articulated criterion was delivery costs.) In response to this problem, from the logistics side, a request was formulated to detail the terms of delivery addressed to the logistics service, and especially what cargo should be delivered (transport dimensions), quantity, point of shipping, and point of destination? Due to the distant time perspective, the question was not asked: for when? In response, a list of spare parts was obtained along with other required data, which are synthetically presented in Table 2. Based on the received delivery conditions, the case research problem was defined: what are the delivery possibilities according to these conditions? It was also clarified that the expected solution to the case research problem of the logistics side and the case decision problem of the wind farm management side will be to provide information on delivery options not only with cost information, but also information on the energy consumption of the logistics process, as an equal criterion for assessing these variants, thus giving a choice or compilation of decision criteria, however, according to the aim of this article the results regarding energy consumption are presented.

Table 2. Conditions of delivery.

Cargo	Quantity	Point of Shipping	Point of Destination
Nacelles:			
– height 4 m	4		
– length 10.4 m			
– width 3.5 m			
– weight 78 tons			
Rotor hubs:		Vestas factories:	
– height 4 m	4	– Lauchhammer (Germany) address: Lauchhammer	Wind Farm:Traffendel, Ille-et-Vilaine, Bretagne, France Latitude: 48°2'0.6" Longitude: –2°1'31.1"
– length 10.4 m		Süd, John-Schehr-Straße 7, 01979	
– width 4 m		– Taranto (Italy) address: Via Archimede, 12, 74123	
– weight 37.5 tons		Taranto	
Rotor blades:		– Daimiel (Spain) address: Avenida de los Vientos, 2,	
– height 3.9 m	12	13250 Daimiel, Cdad. Real	
– length 59 m			
– width 3.9 m			
– weight 9 tons			

5.2. Identification of Delivery Variants

The solution of the above research problem of the analyzed case was undertaken in accordance with the practical methodological approach adopted in Sections 3 and 4, in the form of stages of identifying delivery options, their analysis and recommendation of the best solutions for decision-making purposes, using the methods and tools described in the previous methodological section. The result of the works of the first stage was to identify nine delivery variants that are also decision variants (Table 3). The presented delivery routes informing about the types of transport used and intermediate points are already the result of optimization activities using the aforementioned HeavyGoods.net application. Variants by air have not been shown, because none of the logistics operators provides such a service within the European continent, possibly intercontinental transport can be performed, but these do not apply to the analyzed case. An exemplary description of the first variant is as follows. From the point of shipping located in Lauchhammer (Germany), four nacells and four rotor hubs will be shipped by road in the form of eight truckloads with semi-trailers via Lauchhammer Süd (DE)–Salzburg (DE)–Givet (FR)–Gace (FR) to its destination in Traffendel (FR). On the other hand, 12 blades will be delivered in 12 transportations by truck tractors with semi-trailers along the route Lauchhammer Süd (DE)–Salzburg (DE)–Marac (FR)–Chartres (FR) to the destination point in Traffendel (FR).

Table 3. Variants of delivery.

Shipping Point	Variant	Transport Type	Transport Mode with Quantity	Route					Cargo							
									Element	Quantity						
Lauchhammer (Germany)	1	Road transport	8 truck tractors with semi-trailers	Lauchhammer Süd (DE)	Salzburg (DE)	Givet (FR)	Gace (FR)	Traffendel (FR)	nacelles	4						
				Lauchhammer Süd (DE)	Salzburg (DE)	Givet (FR)	Gace (FR)	Traffendel (FR)	hubs	4						
			12 truck tractors with semi-trailers	Lauchhammer Süd (DE)	Salzburg (DE)	Marac (FR)	Chartres (FR)	Traffendel (FR)	blades	12						
	2	Rail transport (combined)	12 truck tractors with semi-trailers	Lauchhammer Süd (DE)			Berlin Brandenburg (DE)		blades	12						
			1 train	Berlin Brandenburg (DE)			Rennes (FR)		blades	12						
			12 truck tractors with semi-trailers	Rennes (FR)			Traffendel (FR)		blades	12						
			8 truck tractors with semi-trailers	Lauchhammer Süd (DE)	Salzburg (DE)	Givet (FR)	Gace (FR)	Traffendel (FR)	nacelles	4						
				Lauchhammer Süd (DE)	Salzburg (DE)	Givet (FR)	Gace (FR)	Traffendel (FR)	hubs	4						
			3	Maritime transport (combined)	20 truck tractors with semi-trailers	Lauchhammer Süd (DE)			Rostock (DE)		nacelles	4				
	hubs	4														
	blades	12														
	1 ship	Rostock (DE)			Saint Malo (FR)		nacelles	4								
							hubs	4								
							blades	12								
							20 truck tractors with semi-trailers	Saint Malo (FR)			Traffendel (FR)		nacelles	4		
													hubs	4		
													blades	12		

Table 3. *Cont.*

Shipping Point	Variant	Transport Type	Transport Mode with Quantity		Route				Cargo	
									Element	Quantity
Taranto (Italy)	4	Road transport	8 truck tractors with semi-trailers	Taranto (IT)	Bolonia (IT)	Turyn (IT)	Lyon (FR)	Traffendel (FR)	nacelles	4
				Taranto (IT)	Bolonia (IT)	Turyn (IT)	Lyon (FR)	Traffendel (FR)	hubs	4
			12 truck tractors with semi-trailers	Taranto (IT)	Bolonia (IT)	Turyn (IT)	Nantes (FR)	Traffendel (FR)	blades	12
	5	Rail transport (combined)	12 truck tractors with semi-trailers	Taranto (IT)			Bari Centrale (IT)		blades	12
			1 train	Bari Centrale (IT)			Rennes (FR)		blades	12
			12 truck tractors with semi-trailers	Rennes (FR)			Traffendel (FR)		blades	12
			8 truck tractors with semi-trailers	Taranto (IT)	Bolonia (IT)	Turyn (IT)	Lyon (FR)	Traffendel (FR)	nacelles	4
				Taranto (IT)	Bolonia (IT)	Turyn (IT)	Lyon (FR)	Traffendel (FR)	hubs	4
								nacelles	4	
	6	Maritime transport (combined)	1 ship	Taranto (IT)		Saint Malo (FR)		hubs	4	
								blades	12	
			20 truck tractors with semi-trailers	Saint Malo (FR)		Traffendel (FR)		hubs	4	
								blades	12	

Table 3. Cont.

Shipping Point	Variant	Transport Type	Transport Mode with Quantity	Route					Cargo	
									Element	Quantity
Daimiel (Spain)	7	Road transport	8 truck tractors with semi-trailers	Daimiel (ES)	Pampeluna (ES)	Bojonna (FR)	Bordeaux (FR)	Traffendel (FR)	nacelles	4
				Daimiel (ES)	Pampeluna (ES)	Bojonna (FR)	Bordeaux (FR)	Traffendel (FR)	hubs	4
			12 truck tractors with semi-trailers	Daimiel (ES)	Valencia (ES)	Barcelona (ES)	Bordeaux (FR)	Traffendel (FR)	blades	12
	8	Rail transport (combined)	12 truck tractors with semi-trailers	Daimiel (ES)			Madrid (ES)		blades	12
			1 train	Madrid (ES)			Rennes (FR)		blades	12
			12 truck tractors with semi-trailers	Rennes (FR)			Traffendel (FR)		blades	12
			8 truck tractors with semi-trailers	Daimiel (ES)	Pampeluna (ES)	Bojonna (FR)	Bordeaux (FR)	Traffendel (FR)	nacelles	4
				Daimiel (ES)	Pampeluna (ES)	Bojonna (FR)	Bordeaux (FR)	Traffendel (FR)	hubs	4
	9	Maritime transport (combined)	20 truck tractors with semi-trailers	Daimiel (ES)			Motril (ES)		nacelles	4
									hubs	4
									blades	12
			1 ship	Motril (ES)			Saint Malo (FR)		nacelles	4
									hubs	4
									blades	12
			20 truck tractors with semi-trailers	Saint Malo (FR)			Traffendel (FR)		nacelles	4
									hubs	4
									blades	12

5.3. Analysis of the Energy Consumption by Delivery Variants

Each cargo from the delivery variants identified in Table 3 was entered into the previously mentioned SolidWorks program along with additional information, including the transport distance. In this program, the logistics process of a given load is identified with the category of transport as one of the important stages of the life cycle of this load, and the calculation of energy consumption of this stage is made automatically based on energy consumption standards stored in the calculation algorithms of this application.

The findings are presented in Figure 3. The method of calculating energy consumption for the first delivery variant, which turned out to be the second most energy-consuming variant or the penultimate least energy-consuming variant, looks as follows. Delivery of four nacelles and four rotor hubs by road on the route from Lauchhammer (DE) to Traffendel (FR) through Salsburg (DE), Givet (FR) and Gace (FR) with a length of approx. 1500 km and for 12 blades running through Salzburg (DE), Marac (FR) and Chartres (FR) with a length of approx. 1700 km, using truck tractors with semi-trailers KESSEL-BRUCKE/TIEFFBET with a capacity of 75 T, 45 T and semi-trailers TELE (48 T), energy consumption calculated by the SolidWorks program was 555,365 MJ. To this figure the following energy consumption caused by additional logistic activities was added.

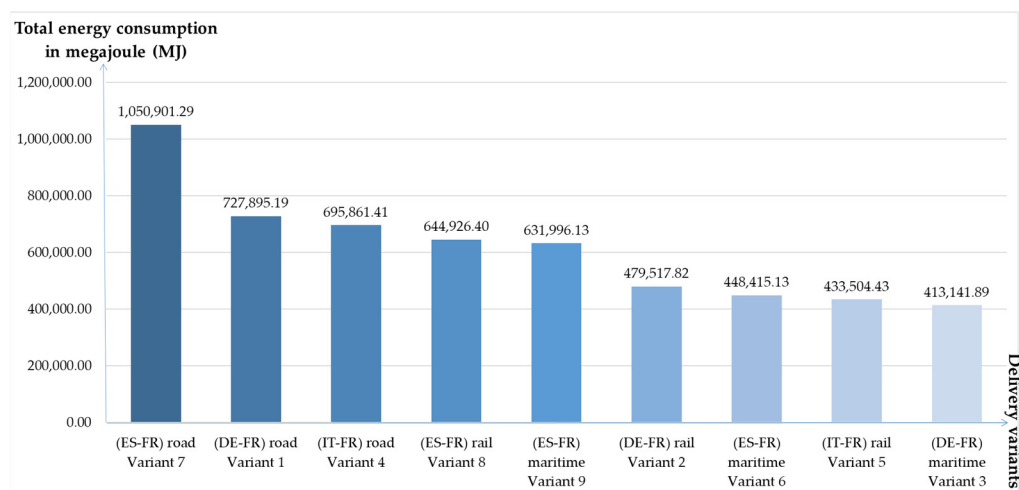


Figure 3. Total energy consumption of delivery variants. Source: own study based on the application of SolidWorks.

Namely, the initial drive (routes inspection) with the VW Golf 1.0 TSI BlueMotion 85 kW car (consumes about 5.4 L of conventional gasoline for 100 km) [65], in order to verify the main and alternative routes for this delivery variant, for a total length of approx. 4900 km, uses about 265 L of conventional gasoline, which multiplied by 32 MJ of energy content in 1 L of the fuel [66], an additional 8500 MJ is generated. In addition, each of the 20 crossings required the route to be secured by pilots. Taking into account the implementation of this task with the Opel Vivaro, 2.0 CDTI 90 KM car, energy consumption had to be increased by another 92,100 MJ. Additionally, the transport of four nacelles and four blades requires a police escort, which increased the energy consumption of this variant by another 72,000 MJ. Thus, the total energy consumption for the delivery variant No. 1 was estimated to be 728,000 MJ.

The energy consumption was estimated in a similar way for the eight other delivery options. The data in Figure 3 was sorted, thus showing not only specific amounts of energy consumption, but also the ranking of delivery options. It shows that the most energy-efficient option was the third delivery option from Lauchhammer (DE) to Traffendel (FR) by combined sea transport: road–ship–road, as the total energy consumption was 413,142 MJ.

In addition, a sensitivity study for the energy consumption by the nine delivery variants was also performed. Table 4 shows that the change of fuel consumption by 1%

results in a change in energy intensity for each of the considered variants, ranging from 0.12% to 0.35%;

- length of the route by 100 km results in a change of energy consumption for each of the considered variants, ranging from 0.17% to 1.03%;
- speed of tractor units by 10% used in each variant results in a change in energy consumption in the range from 4.26% to 14.36%.

Table 4. Sensitivity analysis of energy consumption for delivery variants.

Variant	Change in Fuel Consumption by 1% Causes Change in Energy Consumption by: [%]	Change of Route Length by 100 km Causes Change in Energy Consumption by: [%]	Change of Average 10 km/h Speed by a Truck Causes Change in Energy Consumption by: [%]	Transportation Mode
1	0.24	0.24	7.93	(DE-FR) road
2	0.34	1.03	13.63	(DE-FR) rail
3	0.17	0.58	6.00	(DE-FR) maritime
4	0.24	0.17	8.01	(IT-FR) road
5	0.35	0.76	14.36	(IT-FR) rail
6	0.12	0.45	4.26	(IT-FR) maritime
7	0.16	0.21	5.23	(ES-FR) road
8	0.23	1.17	9.57	(ES-FR) rail
9	0.13	0.49	4.45	(ES-FR) maritime

The above results of the analysis of the sensitivity of the energy consumption of individual delivery options prove that the possible underestimation of the length of the route or the need to make detours does not have such a significant impact on energy consumption as the correct selection of the means of transport.

5.4. Identification of Energy Savings in the Logistics of the Wind Farm Repowering Process

The adopted methodological approach allows to identify energy savings in at least two terms. In absolute terms, the difference between the minimum energy-consuming option 3 (DE-FR maritime) and the next-ranked option 5 (IT-FR rail) is 20,363 MJ, which in relative terms reduces the energy consumption of option 5 by 4.7%, but consumes up to 19.4% less energy compared to variant 7 (ES-FR road). To get an idea of whether this is a big or a small saving, it can be possible to convert MJ to kWh. If 1 MJ = 0.278 kWh, then 20,363 MJ is equal to 5661 kWh (5.661 MWh). Comparing this figure even with the very unequal level of yearly electricity consumption per dwelling: from 1.7 MWh in Romania, to 3.7 MWh for the EU average, 5.4 MWh in France, to 9.5 MWh in Sweden, and even 17 MWh in Norway [67], it can be said that this figure corresponds to the average annual energy demand of a household in France. Even considering the estimation error at the level of 2%, it is still a significant saving.

The above-mentioned energy savings are those that are directly influenced by logistics through its activities. However, it is possible to attempt to estimate energy savings indirectly influenced by logistics, namely the operation of the wind farm during its next life cycle, which is possible, inter alia, thanks to logistic activities. It is estimated that the wind farm in Treffendel, after completing the repowering process and at the same time restoring its production capacity, should increase the averaged amount of energy produced annually by about 15%, which means energy production in the amount of about 21.28 GWh/year. Assuming that the life cycle is not 15 years as before, because the manufacturer declares 25 years, the total energy production during its next life cycle amounts to 532 GWh. Of course, it cannot be argued that this is the amount of energy produced or saved by logistics directly, but it can be argued that it is so-called alternative amount of energy which, if it were not produced by the Treffendel wind farm, would have to be obtained from alternative sources. In this context, it seems legitimate to say that logistics contributed indirectly, but significantly, because without logistics it would not be possible to restore the production capacity of this farm, to save 532 GWh/25 years of production from alternative energy sources, possibly including non-renewable sources. Moreover, if the generation of 1 TWh of

electricity from wind energy reduces the following emissions of chemical compounds to the atmosphere, slags and dust—49,000 Mg, NO_x—4222 Mg, CO₂—700,000 Mg, SO₂—5500 Mg, the above context of energy savings can be extended over the case of harmful emissions savings amounted to slags and dust—1042.72 Mg, NO_x—89.84 Mg, CO₂—14,896.00 Mg, SO₂—117.04 Mg, which logistics also contributed to indirectly.

6. Discussion

Wind energy is one of the most dynamically developing sectors of renewable energy [21]. The increase in investments in renewable energy sources, including wind farms, around the world, allows for the diversification of the energy structure in individual countries, which in turn makes it possible to reduce dependence on traditional energy resources. The undeniable advantages of obtaining energy from wind farms include the negligible harmfulness to the natural and anthropogenic environment. Wind energy fits well with the objectives of energy policy in the field of environmental protection and sustainable development [33]. The policy of controlling energy consumption [22], its distribution and participation in the overall energy production are not without significance [27].

The development of wind energy is limited by a lot of barriers mainly of technical, economic, location, infrastructure, administrative, social, financial, and legal aspects. However, the benefits seem to outweigh the barriers. Therefore, wind farms are expected to grow strongly around the world, causing a strong development trend for wind farms.

Since the paper focuses on issues related to logistics services for wind farms [15], it should be noted that the dynamically developing sector of wind energy results in increasing wind farms' volume and energy production values. This situation creates demand, among others, for logistics support related to wind farm activities. Although the article focuses on the logistics of the wind farm repowering process, the need for logistics service can occur at any time during the wind farm operations [43]. Starting from the investment moment, construction of the wind farm, through operation, up to possible decommissioning, logistics is an essential element of the overall efficiency of the wind farm operations. Therefore, identification, assessment and selection of the most effective variant of the logistics support for the repowering process become very important issues in the economics of wind farms [44].

According to the literature, the most frequently taken criterion for decision variants assessment is the cost, however, time, safety, reliability, functionality, etc., or multi-criteria assessment can be considered, as well [46]. In the light of global trends to achieve climate neutrality by 2050 by all key sectors of the economy [51], the energy consumption and other environmental criteria are still taking greater attention. There is a limited amount of scientific achievement that addresses these issues, and no publication on the assessment of logistics for repowering process according to the criterion of energy consumption. Thus, the solution presented in this study, considering the criterion of energy consumption by delivery variants, can be perceived in the category of originality as well as scientific added value. The application of SolidWorks software with other methods and tools to find the delivery variant with the lowest energy consumption, seems also valuable from methodological and practical points of view.

In the discussion section, the authors would like also to respond to the issue on other possibilities of energy reduction in the analyzed case of logistics of the wind farm repowering process. They are:

- the usage of low-emission vehicles, characterized by a low level of combustion, and therefore also lower energy consumption;
- minimizing the weight of the means of transport, in this case a tractor with trailers, trains, ships, e.g., by using, where structurally possible, instead of heavier steel elements, lighter aluminum ones and by refueling their fuel tanks, e.g., only halfway;
- minimizing air resistance by reducing the dimensions of the means of transport or using aerodynamic covers, spoilers, etc.;

- changing the tires to ones with lower rolling resistance (light-running tires), bearing higher air pressure, or using single tires, or lifting one axle;
- the application of more technologically advanced cruise control systems, such as Predictive Powertrain Control (PPC);
- the usage of routes with better infrastructure, especially with the higher quality of the road surface;
- driving vehicles according to the principles of eco-driving.

The use of the above-mentioned methods of energy reduction is in progress and even recommended as a general trend in the development of low-emission, and therefore also low-energy logistics. However, a polemical issue is the possibility of their application to the logistics of oversized and heavy cargo. The specificity of this kind of cargo delivery is exceeding the standard spatial dimensions or axle load on the road/rail from the point of shipping to the point of destination. In other words, the logistics of oversized and heavy cargo is not a type of standard service, but an extreme, project service, that requires specialized means of transport, which meet specific requirements, sometimes not in line with general trends. For example, it is rather impossible to use low-power, low-emission vehicles to carry heavy loads. Since the transport of oversized and heavy cargo does not generally exceed the speed of 40 km/h, all kinds of activities aimed at reducing air resistance, better cruise control or eco-driving have also limited application. Moreover, due to this speed limit, it turns out that vehicles classified to Euro 5 emission class, i.e., with a higher emission level than Euro 6 vehicles, just when used for the transport of this kind of cargo, achieve lower emission values than Euro 6 vehicles [68], thus generating savings in terms of total energy consumption, carbon footprint and costs. Unfortunately, according to the tool rate tables, they are “penalized” for these savings, because in the case of Euro 5 vehicles (more than 18 t from four axles) they are charged a tool rate of 19.8 cents/km, while Euro 6 vehicles—18.7 cents/km [69], i.e., 5.9% more.

In relation to the research questions formulated in Introduction section, the analyzed case of logistics of the repowering process of a wind farm in Treffendel (Brittany, France), and especially the demonstrated possibilities of obtaining energy savings, is another example confirming the theses posed by energy economics and logistics management on the imperative to increase the energy production and save energy at the same time possibly. This example also shows that there is no alternative, neither substitute to logistics services, because without logistical support it would be impossible to perform repowering processes restoring the wind farm production capacity.

7. Conclusions

The article presents an analysis of the logistics variant of delivery for the wind farm repowering process. The purpose of the study was to analyze delivery variants of oversized and heavy goods according to the energy consumption criterion for the repowering process on the example of the onshore wind farm located in Treffendel (Brittany, France). The main value of the study and its originality was the use of the methodology of evaluation and selection of the most energy-efficient delivery variant. Contrary to the traditionally used cost-effectiveness criterion, the main criterion in this case was the lowest energy consumption.

Regarding the main findings of the study, the case of the Treffendel wind farm shows that there are different variants and possibilities for the supply of oversized and heavy goods in the repowering process. The study distinguishes nine potential delivery options using various modes of transport. Among the considered means of transport, road, rail and sea transport are of primary importance. Air transport is used sporadically and only for intercontinental deliveries. Therefore, in this case, such a variant was not considered. The adoption of the lowest energy consumption criterion allowed for the identification of delivery variants with different levels of energy consumption and the selection of the most energy-efficient delivery option. On the basis of the presented case, the delivery variant with the lowest energy consumption is variant No. 3, with an energy consumption of

413,141.89 MJ (Figure 3). In absolute terms, the difference between this option and the next delivery option No. 5 is 20,363 MJ, which in relative terms reduces energy consumption by 4.7% and as much as 19.4% compared to the seventh, most energy-consuming option.

The development of an appropriate methodology for the analysis of the logistics service of the repowering process has many theoretical implications. Mostly, it contributes to the enrichment of the theory of energy economics as well as the decision calculus in logistics management. Due to the fact that repowering processes are repeatable not only in Europe, but also around the world, the development of an appropriate methodology of analyses in the logistics of the repowering process may be a business practice for many similar projects. It can also be a supplement or an alternative to analyses based on traditional cost selection criteria.

This unique case study also shows that the identification of delivery variant characterized by the lowest energy consumption is not complicated too much, which may be an optimistic incentive for practical implications. In the light of global tendencies to achieve climate neutrality and the functioning of enterprises in accordance with the principles of the concept of sustainable development, the presented methodology based on the criterion of energy consumption is certainly an interesting solution in this regard.

A significant limitation of research in this area may be the availability of data. With regard to the presented research problem, which is the process of repowering the wind farm in Treffendel (France), the research study provides a detailed description of the real economic phenomenon, the process of repowering the wind farm operated by Total Quadran. However, obtaining real and up-to-date data is not always possible.

In future works, further research will be carried out on the interdependence of the processes of wind farm operation and their logistics service. Logistics of the repowering process is not an isolated problem of wind farm operation. Numerous issues in this area, related to the logistics of appropriate staff, appropriate operating resources or even logistics for the distribution of electricity generated by wind farms, constitute an important element of energy economics, unfortunately still modest in its theoretical and practical achievements related to logistics support. Therefore, the recommended direction for further research is to continue the analysis of similar cases, not necessarily limited to wind farms, but also other types of power generation or distribution facilities.

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Appendix A

Interview Guide

We are currently carrying out analysis on energy savings in logistics of a wind farm repowering process, which results we intend to publish in a scientific journal. For this purpose, we focus on a specific case of onshore wind farm in Treffendel (Brittany, France), which needs deliveries of oversized and heavy loads. We have reached the point, where we would like to verify the variants identified for consideration with your expert knowledge. For this reason, we propose to interview you remotely. It will take up to one hour. During this interview, we would like to discuss the following problem questions:

- (1) Are the proposed routes real and feasible in your opinion for analyzed load and means of transport? If not, which ones need improvement or verification and for what reasons?
- (2) What is the process of planning oversized transport and its subsequent implementation for the adopted boundary conditions?
- (3) What are the limitations of the analyzed means of transport on the proposed routes? What means of transport would you suggest?
- (4) What additional activities (except movement of the target means of transport with the load) be reckoned with from an energy consumption perspective, for each of the options?
- (5) What are the technical possibilities of minimizing energy consumption in the proposed oversized transports? Which of them could be adapted to the implementation of the discussed variants, and which not, and why?
- (6) What are the organizational possibilities of minimizing energy consumption in the proposed oversized transports? Which of them could be adapted to the implementation of the discussed variants, and which not, and why?
- (7) What other recommendations would you have for us?

Thank you very much for your kind cooperation

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