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Review

Utilisation of Spatial Data in Energy Biomass Supply Chain Research—A Review

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Abstract: The supply logistics of energy biomasses generally involves a complex system of supply chains, which aim to achieve timely and cost-efficient feedstock deliveries to biomass demand points. The performance of supply chains is often examined in case studies where spatial data about biomass sources and transportation networks are deployed in varying resolutions and to different geographical extents. In this paper, we have reviewed 94 publications, in which spatial data were used in case studies that focused on analysing and optimising energy biomass supply chains. The reviewed publications were classified into 16 categories, according to the publication year, study methods and objectives, biomass types, supply system complexity and the spatial features of each study area. This review found that the use of geographical information systems in this context has increased in popularity in recent years, and that and the multiformity of the applied methods, study objectives and data sources have increased simultaneously. Another finding was that most of the studies that we reviewed focused on countries in which spatial biomass and transport network data of high quality were unrestrictedly available. Nevertheless, case studies, including spatial data from multiple countries, were represented marginally in the papers that we reviewed. In this paper we also argue that a standard way of reporting geographical contents in biomass case studies should be developed to improve the comprehension and reproducibility of the publications in this field of research.

Keywords: bioenergy; geographical information systems (GISs); biofuels; logistics; biomass procurement

Citation: Korpinen, O.-J.; Aalto, M.; KC, R.; Tokola, T.; Ranta, T. Utilisation of Spatial Data in Energy Biomass Supply Chain Research—A Review. *Energies* **2023**, *16*, 893. https://doi.org/10.3390/en16020893

Academic Editors: João Fernando Pereira Gomes and Toufik Boushaki

Received: 27 November 2022
Revised: 23 December 2022
Accepted: 4 January 2023
Published: 12 January 2023

1. Introduction

One of the main contributors to the profitability of energy production in large-scale, biomass-fired heating and power plants is the success of feedstock supply chains. At each moment, the plant needs a certain amount of biomass to fulfil certain quality requirements, while the plant simultaneously aims to optimise the combustion process, based on the information it receives from the boiler [1]. The supply chains try to achieve the quantitative long- and short-term targets that the plant has set, and to make sure that the biomass meets the quality criteria upon arrival at the plant. The supply balancing problem is similar in biomass conversion plants that produce standardised products, such as gaseous, liquid or solid fuels. However, the demand is usually more stable if it is compared to heat or electricity production, where daily and seasonal variation in feedstock demand can be substantial.

In general, the supply logistics of energy biomasses often involves a set of complex supply chains, in which regular temporal variations of many processes are distracted by contingent factors, which cause uncertainty and instability. The seasonal variation of ecological processes usually involves the accumulation and, accordingly, the availability of different feedstock types, at different times. The long-term variation of the availability of certain feedstock types can be roughly estimated based on the historical weather and climate data for the focus area. Instead, sudden impacts (e.g., storms, floods or droughts) may lead to a significant deviation from the forecasted biomass volumes in the realised accumulation. Uncertainties can also occur at later stages of the supply chain, such as during the transportation and material handling (e.g., machine breakdowns), or the biomass storing stages (e.g., weather impacts and stack fires). The profitability challenge is increased by the fact that the energy density of biomass is low, when compared to fossil fuels such as coal or oil [2]. It is also understood that the feedstock catchment area can be larger than estimated due to heterogenic ecological factors or land ownership issues in the focus area [3].

In addition to the abovementioned real-world problems, the research into energy-biomass supply chains and systems (EBSCs) and applying the results of this research in practice is also challenging. Because the performance and profitability of a supply chain depends strongly on the local ecosystem and its conditions for biomass growth, the results from one study should not be generalised to studies from other geographical regions. This would usually be the case, even if the remaining operational environment in the supply chain (i.e., technosystem, economic, legislative and social factors) corresponded with the study reported. Therefore, in practice, each implemented real-world supply system is unique. Accordingly, the research of EBSCs includes a significant amount of case studies, in which spatial data about feedstock origins, destinations and the network between them play an important role. Geographical information systems (GISs) have become an essential tool in data management, and processing and the rapid development of computing capacity and data repositories have potentially increased the possibilities of using GISs in more and more complex research problems.

On the other hand, mathematical problem solving tends to be a common approach in EBSC studies, globally. Hence, the studies often highlight the research problems and methods (e.g., analytical models) as their most important contributors to the scientific society, while the role of the case studies are only to illustrate the methodological workflow in a real, geographical environment. The case study also provides an important demonstration, which elaborates and discusses the balance between theory and practice to report further methodological development needs, based on the case study's findings.

Purpose of the Work

Former EBSC studies have been reviewed several times during the last decade (e.g., in studies [4–17]). These reviews have mostly concentrated on certain feedstock types, conversion technologies or problem-solving methods (Table 1). Geospatial properties have been discussed on many occasions; however, to our knowledge, the sources used, the processing methods and the quality of the data from the GISs have been, for the most part, set aside in these reviews. In contrast, in 2011, Calvert reviewed approximately 70 bioenergy feasibility studies, and he examined how spatial data were used in relation to the different study approaches towards EBSCs [18].

The spatial data used in EBSC studies usually have many sources, and the datasets have varying spatial extents and resolutions, both within and among the studies. In theory, spatial data should be as accurate and correct as possible, however, in practice, the researcher is forced to compromise on data quality, for example, due to the following reasons:

1. A dataset fulfilling the requirements is not available or is too expensive (e.g., in countries or regions in which the public distribution of spatial datasets is restricted);
2. Collecting the required data independently is too laborious or expensive (e.g., accurate data presumes a vast amount of field measurements);
3. Data processing capacity is insufficient with regard to the high spatial resolution (e.g., the large spatial extent of the study area and the high number of origin and/or destination locations);
4. The importance of spatial information is low in relation to the scope of the study.

Table 1. Earlier papers that used different approaches to review EBSC-related studies.

Authors	Focus of the Review
Gnansounou and Dauriat [4]	Ethanol production cost comparison.
Awudu et al. [5]	Decision making and uncertainties in supply chains.
Elia et al. [6]	Categorization, based on specific features of the mathematical models in studies including heat, power and liquid biofuel production.
O'Keeffe et al. [7]	Classification of LCA studies of bioenergy production systems in three regional contexts.
Ghaderi et al. [8]	Optimisation methods used in the design and management of supply chains.
Mirkouei et al. [9]	Techno–economic studies, focusing on supply chains for bio-oil production.
Ghaffariyan et al. [10]	State-of-the art of machines and working methods in forest biomass supply chains.
Erber and Kühmaier [11]	Technology and productivity of machines in forest fuel supply.
Aalto et al. [12]	Use of geographical information systems, life-cycle assessments and discrete time simulations and their combinations in EBSC studies.
Azevedo et al. [13]	Total scholarly production of studies on supply chain performance; number of citations; and the most productive authors, journals and countries.
Santos et al. [14]	Assessment and optimisation studies considering forest wood supply chains and their sustainability dimensions.
Visser et al. [15]	Optimisation of wood pellet supply chain costs.
Nunes et al. [16]	Characterization of supply chain management models.
De Meyer et al. [17]	Classification of BSC studies, according to decision-making levels, and the optimisation methods and their objectives.
Calvert [18]	Spatio-temporal variables used in bioenergy feasibility studies.

There are no universal regulations or instructions describing how detailed and accurate spatial data should be for a trustworthy study. It is generally the author's responsibility to assess the sufficiency and quality of spatial data and, whenever needed, to discuss the impact of data selection on the results of the case study.

The primary purpose of this paper was to survey the EBSC-related publishing activities in the 21st century, and to assess what kind of spatial data have been used and in what ways. The second objective was to explore the relationship between spatial data properties and other features, such as the research problem and the selected research method, the biomass types under focus, the complexity of the supply chains or the time the research was conducted. These issues have not been addressed systematically in any of the previous reviews. It was assumed that the publication date, in particular, would correlate, to a certain extent, with the complexity issues because GISs' infrastructure—including the processing and distribution capabilities of large spatial datasets—has developed rapidly over the last 10–20 years [19,20].

2. Materials and Methods

The material for this review was collected in a bibliometric analysis, from two online database services: Thomson Reuters' Web of Science (WoS) and Elsevier's Scopus. Both services are commonly used citing data sources for articles that are published in globally available scholarly journals [21]. The bibliometric analysis was limited to full texts, which were written in English only. The output records were then analysed in the systematic paper screening stage, during which all ineligible texts were removed from our findings. The last stage was an analysis, in which the eligible papers were classified based on their contents, for further discussion in the context of this review.

2.1. Bibliometric Analysis

Aalto et al. [12] used a bibliometric analysis for surveying EBSC studies in which different computational methods, i.e., GISs, life cycle assessments (LCAs) and discrete-time simulations (DTSs), were used in combination. The survey included three categories of query headwords, limiting the search output to papers focusing on biomass, supply chains and up to three of the aforementioned methods. In our study, we used the same search criteria, although we dropped LCAs and DTSs from the methods category. For the WoS query, the following search statement was used:

TS = (Biomass OR Bioenergy OR Biofuel OR Bioethanol OR Biodiesel OR Biogas OR "Energy wood" OR "Forest fuel" OR "Wood chip*" OR Woodchip* OR "Wood waste" OR "Pellet*" OR "Energy Crop*" OR "Sugarcane" OR "Agricultural waste" OR "Municipal solid waste") AND TS = ("Supply chain" OR "Supply system" OR "Supply network") AND TS = ("Geographical information system" OR GIS OR "Spatial analysis" OR "Spatial statistic").*

Here, *TS* stood for topic search and the asterisk (*) for a wildcard. The quotation marks ruled that the words must be found as they were written inside the quotation marks (e.g., *wood chip*) and that separate words, alone (e.g., *chip* or *wood*) did not meet the criteria. The words *AND* and *OR* are Boolean operators, which defined that from each three categories (i.e., biomass, supply-chain and GIS) at least one of the headwords (separated by *OR*) should be found. The search statement for the Scopus query was as follows:

TITLE-ABS-KEY (Biomass OR Bioenergy OR Biofuel OR Bioethanol OR Biodiesel OR Biogas OR "Energy wood" OR "Forest fuel" OR "Wood chip*" OR Woodchip* OR "Wood waste" OR "Pellet*" OR "Energy Crop*" OR "Sugarcane" OR "Agricultural waste" OR "Municipal solid waste") AND TITLE-ABS-KEY ("Supply chain" OR "Supply system" OR "Supply network") AND TITLE-ABS-KEY ("Geographical information system" OR GIS OR "Spatial analysis" OR "Spatial statistic").*

Here, the words *TITLE-ABS-KEY* refer to the paper sections (i.e., title, abstract and keywords), in which the headwords were searched for. This was considered as mostly corresponding with *TS* in the WoS query.

2.2. Paper Screening

It was assumed that the bibliometric analysis would result in a substantial number of duplicate records because two database services with similar search criteria were used. These duplicates were converted to single records as the first procedure of paper screening stage. Additionally, all records that were possibly missing the necessary information about paper title or its authors were removed from the material. After these technical operations, we moved on to screening the papers based on their publication format and their contents. First, we accepted all full, peer-reviewed texts that were published in scientific journals or at scientific conferences that provided online access to the conference proceedings, free of charge. Second, the following qualifying questions were presented while reading the papers:

- Does the article include a case study in which
    - biomass is considered as a source of energy and
    - in which biomass is procured from several geographical locations, and moved to one or many locations for end-use or intermediate storage purposes?
- Was the focus area of the case study smaller than or equal to 10,000,000 km^2?
- Was the biomass transported by road, rail, waterway or by pipelines from the origin to the destination, or to an intermediate location mentioned in the case study?

The purpose of the questions was to screen out those studies that obviously did not serve the purposes of this work. An affirmative answer to all these questions was required to qualify the study for further review. For example, studies that had used GISs to produce biomass availability maps, but which had not taken the logistics issues into consideration were disqualified. Setting the maximum geographical extent for the focus area, which corresponded approximately with the land area of Australia, was made to exclude global EBSC studies, in which the origins and destinations are usually individual countries or even continents, and in which the level of EBSC abstraction is low.

2.3. Classification of Case Studies

After the screening, the eligible papers were classified based on the properties of the case studies. The classification was made in 16 categories, which were divided into five thematic groups, according to the field of study under review. The grouped categories are presented in Figure 1. Group 1 included background information on the publications, e.g., publication year and location of the focus area. Two classification variables were used for the location: world region and country. Despite the fact that there can sometimes be a substantial delay between the conducting of the research and the publication date, it was assumed that publication year was adequate for a chronological comparison and assessment of the methods and data development of the research field.

Group 1: General information

a) Publication year
b) World region
c) Target country

Group 2: Biomass origins and destinations

a) Biomass origin
   - ✓ Forests and tree plantations
   - ✓ Farms and fields
   - ✓ (Other sources)
b) End product
   - ✓ Heat and/or electricity
   - ✓ Gaseous fuels
   - ✓ Liquid fuels
   - ✓ Solid fuels
   - ✓ (Other products)

Group 3: Methodology

a) Study method
   - ✓ Regression analysis
   - ✓ Optimisation
   - ✓ Life-cycle analysis
   - ✓ Discrete-time simulation
   - ✓ (Other approach)
b) Study objective
   - ✓ Economic performance
   - ✓ Energy balance and emissions
   - ✓ Social impacts
   - ✓ (Other impacts)

Group 4: Spatial framework

a) Study area
   - ✓ 1 – 100 km^2
   - ✓ 101 – 1000 km^2
   - ✓ 1001 – 10,000 km^2
   - ✓ 10,001 – 100,000 km^2
   - ✓ 100,001 – 1,000,000 km^2
   - ✓ 1,000,001 km^2 – 10,000,000 km^2
b) GIS data format
   - ✓ Raster
   - ✓ Vector
   - ✓ (Other)
c) Transport network data source
   - ✓ Authority or enterprise
   - ✓ OpenStreetMap
   - ✓ (Other sources)

Group 5: Supply system complexity

a) Origin points
   - ✓ 1 – 100
   - ✓ 101 – 1000
   - ✓ 1001 – 10,000
   - ✓ 10,001 –
b) Destination points
   - ✓ 1
   - ✓ 2 – 10
   - ✓ 11 – 100
   - ✓ 101 –
c) Multi-stage network, Y/N
d) Multi-modal network, Y/N
e) Biomass property changes, Y/N
f) Transport cost basis
   - ✓ Distance
   - ✓ Time
   - ✓ (Other)

Figure 1. Grouped categories of the case study classification analysis. Classes in parentheses indicate findings that did not fit in any of the predefined classes. Y/N (i.e., yes/no) indicates the factor being taken (or not taken) into account in the study.

In Group 2 the studies were classified according to the biomass sources and the finished energy products. In the biomass origin-based approach, the classifying question was whether the biomass was sourced from agricultural (i.e., farms and fields), silvicultural (i.e., forests and tree plantations) or other origins (e.g., municipal or industrial waste). At the other end of the supply chain, the classification was based on the biomass conversion process, i.e., Is the feedstock used for producing heat or electricity or is it converted to gaseous fuel (e.g., biomethane), liquid fuel (e.g., bioethanol or biodiesel) or to some standardised solid fuel product, such as briquettes or pellets?

Study methods and objectives were analysed in Group 3. In the methods category, the studies were classified according to the principal mathematical method used for solving the research problem. For example, a study was classified as regression analysis if the purpose was to report average or total distances, costs or environmental impacts as a function of the required biomass volume, within a particular time period. If the study contained the basic elements of a mathematical optimisation model, i.e., an objective function and possible constraints, the study method was considered as optimisation. Two other classes were the use of a life cycle assessment (LCA)—which is a popular method in studies focusing on environmental system impacts—and the simulation approach—which is often used in studies that focus on temporal aspects of biomass supply systems [2]. The study objective classification was based on the reference variables used in the studies. For example, if the objective of the study was to minimise EBSC costs, the study was classified as economic performance-oriented. Moreover, if the goal of the study was to discern EBSCs' emissions or energy balance (i.e., input/output ratio of EBSCs), the study was placed in a separate class. Social impacts were used as the third class, indicating the studies in which EBSCs' impacts on the local population (e.g., jobs and welfare) were evaluated.

Group 4 focused on the spatial properties of the studies. The classification of study area extents was as important as the first evaluation of the spatial level of standard. It was roughly assumed that if a land transportation system was very large, the number of route choices between different origin and destination points would grow, on average, thus increasing the complexity and calculation demand of the case. In addition, a larger area may have affected the need to find and use more sources for biomass data, which would probably compound the challenges of data management and processing. Another interesting issue concerning data quality and availability was the source of transport network data. In this division, the studies that used crowd-sourced and worldwide OpenStreetMap (OSM) data [22] were distinguished from studies that used data provided by commercial operators or public authorities. The distribution of GIS datasets into raster and vector formats was also analysed. It was anticipated that some studies would process both data formats because raster format is usually suitable for the representation of continuous surfaces—such as fields or forests—while discrete objects—such as transport routes—are more often stored as vector data [23].

The complexity of supply systems was analysed in Group 5. This analysis was carried out by comparing the number of origin and destination points in the system and by searching for multi-stage and multi-modal systems. The system was identified as 'multi-stage' if the routes did not run directly from the origin to destination, but included an intermediate stage (e.g., for storage, processing or transhipment). 'Multi-modal' indicated a system including more than one vehicle type (e.g., lorry, train or vessel) and more than one transport route type (e.g., road, rail or waterway). Because the quantity (e.g., material losses) and the quality (e.g., moisture) of heterogenic biomass tends to change over time, we also assessed whether these changes during the time span of an EBSC had been taken into account. As the final step, the studies were classified according to cost bases of transportation. In this context, the cost of moving along the network does not mean only money, as the impact can also be seen in factors other than economic ones, such as time spent (e.g., in studies focusing on the vehicle fleet sufficiency) or emissions emitted (e.g., in studies with an environmental focus).

It was obvious that some studies did not fit in any of the predefined classes within the category; therefore, we added a class named 'other' for the categories in which this was probable. In addition, there was a possibility that some studies would fulfil the criteria of more than one class. These records were separated, and new classes were established for them.

This analysis was first carried out category by category, and then as a cross-classification between the different categories, starting from the comparisons between the publication year and all other categories. From the remaining category pairs, only the most significant findings were highlighted. In other words, pairs that did not include strong correlations (positive or negative) between any classes were not examined in the results section.

3. Results

3.1. Bibliometric Analysis and Paper Screening

The output of the bibliometric analysis was 150 records from the WoS database and 130 records from the Scopus database (Figure 2). After removing all the duplicate records, the total output of the analysis was 191 publications. Seven of the records were conference proceedings (titles were given without authors), which were also excluded from the paper eligibility assessment. Out of the 184 assessed papers, 90 were disqualified because of their contents, and the final number of papers [24–115] that proceeded in the review for further analysis was 94. The principal reasons for the exclusion of a paper were that no EBSC case study was included (24 papers) or that the EBSC case study did not focus on biomass transportation at all (49 papers).

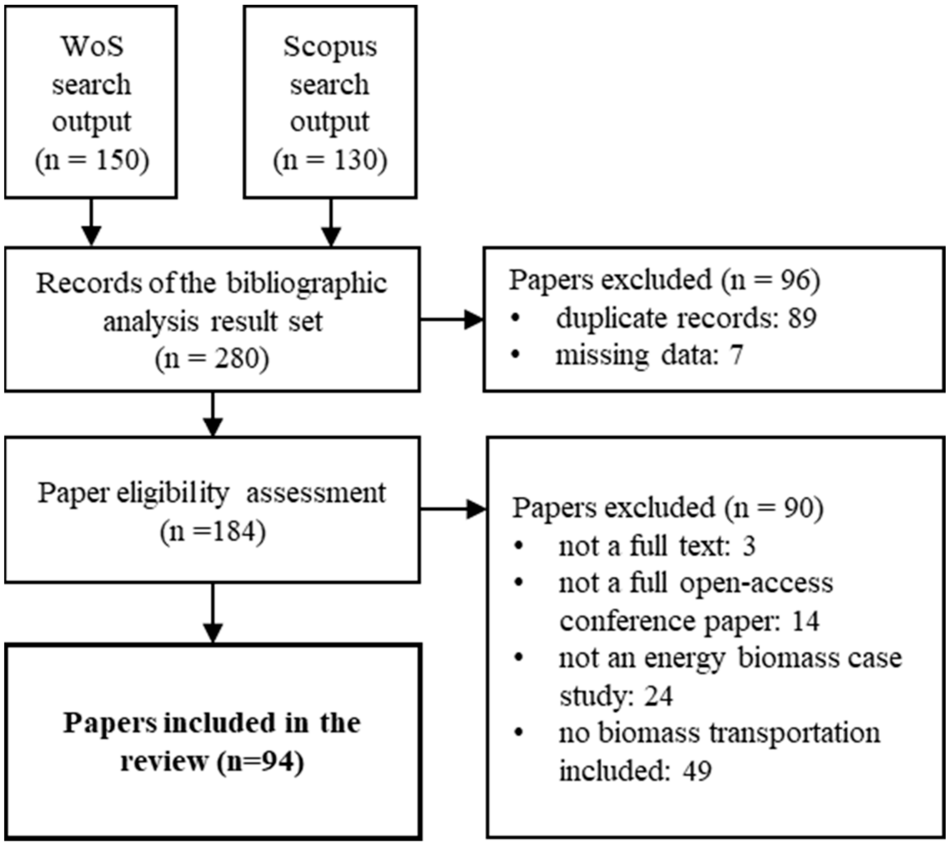

Figure 2. Workflow and results of the paper screening process.

3.2. Classification Analysis

The results of the classification analysis are presented in table format, in relation to the publication year in Appendix A, and in a spreadsheet format in the Supplementary Materials (Table S1). The spreadsheet file was used as the source for the cross-classification pairs, where publication year was not examined.

The oldest publication that was reviewed was from 2003 [24] and, in addition, only three other papers had been published before 2010 [25–27]. In accordance with the search and filtering methods used in this review, the research interest in the field was found to be growing—the first year in which we found at least 10 reviewed papers was 2016, and 2020 was a record year, with 21 papers (Figure 3). The United States was the country with the most case studies (32) that qualified for this review, and, together with Canada (three) and Mexico (two), it represented North America as the largest class (37) in our comparison between the world regions. Europe, which contributed to the most papers published prior to 2010, was the second largest class, with 32 publications. Despite the fact that a separate class was established for a case study of a transatlantic system that served biodiesel production in Europe [43], the appearance of multi-national studies was marginal. A multi-objective optimisation study, which was located in Armenia and Iran, [110] was another case study that went beyond country borders.

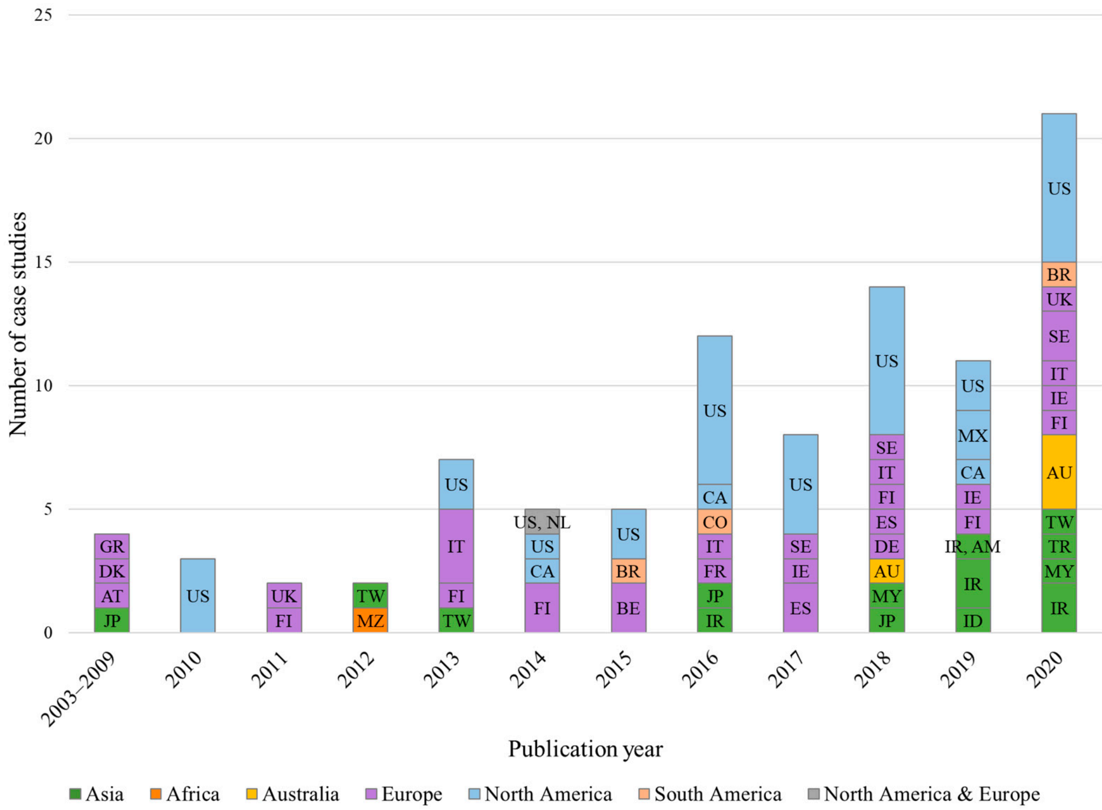

Figure 3. Classification of case studies according to their publication year, target country and world region. The country codes are listed in Appendix A.

Forest biomass was slightly more represented than agricultural biomass among the papers. In 38 studies, biomass was sourced only from forests or tree plantations, while in 27 studies the biomass originated only from farms and fields. Both origin types were used in 18 studies. The other sources used in these 18 studies principally included side products from the wood processing or food industries, and livestock and municipal waste. Microalgae was studied as the feedstock type in four studies [59,91,97,110]. There was a significant difference between Europe and North America both in terms of biomass origins and end products. Among the North American cases, 19 studies focused only on agricultural biomasses, and nine focused solely on forest biomasses, while both origin types were included in seven studies. In Europe, the records were 3, 22 and 6, respectively. From the perspective of the end product, the ESBCs in North and South America mainly provided feedstock for liquid fuel production; however, European and Australian studies focused on heat and power production (Figure 4). Within the 16 studies that focused on Asian countries, different biomass types and end products were represented in a range of different ways.

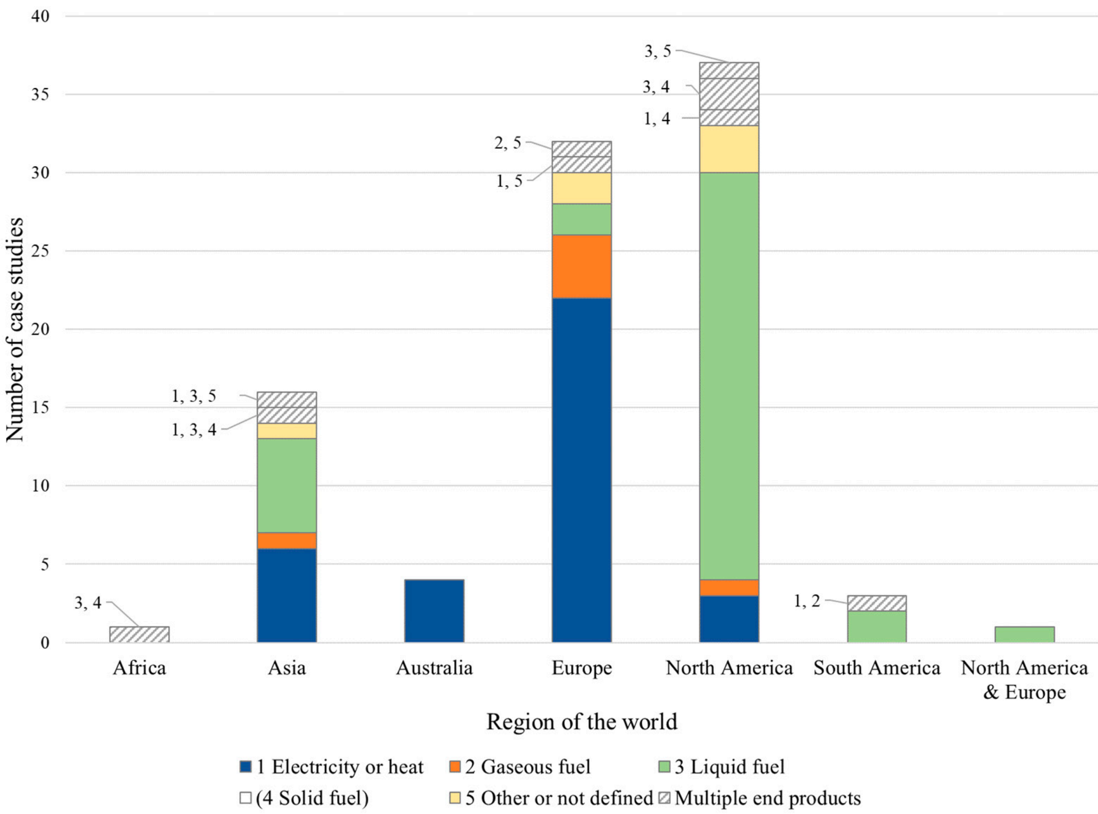

Figure 4. Classification of case studies according to their world region. The country codes are listed in Appendix A.

Solid fuels (e.g., pellets or briquettes) were not included in any of the studies as the only biomass conversion output; however, pellets were represented in four studies as a parallel end product with electricity [54,90], heat [90] or liquid fuels [34,53,90]. In one study [103], biochar was produced together with liquid biofuel. In six studies, the end product was not clearly defined (the EBSC customer was generally referred to as a biomass plant or biorefinery), and, in one study, CO_2 was studied as a secondary-produced commodity, together with biomethane [112]. With respect to that study, we found that studies that have focused on gaseous fuels and studies that have focused on multiple types of end products have emerged in recent years, whereas the papers published before 2016 focused almost solely on either heat or power generation, or on the production of liquid fuels (Figure 5).

Optimisation was used as study method in the vast majority (65) of the cases that we reviewed. The second largest class was regression analysis, with 20 records, while LCA was used in eight studies and simulation was used in six studies. Among these, there was one study that combined regression analysis and LCA [87]; two studies that combined optimisation and LCA [37,103]; three studies that combined optimisation and simulation [26,60,82]; and one study that combined LCA and simulation [107]. Two studies used the analytic hierarchy process (AHP) [80] and a weighted overlay analysis (WOA) [44] as decision-making tools, which resembled optimisation; however, they were classified as 'other methods' due to the absence of a mathematical formula for problem solving in the paper.

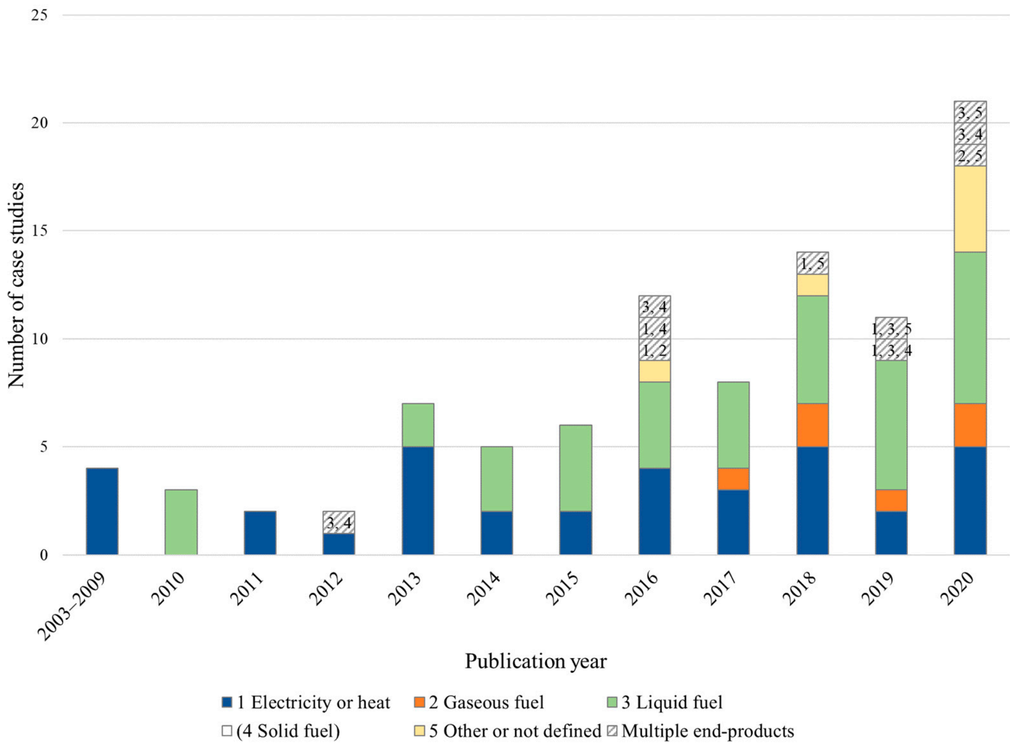

Figure 5. Classification of case studies according to their publication year. The country codes are listed in Appendix A.

Economic performance was clearly the most popular study objective used. It was the only objective in 61 of the case studies. Energy balance and emission objectives and social or other impacts were more often combined with economic targets (22 papers), rather than included as the only study objectives (10). Many of the studies that had multiple objectives used optimisation or, more specifically, multi-objective optimisation as the principal study method (18 papers). In this classification, the objectives, other than economic ones, that were included in the studies were found to be as follows: ecological and biodiversity impacts [50,80], system link failure [58], terminal utilisation rate [72] and temporal variation of feedstock availability [94].

Most study areas covered tens of thousands (30 papers) or hundreds of thousands (31 papers) of square kilometres. In 16 studies, the extent was 10,000 km^2 or less, and in 12 studies the focus area was larger than 1,000,000 km^2. The largest area, ca. 8,500,000 km^2, was used in a case study that focused on jet fuel supply chains, from biomass origins in Brazil [106]. According to the cross-classification with the publication year, study areas smaller than 1000 km^2 have become more uncommon during the last 10 years (Figure 6).

The vector format was the most commonly used way to process geographical information. It was used in 58 studies, out of which two studies also used the raster data format. In 11 studies, geographical information was only deployed in the raster format. A significant number of studies (25 papers) did not report the data format at all. There was a similar outcome in terms of undefined sources for the transport network data (29 papers). Additionally, 13 papers did not use a transport network layer at all but, instead, they used rectilinear origin–destination distances, which were calculated by a GIS. In two cases, the rectilinear distances were multiplied with a general tortuosity factor, which produced transport distances that were closer to the real-world conditions [46,77]. In 35 studies, the data were acquired from a public authority or private enterprise or association, while six studies used OSM data. In 12 cases, other data were used, including datasets completely created by the authors.

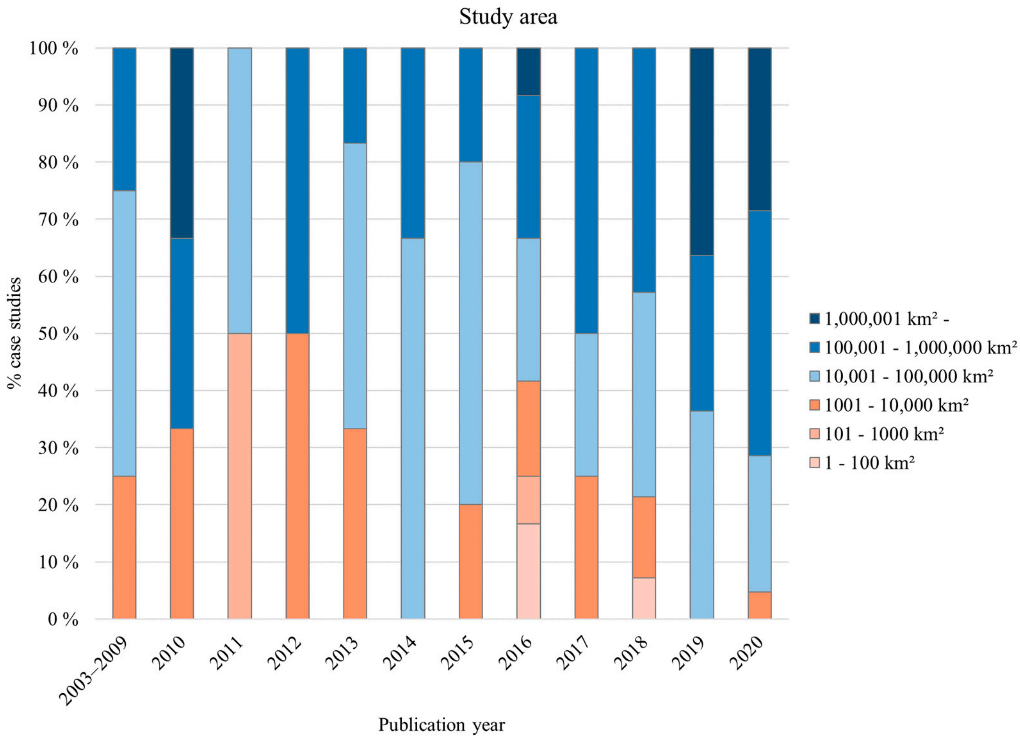

Figure 6. Classification of case studies according to their publication year and study area. The country codes are listed in Appendix A.

The variety in the number of origin points was great, as the quantity ranged between three and ca. 8,136,688,000 points. In 15 studies, the number was not reported. The three-point case focused on macroalgae as feedstock [112], having only the centroids of the oceanic procurement areas (the largest exceeding 3,000,000 km^2) as the starting points of the feedstock transportation. Consequently, the contrast between the number of origin points and the study area's extent was significant. In the study with the most origins [84], the raster analysis method, the least-cost path (LCP), was used to estimate the available forest biomass as a function of the paying capacity at the end-use point. The study used cost functions for the travel times of the off-road skidding and road transportation, so that the LCP could solve the optimal route across the surface, which consisted of 10 m^2 raster cells. The authors reported that it took less than eight hours to complete the whole GIS analysis using a laptop computer. A raster analysis was also used in several other studies with a significant amount of biomass origins. In the class of at least 10,000 origin points (18 studies), half of the studies (nine) processed data in a raster format.

The largest proportion of the studies (79 papers) was divided quite evenly into the classes of 1, 2–10 and 11–100 destination points (26, 27 and 26 papers, respectively). Regression analysis was the most commonly used study method in the class of one destination point (12 papers), while optimisation was the dominant method used in the studies with multiple destination points (55 out of 65 papers) (Table 2). In the studies with multiple methods, there were principally multiple destination points in the system. For example, a study combining optimisation and simulation investigated the potential of 13 switchgrass fields to contribute to bioethanol production in 24 refineries, which were located across the Southern Great Plains region of the United States [82]. The setting of more than 10 origins and more than 10 destinations was popular in studies that focused on the US's biomass supply (12 out of 32 US cases). A common approach in these cases was to use county-level biomass data and county centroids as origin points for transportation (10 papers). In six studies, the centroids were modelled as both origins and potential feedstock destinations [35,39,51,58,66,109].

Table 2. Cross-classification results between study method and number of supply chain destination points.

Study Method	Number of Supply Chain Destination Points 1	2–10	11–100	101–	Unknown
1 Regression analysis	12	4	1	1	1
2 Optimisation	8	18	21	11	2
3 Life cycle assessment	2	2	-	-	-
4 Simulation	1	1	-	-	-
5 Other	2	0	-	-	-
1, 3	-	1	-	-	-
2, 3	-	-	2	-	-
2, 4	-	1	2	-	-
3, 4	1	-	-	-	-

Slightly under half of the papers (44 records) included a multi-stage network in their case studies, which meant that direct transportation from the origins to the destinations was not the only alternative in the supply system. Road transportation was the most common means of transportation, and, in 20 cases, other modes (i.e., rail, waterways and pipelines) were also included, making the system multi-modal. The multi-stage system was common, especially in studies in which the process aimed at liquid fuel production (28 out of 44 studies). In these cases, it was also typical that the study area was large (over 100,000 km^2 in 22 papers) and that optimisation was the principal method (24 papers).

The changes in biomass properties were considered in nine supply systems. Four studies that focused on woody biomass supply ([24,83,94,107]) used moisture as the variable that represented biomass quality, and four studies that focused on agriculture biomasses ([30,47,52,74]) expressed dry matter losses as the key indicator. A study that optimised the palm oil supply chain in Indonesia, used a time constraint for transportation because of the unwanted quality changes that would take place within 24 h of harvesting it [95]. Spatial scale was relatively small in most of these papers, as the study area extended over 100,000 km^2 in only two studies [83,95]. According to the methodological cross-comparison, three studies (out of seven) that used simulation as a study method took quality changes into account as system variables.

Distance was the most used variable to determine transport costs (58 papers). In 10 cases, the costs were based on travel time consumption, which was often the result (i.e., quotient) of the distance and some road class-specific speed parameter. In 18 studies, distance and time were used together as cost determinants. Two studies used fixed values for the average transportation distances [85,87], indicating that individual routes between origins and destinations had no impact on the results. In other studies (six papers), the cost was outside of the scope, or it was not reported. For example, in the WOA study by the authors of [44], the distance from the biomass origins to the road and rail network was used as a determining variable, but it was not included in the distance-based class because travelling along the network was not within the scope of the study. Cross-classification between the transport-cost basis and other categories did not signal any significant interconnections.

4. Discussion

The bibliometric analysis returned 280 records, which was reduced to 184 after the removal of duplicates and papers with missing data. Regardless of the fair number of the reviewed papers, this analysis obviously skipped over some potential EBSC- and GIS-related case studies, due to the limited number of headwords in the search criteria. For example, an earlier review, which included a similar headword query, but which focused on different EBSC optimisation methods [8], identified some GIS-based studies that were not included in our review [116–120]. This was also true in studies that our search found [24,25,28,29]. It is undeniably true that the bibliographic analysis is not a perfect method for discovering all publications of the desired type (and nothing else); however, its advantage is that it is objective, which we value more highly than obtaining the broadest possible coverage of articles that have been published in the research field. As our headword selection was already stated to provide a 'good coverage' in the earlier review [12], we did not see any reason to make any adjustment to the settings.

The main findings of thisreview were that GIS-based methods have become prevalent in EBSC case studies, and that the multiformity of the applied methods, study objectives and GIS data sources have increased simultaneously during the last decade. Moreover, the growing progress of study areas and the increased number of origin and destination points and, accordingly, of the modelling complexity reflect the rapid progress in computing capacity and software development. In this review we did not focus on GIS software, but we assumed that the availability of open-source GIS applications, which was already significant in 2012 [121], has resulted in the increased interest in GIS methodology. In addition, it may have spurred commercial GIS software providers to accelerate their product development in favour of the researchers.

Besides the software applications, important sources of motivation for using GISs are the availability and quality of the data. In this context, it can be seen that developed countries—in which unrestrained access to GIS data has already been on the political agenda for some decades (e.g., Australia, Canada, the US and many European countries [122])—had a strong presence among the papers classified in this review. In the US, for example, it is straightforward to use county centroids as origin points, or even as destination points, because many supply-related (e.g., agriculture statistics) and demand-related (e.g., population census) figures are available at a county level. However, many developing countries were under-represented in the materials, despite their biomass reserves and their potential to respond to the prospective global demand for energy biomasses. For example, the transportation network of the GIS model in a case study that focused on Mozambique was validated by combining several datasets and using the authors' own experience, because the impacts of different road types and their condition on ESBC profitability was considered significant [34].

Surprisingly, only a small proportion of studies utilised OSM data for transportation network modelling in the reviewed studies, regardless of the fact that the data have expanded rapidly in recent years in many regions of the world and even in some developing countries [123,124]. Moreover, the data is available as one downloadable file, which enables the transport network model to include multiple countries in the GIS. This kind of model would be requested for real-world cases, in which a plant is located near the border, and, thus, the biomass procurement also covers parts of a neighbouring country (e.g., tariff-free transportation crossing national borders within the EU). To discuss why OSM data are still used so marginally in this context, we recognise that the quality (i.e., spatial accuracy, coverage and coherency) of this volunteered geographical information is not always as high as the quality of the data from national mapping agencies. In addition, the collection of high-resolution biomass data is often conducted on a country-by-country basis, therefore, applying OSM data does not totally solve the challenge of multiple data sources in multinational case studies.

Because the case studies from different parts of the world were very much concentrated in European and North American countries, it was reasonable to focus only on these continents in the closer examination of the regional differences in the studies' objectives, materials and methods (Table 3). It was found that a typical setting in North America, especially the United States, was an economic optimisation of feedstock supply chains, from farms to bioethanol refineries. In contrast, forest-based biomass and heat and power plants were evidently the most used feedstock sources and sinks, respectively, in European cases. This reflects the fact that the US has, on one hand, a high number of petrol cars that use ethanol as an additive fuel component [125] and, on the other hand, it also has vast cultivation areas that produce high amounts of agricultural waste, especially in the Great Plains region. In the North American cases, we also recognised that the study areas were most often larger than 100,000 km^2 (corresponding with the areas of many mid-size states in the US), and that a multi-stage supply system was applied, potentially, due to the feedstock characteristics (calling for interim storage and processing) and long-distance transportation (calling for transhipment) on the way to the plant. In European cases, multi-stage systems were less common, and the studies were usually limited to smaller areas, often surrounding only one selected point of biomass consumption. This could be due to the lower annual feedstock demand created by the heat and power production (vs. the profitable production of liquid biofuels) in one plant and that the case studies focused almost entirely on only one country.

Table 3. The most significant differences between the European and North American case studies according to the classification analysis. The proportion of the class in the respective category is presented in parentheses, after the name of the most frequent class.

Category	Europe	North America
2 a. Biomass source	Forests and tree plantations (72%)	Farms and fields (53%)
2 b. End product	Heat and/or electricity (65%)	Liquid fuels (71%)
4 a. Study area	10,001–100,000 km^2 (41%)	101,000–1,000,000 km^2 (54%)
5 b. Destination points	1 (41%)	2–10 (33%)
5 c. Multi-stage system	No (66%)	Yes (65%)

As a final point and, thus, a suggestion for enhancing biomass and bioenergy studies with a GIS approach in the future, we encourage the more diligent and systematic reporting of spatial data and GIS methodologies than those that have been included in the existing research. In this review, we found that many authors had neglected to provide source references and format descriptions for the transport network data, which goes against the reproducibility principle of scientific articles. In addition, some studies also omitted to report the count of origin or destination points in the EBSC network. Obviously, such negligence is rarely intended, rather, it could be based on the authors' lack of concern about the influence of geospatial details or about the impact of the EBSC's structure on the final outcome of the study. In this review we have touched upon the LCA and simulation approaches, which both have established practices of reporting the system and data descriptions in a concise and consistent way. In an LCA, this is conducted in compliance with an ISO standard [126], and many simulation studies follow the 'overview, design concepts and details' protocol (ODD) [127]. In EBSC studies with a GIS approach, we would like to see a similar style of reporting the spatial data properties, to gain ground in the future in a standardised way.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16020893/s1, Table S1: Complete results of the classification analysis.

Author Contributions: Conceptualization, O.-J.K.; methodology, O.-J.K. and M.A.; investigation, O.-J.K.; resources, M.A.; writing—original draft preparation, O.-J.K.; writing—review and editing, M.A., R.K., T.T. and T.R.; visualization, O.-J.K.; supervision, T.T. and T.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: DOIs of the reviewed articles are given in the supplementary material file.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The Results of the Classification Analysis, in Relation to the Publication Year of the Study

Country codes: AU—Australia; AT—Austria; BE—Belgium; BR—Brazil; CA—Canada; CO—Colombia; DE—Germany; DK—Denmark; ES—Spain; FI—Finland; FR—France; GR—Greece; ID—Indonesia; IE—Ireland; IR—Iran; IT—Italy; JP—Japan; MX—Mexico; MY—Malaysia; MZ—Mozambique; NL—the Netherlands; QA—Qatar; SE—Sweden; TR—Turkey; TW—Taiwan; UK—the United Kingdom; US—the United States.

Table A1. The classification results of the world regions, in relation to the publication year of the study.

1 b. World Region	**2003–2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Total**
Africa	-	-	-	1	-	-	-	-	-	-	-	-	1
Asia	1	-	-	1	1	-	-	2	-	2	4	5	16
Australia	-	-	-	-	-	-	-	-	-	1	-	3	4
Europe	3	-	2	-	4	2	2	2	4	5	2	6	32
North America	-	3	-	-	2	2	2	7	4	6	5	6	37
South America	-	-	-	-	-	-	1	1	-	-	-	1	3
North America & Europe	-	-	-	-	-	1	-	-	-	-	-	-	1
Total	4	3	2	2	7	5	5	12	8	14	11	21	94

Table A2. The classification results of the countries, in relation to the publication year of the study.

1 c. Focus Country	**2003–2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Total**
AT	1	-	-	-	-	-	-	-	-	-	-	-	1
AU	-	-	-	-	-	-	-	-	-	1	-	3	4
BE	-	-	-	-	-	-	2	-	-	-	-	-	2
BR	-	-	-	-	-	-	1	-	-	-	-	1	2
CA	-	-	-	-	-	1	-	1	-	-	1	-	3
CO	-	-	-	-	-	-	-	1	-	-	-	-	1
DE	-	-	-	-	-	-	-	-	-	1	-	-	1
DK	1	-	-	-	-	-	-	-	-	-	-	-	1
ES	-	-	-	-	-	-	-	-	2	1	-	-	3
FI	-	-	1	-	1	2	-	-	-	1	1	1	7
FR	-	-	-	-	-	-	-	1	-	-	-	-	1
GR	1	-	-	-	-	-	-	-	-	-	-	-	1
ID	-	-	-	-	-	-	-	-	-	-	1	-	1
IE	-	-	-	-	-	-	-	-	1	-	1	1	3
IR	-	-	-	-	-	-	-	1	-	-	2	2	5
IT	-	-	-	-	3	-	-	1	-	1	-	1	6
JP	1	-	-	-	-	-	-	1	-	1	-	-	3
MX	-	-	-	-	-	-	-	-	-	-	2	-	2
MY	-	-	-	-	-	-	-	-	-	1	-	1	2
MZ	-	-	-	1	-	-	-	-	-	-	-	-	1
SE	-	-	-	-	-	-	-	-	1	1	-	2	4
TR	-	-	-	-	-	-	-	-	-	-	-	1	1
TW	-	-	-	1	1	-	-	-	-	-	-	1	3
UK	-	-	1	-	-	-	-	-	-	-	-	1	2
US	-	3	-	-	2	1	2	6	4	6	2	6	32
IR, AM	-	-	-	-	-	-	-	-	-	-	1	-	1
US, NL	-	-	-	-	-	1	-	-	-	-	-	-	1

Table A3. The classification results of the biomass origin, in Relation to the Publication Year of the Study.

2 a. Biomass Origin	**2003–2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Total**
1 From forests and tree plantations	3	-	2	-	2	3	-	5	6	5	4	8	38
2 From farms and fields	1	1	-	1	3	-	4	4	1	4	4	4	27
3 From other sources	-	-	-	-	-	-	-	1	-	-	2	5	8
1, 2	-	-	-	1	1	2	1	1	1	3	-	1	11
1, 3	-	-	-	-	-	-	-	-	-	1	-	1	2
2, 3	-	-	-	-	-	-	-	-	-	-	-	1	1
1, 2, 3	-	2	-	-	1	-	-	1	-	1	1	1	7

Table A4. The classification results of the end product, in relation to the publication year of the study.

2 b. End Product	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Electricity or heat	4	-	2	1	5	2	2	4	3	5	2	5	35
2 Gaseous fuel	-	-	-	-	-	-	-	-	1	2	1	2	6
3 Liquid fuel	-	3	-	-	2	3	3	4	4	5	6	7	37
4 Solid fuel	-	-	-	-	-	-	-	-	-	-	-	-	-
5 Other or not defined	-	-	-	-	-	-	-	1	-	1	-	4	6
1, 2	-	-	-	-	-	-	-	1	-	-	-	-	1
1, 4	-	-	-	-	-	-	-	1	-	-	-	-	1
1, 5	-	-	-	-	-	-	-	-	-	1	-	-	1
2, 5	-	-	-	-	-	-	-	-	-	-	-	1	1
3, 4	-	-	-	1	-	-	-	1	-	-	-	1	3
3, 5	-	-	-	-	-	-	-	-	-	-	-	1	1
1, 3, 4	-	-	-	-	-	-	-	-	-	-	1	-	1
1, 3, 5	-	-	-	-	-	-	-	-	-	-	1	-	1

Table A5. The classification results of the end product, in relation to the publication year of the study.

3 a. Study Method	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Regression analysis	1	1	2	2	1	3	-	2	1	4	-	2	19
2 Optimisation	2	2	-	-	4	-	5	8	7	8	9	15	60
3 LCA	-	-	-	-	1	1	-	-	-	-	-	2	4
4 Simulation	-	-	-	-	-	-	-	1	-	-	1	-	2
5 Other	-	-	-	-	-	1	-	-	-	1	-	-	2
1, 3	-	-	-	-	-	-	-	-	-	-	1	-	1
2, 3	-	-	-	-	1	-	-	-	-	-	-	1	2
2, 4	1	-	-	-	-	-	-	1	-	1	-	-	3
3, 4	-	-	-	-	-	-	-	-	-	-	-	1	1

Table A6. The classification results of the study objective, in relation to the publication year of the study.

3 b. Study Objective	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Economic performance	3	3	2	1	4	2	2	10	5	8	6	15	61
2 Energy balance and emissions	-	-	-	-	2	1	1	-	-	-	-	3	7
3 Social impacts	-	-	-	-	-	1	-	-	-	-	-	-	1
4 Other impacts	-	-	-	-	-	-	-	-	-	1	1	-	2
1, 2	-	-	-	1	1	1	1	1	3	2	2	2	14
1, 4	-	-	-	-	-	-	-	1	-	-	-	-	1
1, 2, 3	-	-	-	-	-	-	1	-	-	-	-	-	1
1, 2, 3	1	-	-	-	-	-	-	-	-	2	2	1	6
1, 3, 4	-	-	-	-	-	-	-	-	-	1	-	-	1

Table A7. The classification results of the study area, in relation to the publication year of the study.

4 a. Study Area	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1–100 km^2	-	-	-	-	-	-	-	2	-	1	-	-	3
101–1000 km^2	-	-	1	-	-	-	-	1	-	-	-	-	2
1001–10,000 km^2	1	1	-	1	2	-	1	2	2	2	-	1	13
10,001–100,000 km^2	2	-	1	-	3	2	3	3	2	5	4	5	30
100,001–1,000,000 km^2	1	1	-	1	1	1	1	3	4	6	3	9	31
1,000,001 km^2 –	-	1	-	-	-	-	-	1	-	-	4	6	12
Unknown	-	-	-	-	1	2	-	-	-	-	-	-	3

Table A8. The classification results of the GIS data format, in relation to the publication year of the study.

4 b. GIS Data Format	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Raster	1	-	-	1	2	-	1	1	-	3	1	1	11
2 Vector	1	2	2	1	4	4	4	7	6	7	6	12	56
3 Unknown	2	1	-	-	1	-	-	4	2	3	4	8	25
1, 2	-	-	-	-	-	1	-	-	-	1	-	-	2

Table A9. The classification results of the transport network data source, in relation to the publication year of the study.

4 c. Transport Network Data Source	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Authority or enterprise	1	1	-	1	5	3	3	2	3	4	4	7	34
2 OpenStreetMap	-	-	-	-	-	-	-	-	2	1	2	1	6
3 No GIS data used	-	1	-	-	-	2	-	5	1	2	1	1	13
4 Other or unknown	3	1	1	1	2	-	2	5	2	7	4	12	40
1, 4	-	-	1	-	-	-	-	-	-	-	-	-	1

Table A10. The classification results of the number of origin points, in relation to the publication year of the study.

5 a. Origin Points	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1–100	-	1	-	1	1	-	-	4	2	3	3	7	22
101–1000	-	-	1	-	2	-	4	5	2	3	5	5	27
1001–10,000	1	-	-	-	-	1	1	-	3	1	2	3	12
10,000 –	1	-	1	1	1	1	-	2	-	5	-	6	18
Unknown	2	2	-	-	3	3	-	1	1	2	1	-	15

Table A11. The classification results of the number of destination points, in relation to the publication year of the study.

5 b. Destination Points	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1	1	1	2	1	1	5	1	2	2	6	2	2	26
2–10	-	-	-	1	2	-	1	3	3	4	5	8	27
11–100	2	1	-	-	3	-	2	4	2	3	3	6	26
101 –	1	1	-	-	1	-	1	1	1	1	1	4	12
Unknown	-	-	-	-	-	-	-	2	-	-	-	1	3

Table A12. The classification results of the multi-stage network, in relation to the publication year of the study.

5 c. Multi-Stage Network	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Yes	1	1	-	-	-	-	1	1	-	2	2	1	9
No	3	2	2	2	7	5	4	11	8	12	9	20	85

Table A13. The classification results of the multi-modal network, in relation to the publication year of the study.

5 d. Multi-Modal Network	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Yes	2	2	1	1	3	2	2	4	4	7	7	9	44
No	2	1	1	1	4	3	3	8	4	7	4	12	50

Table A14. The classification results of the biomass property changes, in relation to the publication year of the study.

5 e. Biomass Property Changes	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Yes	-	2	1	-	2	2	-	1	1	-	5	6	20
No	4	1	1	2	5	3	5	11	7	14	6	15	74

Table A15. The classification results of transport cost basis, in relation to the publication year of the study.

5 f. Transport Cost Basis	2003–2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
1 Distance	-	-	1	2	4	3	5	6	5	8	6	18	58
2 Time	2	1	-	-	2	-	-	2	1	1	1	-	10
3 Other or unknown	1	-	-	-	-	1	-	-	-	3	3	-	8
1, 2	1	2	1	-	1	1	-	4	2	2	1	3	18

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