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Evaluating Logistics Performances of Agricultural Prunings for Energy Production: A Logistics Audit Analysis Approach

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Abstract: The utilization of agricultural prunings as renewable energy sources requires effective and efficient logistics systems. The objective of this paper was to map out logistics activities along the agricultural pruning-to-energy (PtE) value chains. It describes the logistics performances based on the existing and potential pruning biomass supply chains focusing on prunings from fruit tree, vineyards, olive groove, and up-rooted tree branches. A logistics audit analysis approach has been used for detailed assessment of logistics performances. The analysis was based mainly on primary data gathered using a structured data survey format targeting the existing and potential PtE initiatives in Spain, Germany, Denmark, France, and Poland. The analysis considered the major stages of the chain, such as pruning, harvesting, processing (e.g., baling and chipping), storage, transport, and the linkage between the different stages. The paper identified the constraints along the logistics chain and recommended appropriate interventions to promote the marketing of agricultural pruning focusing on the supply of quality bales and chips for renewable energy production, and to increase the sustainability of renewable energy generation from PtE initiatives. The study has indicated that there are economic, social, and environmental benefits of PtE initiatives, as well as opportunities to increase the implementation and sustainability of the system.

Keywords: agricultural pruning biomass; logistics audit analysis; logistics performance; renewable energy

1. Introduction

1.1. Biomass as Renewable Energy Source

Biomass is one of the renewable energy sources being promoted globally [1,2], as fossil fuels are associated with problems. There are two major problems clearly observable concerning the fossil fuels in the world, namely: (i) fossil fuel reserves are limited resources and spread over a small number of countries, and (ii) fossil fuels are associated with high greenhouse gas emissions. Therefore, the development of renewable energy sources is important in order to enhance the global energy systems.

Within the EU-28 countries, the quantity of renewable energy produced increased by 73.1% over a decade, from 2004 to 2014 [3]. In 2014, about 196 million tons of oil equivalent were produced as a primary production of renewable energy within the EU-28. Solid biofuels and renewable waste have been considered as the most important renewable energy source in the EU-28, accounting for about two thirds (63.1%) of the primary renewables production in 2014, followed by hydropower with 16.5% [3].

Agricultural residues are among the biomass-based important renewable energy sources [4–7]. The agricultural residues from the pruning operations of fruit trees need attention in this regard. This is because the utilization of fruit tree prunings has been limited as a result of logistics related problems in harvesting, processing, and transporting activities [1,8,9]. To address this issue, the EuroPruning project was initiated and implemented during 2013–2016. The project aims at the development of new improved logistics for agricultural prunings, including harvesting, storage, and transport. Part of this project is reported in this paper.

The objective of this part of the study was to map out the logistics activities along the agricultural pruning-to-energy (PtE) value chains and to describe the logistics performances based on the existing and potential pruning biomass supply chains. For this study, a logistics audit analysis approach was used. We systematically investigated the characteristics of the pruning-to-energy (PtE) value chains by considering each main logistics stage, such as harvesting, storage, and transport, as well as the associated cost and information flow along the logistics chain. Specific objectives include identifying the existing and potential pruning-to-energy (PtE) value chains in the study areas, describing the logistics operations along the chain from the farm to final consumer, identifying the critical logistics stages and knowledge gap along the logistics chain, and recommending appropriate intervention strategies for sustainable PtE initiatives.

1.2. Some Relevant Biomass Properties in Investigating PtE Value Chains

There are important parameters used to describe the characteristics of different biomass types. These include volumetric mass, moisture content, ash content, and heating value [10]. The mass of a biomass product per unit volume varies within and between the species of the biomass sources. The moisture content is an important parameter that influences the biomass chemical characteristics, bulk density, and heating value (i.e., it affects significantly the energy production processes). Ash content is another important parameter that increases if the raw material is contaminated with soil, sand, or grit. In some cases, the ash content of wood chips contaminated in this way can reach 5–10% [11].

1.3. Main Characteristics of Logistics Chain in PtE Value Chains

Traditionally, biomass has been used as a source of mainly thermal energy in the vicinity of its production sites. However, the current trend is that a large amount of biomass is required at energy production sites for the continuous production of different forms of energy. This requires more sophisticated biomass supply chain management [4]. Figure 1 presents the typical PtE value chain. The main distinctive characteristics of the biomass supply chains have been compiled in Table 1.

Table 1. Major characteristics of the biomass supply chain and the related impacts on biomass-energy systems.

Distinctive Characteristics That Affect the Biomass Supply Chain Management Performance	Major Impacts on the Biomass-to-Energy System
Multiple biomass suppliers	It increases the complexity of the system and the difficulty in biomass procurement
Seasonality problem	It increases the storage volume, storing time, and inventory costs
Perishability of some (or all) biomass to be supplied	It constrains the transportation lead time and length of storage time
Low energy density per unit mass (for most forms of biomass) compared to fossil fuels	It increases the logistics (handling, storage, and transportation) cost per unit of energy to be generated
Dependency of demand of produced energy on type of biomass-to-energy conversion plants and/or price of fuel substitutes	A robust and flexible supply chain is required for the system
Supply and demand uncertainty	It makes the decision making process more complex; it could interrupt the supply of biomass
Dispersed geographical distribution of biomass	It requires biomass identification and selection processes

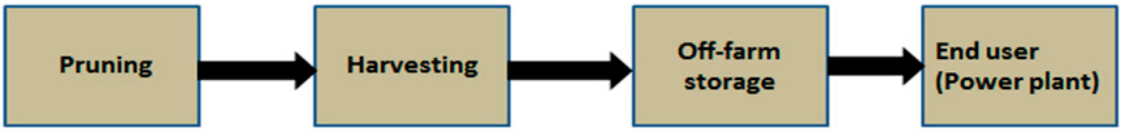

Figure 1. Typical pruning biomass logistics chain (source: authors own illustration).

1.4. Main Logistics Operations in PtE Value Chains

1.4.1. Pruning

In this study, pruning refers to the act of removing the top or unwanted branches of fruit trees (Figure 2). It is often done by farmers on an annual or biennial basis, in order to maintain the desired tree form and structure, remove dead or dying branches injured by disease, and increase the productivity of fruit trees. Agricultural pruning refers to the branches cut during the pruning activity.

Figure 2. Plum tree pruning [12].

1.4.2. Biomass Harvesting

Logistics activities at the harvesting stage include the preparation of harvesting equipment/machineries and the collection (harvesting) of biomass. Pruning and harvesting activities can be integrated with chipping or baling [13,14]. 'Chipping' is cutting pruning wood into woodchips, which can be used as solid biomass fuel. Pruning can also be mulched and used as source of organic fertilizer in gardens [15]. 'Baling' is a process of compressing the pruning biomass (branches removed from vineyards, fruit, and olive plantations) into compact bales (round or rectangular bales). Biomass bales can be easily handled, transported, and stored. Pruning biomass can be collected and stored near the farm in the form of bale or in the form of chips. The bale or the chips might stay on field for days in order to let it dry before being transported to next stage for further processing, storage, or use. It may be transported to a processor, distributor, or directly to the end user.

1.4.3. Storage

The storage of biomass is one of the major issues in biomass logistics and handling as it is related to the seasonal variability and cost of logistics operations [13,14]. The storage of biomass should be located and designed in a way that it could improve the total system efficiency. The pruned biomass is recommended to be used within 6–12 months, leading to a reduction of greenhouse gas (GHG) emission related to long term storage [16]. The location of the biomass storage can be different for different supply chains [4,14], as follows:

- On-field biomass storage is less costly but has some disadvantages, such as material loss, difficulty in controlling biomass moisture, potential risk to health (formation of spore and fungus) and safety issue (self-ignition may happen), and difficulty in land management if the farmer uses the storage place for the following cultivation. Because of these risks, the on-field storage is limited to short-term storage.
- Intermediate storage is storage located between the fields and power plants.

- A storage facility at biomass power plant is a type of storage that can facilitate the biomass drying process (controlling moisture content) by using the dumped heat (without extra energy consumption).

Often, it is difficult to let the agricultural residue biomass to dry on field because [14] they have high moisture content (up to 50%) during collection, and the drying may take longer time; the farmers may need to prepare the land; the biomass will decay if it is left in the field for a longer time, especially if large piles with many fines and low aeration are built; and storage without drying (especially when moisture content is high) could lead to material and quality loss, and health risks as a result of the formation of microbes.

1.4.4. Biomass Pre-Treatment Activities

The pre-treatment of biomass includes handling and processing, drying and cleaning, sorting, blending, grading, and increasing bulk density (processing into wood chips and bales); torrefaction; pelletising; and pyrolysis [17,18]. Pre-influences significantly influence the logistics performance of biomass energy chains. In PtE value chains, the drying and processing of the pruning biomass is important. The harvested biomass could dry on the field before collection, and baling or chipping. It could be further dried to the required level at the storage stage (near farm or at the processor stage). Quality control activity, which includes cleaning (from impurities), controlling the size of chips, moisture content, and ash content, is important to increase the effectiveness of the PtE initiatives.

1.4.5. Biomass Transport Activities

The biomass transportation includes the primary (inside farm) transportation and main transportation from the farm to the required destination (to storage or power plant). The primary transportation includes moving (forwarding) the collected and/or crushed biomass to on-field storage or to the roadside [9]. Appropriate vehicles can be determined based on the average distance, biomass density, vehicle capacity and speed, and the availability of the vehicles [14,16]. In-field transportation is usually done by tractors. The transportation to intermediate storage and/or a power plant site is mainly done by trucks.

1.5. Main Actors and Their Roles in the PtE Value Chain

In the organizing the logistics operations for the PtE value chain, well defined roles of actors are important for integrated value chain management. To make it more understandable, we described the role of actors as simple or complex. In the simple role case, the actor could have influence only in parts of the logistic chains; would not interact with multiple actors; and would not organise several steps of the logistics. In the case of the complex role, the actor organises the whole chain and has a comprehensive view of the chain. A farmer is a stakeholder in the chain that could have the option to participate as an actor in the chain in different ways (i.e., as a biomass producer, biomass trader, and biomass logistic operator). Its role fully depends on the entrepreneurship, vision, and capacities of the farmer. In the context of this study, the major actors and their respective roles can be described as follows:

- **Biomass producer**: at a farm level, a producer carries out activities such as raw material (biomass) production; pruning and collection, and processing (chipping and baling); on-field storage; and loading for transport; as well as, in some cases, delivering the biomass to the end user.
- **Processor**: can be a trader and performs treatment/processing (drying, baling, and chipping), storage, buying/selling, and unloading/loading.
- **Distributor**: performs activities such as procurement and trading; treatment (storage, drying, baling, chipping, blending, and grading); quality control; inventory; and unloading/loading for transport and transportation.

- **End user:** performs activities such as procurement, biomass quality control, storage, and mainly energy/heat production.

1.6. Identification of Knowledge Gap and Required Interventions

The development of effective biomass logistics for agriculture needs a careful consideration of the energy production potential of the biomass type available in the study area, the land use situation of the area, seasonal variation of biomass supply, the availability of effective transport network, and the major constraints hindering the development of renewable energy systems from biomass.

Energy production technologies have gotten more attention in the study of biomass-to-energy production. Relatively, research focusing on the biomass supply chain management issues are rare [4]. This gap should be addressed, as the biomass supply chain issue is very critical. Biomass supply chain management is related to the cost and complex logistics operations in the biomass energy production and utilization [4]. The residues of fruit plantations can be a considerable source of energy if they are collected appropriately and transformed into biofuels. Although the quantity varies for different fruit trees and regions, the potential quantity of pruning prior to harvesting has been estimated as follows, in tons per hectare (wet base). In Spain, for almond, olive, vineyard, and peach, the estimated values were 0.62, 4.29, 1.14, and 2.64, respectively [19]. The optimality of the management and utilization of biomass energy resources could be affected by many factors, such as logistics system, biomass resources property (quantity, quality, and seasonality), plant size, available technology for energy conversation, CO_2 emission balance, and available potential consumers [20]. Velázquez-Martí et al. [1] pointed out the knowledge gaps in utilizing biomass from fruit plantations to produce bioenergy. These knowledge gaps include technical limitations regarding harvesting systems, information limitations regarding the quantity and quality of residues, data limitation regarding biomass resources at local and national levels, and a lack of adequate tools and techniques to reduce the cost of logistics operations along the entire chain of the biomass supply. For instance, compaction (prior transport) could reduce the specific transport cost of biomass and CO_2 emissions [20].

2. Material and Methodology

2.1. Data Survey and Study Area

The data was gathered during 2014–2015, using a comprehensive questionnaire. Questions that were relevant in order to acquire data (for investigating logistics operations along the PtE value chain) were prepared. The questionnaire covered all of the stages of the pruned biomass supply chain and consisted of 130 questions in total. The same questionnaire was used in each country, but the cultivation types were not necessarily the same. First, the availability of the pruned biomass supply chain was assessed and 25 chains were identified with potential to be investigated. The required data was gathered for each of the 25 PtE value chains (from Germany, Spain, Italy, Poland, France, and Denmark). The respondents included major actors such as farmers, traders and transporters, service providers (processing such as chipping and baling), relevant experts, and the end users of biomass. Although there were difficulties in acquiring adequate data, a comprehensive assessment has been carried out successfully.

2.2. Logistics Audit Analysis

2.2.1. Logistics Audit Concept and Methodology

A logistics audit is "a systematic and independent analysis aiming at the statement whether activities referring to the quality of functioning of a logistics system and whether its results are consistent with planned assumptions" [21]. In study by Sekulova et al. [22], a logistic audit is stated as "standardized, evaluation and project process which is focused on logistics functions of corporate governance". At a regional or national level, auditing the logistics performance provides important inputs for policy-making [23]. Based on the result of the interviews with managers of agricultural enterprises, with especial focus on enterprises with potentially big logistics problems, Wawrzynowicz and Wajszczuk [21] proposed a model of a logistics audit for agricultural enterprises that has the following three stages: the development of an audit plan, making an audit, and a verification of the audit results. The authors concluded that such a permanent auditing of the logistics, with the help of a comprehensive logistics audit methodology, should minimize the cost of logistics systems.

Logistics audit addresses important topics, such as [22] quality assessment (for instance quality and reliability in planning of logistics operations), technology assessment, productivity assessment, and external factors assessment (for instance the influence of relations between customers and suppliers). In this study, the logistics audit method is used as an assessment tool for identifying the constraints along the logistics chain, and identifying opportunities for a further improvement of the logistics processes or as a supporting tool to (re)design sustainable logistics strategies for agricultural residues in relation to environmental and customer requirements.

2.2.2. Logistics Audit Check List That Can Be Applied for Biomass Flow

In the process of a logistics audit, understanding all of the logistics processes helps to identify the following [22]: (i) bottle neck areas, (ii) potential area and methods for improvement, and (iii) advanced technologies and techniques that can be applied effectively. In the case of a PtE value chain, these factors have been identified at different levels of the supply chain, namely: pruning, harvesting, storage, and transport. In this regard, the logistics audit check list that can be used for the evaluation of a biomass logistics chain is important [23,24]. Based on diverse literature sources [4,17,21,24], the following logistics audit check list with some critical points (crucial areas) has been prepared and used for the investigation of pruning biomass logistics in the identified 25 PtE value chains:

- **Biomass sources and productivity**: identifying all biomass potential sources (e.g., single source or multi-biomass sources), seasonal variation, and productivity per hectare.
- **Collection/harvesting of biomass**: identifying types of harvesting and collection techniques and/or machines.
- **Purchasing and procurement of biomass product**: considering the (available) supply and demand contracts during biomass procurement, identifying the regulatory interventions and stimulation measures (government programs, tax cuts and exemptions, subsidies, and mandatory blending for biofuels) included in contracts, selection of biomass suppliers, and biomass transport during procurement process
- **Storage and activities at storage level**: types of storages (on-field storage, intermediate storage, or near-plant storage), location of storage facilities, types of pre-treatment methods used, location and capacity of storage for semi-finished and finished products, technical conditions, and facilities of storage infrastructures.
- **Transportation:** type of primary transportation; biomass transport to storage and/or to energy plants; transport of semi-finished and finished products; and management of packaging, loading, and unloading activities.
- **Power plant/biomass consumer characteristics:** capacity, flexibility, and limitation of the plant; types of conversion technologies; condition of machines and transport facilities at the power plant; operation time window; and load factor (percentage of time the equipment used within the operation time window).
- **Information technology (IT) at different levels of biomass supply chain**: identifying types of IT tools, means of communication, and information and data gathering and handling methods at different levels of the PtE value chain.
- **System cost:** This may include investment costs, biomass buying and selling prices, pruning costs, harvesting and processing costs, storage costs, and transportation costs.

- **Sustainability of PtE system:** investigating the economic, environmental, and social impacts; constraints; and opportunities that impact the sustainability of the system; as well as using techno-economic analyses.
- **Performance improvement:** providing recommendations for the improvement of the PtE value chain design and management system.

3. Results and Discussion

3.1. Logistics Configurations and Major Actors

Table 2 and Figure 3 describe the logistics configuration types (LCT) based on the logistics operations in the investigated PtE value chains. From Table 2, it is known that about 60% of the PtE value chains have biomass storage at an intermediate site and/or at farm site. Figure 3 illustrates that biomass can be used as an energy source for the self-consumption or for marketing it. In LCT1, the pruning is collected, stored, and used for own energy consumption by the biomass producer (farmer). In LCT2, the pruning is harvested, temporarily stored on field, and transported to the end user. In LCT2, the collected pruning will be stored at an off-farm storage site and then transported to the end user. In the LCT4 and LCT5 cases, the pruning is delivered to the end user directly, but LCT4 uses storage near a power plant. The harvested biomass could be dried and stored temporally on the field in the form of baling and/or chips. In the case of intermediate storage, the pruning biomass can be collected from multiple fields and biomass varieties. Similarly, there may be multiple end users with power plants of different capacities. Table 3 highlights the major actors and main logistics operations of each of the PtE value chains. Farmers, biomass traders, and end users were found to be the major actors in these PtE initiatives.

Table 2. Major logistics configuration types. PtE—pruning-to-energy.

Logistics Configuration Type (LCT)		PtE Value Chain	
		Number	%
LCT1	Self-consumption (with or without storage), no significant transport	4	16
LCT2	On-farm storage, then direct delivery to final user	6	24
LCT3	Intermediate Storage	9	36
LCT4	Direct delivery and storage at final user	3	12
LCT5	No-storage but direct delivery	3	12
	Total	25	100

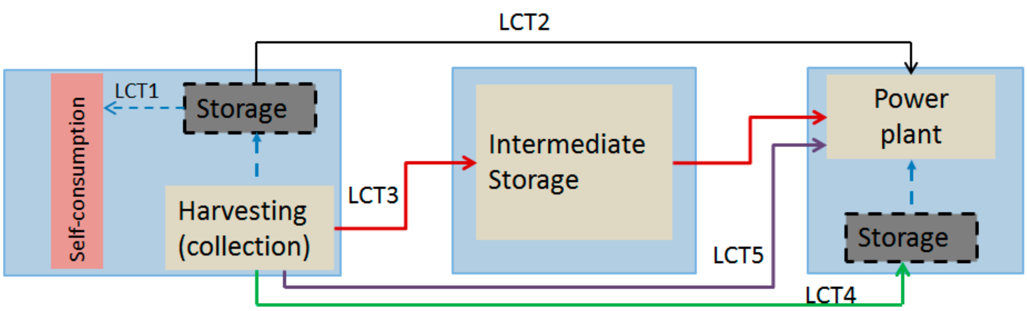

Figure 3. Major logistics configuration types identified in the investigated pruning-to-energy (PtE) chains (source: authors own illustration).

Table 3. Main actors and logistics activities in the 25 PtE value chains investigated in this study.

PtE	LCT	Majors Actors	Logistics Activities
PtE1	LCT3	Farmers, trader (transporter), and end user	Pruning is collected manually, chipped on farm, and transported to end user.
PtE2	LCT2	Farmer, service provider, subcontractor, consumer	Pruning is collected, stored, and chipped at the side of the field (by subcontractor), and transported to the end user.
PtE3	LCT4	Farmer	Pruning is processed into bales and transported to storage for own consumption.
PtE4	LCT3	Farmer and a company owning pelletizing truck.	Pruning is processed into bales and transported to off-farm storage where it will be processed into pellets.
PtE5	LCT3	farmer	Pruning is processed into bales and transported to storage for own consumption.
PtE6	LCT1	Farmer	Pruning is harvested (chipped) and stored for own consumption by the actor.
PtE7	LCT1	Farmers	Pruning is collected, stored on-farm, and chipped for own consumption for heating.
PtE8	LCT2	Farmer (main actor) and consumer	Pruning is processed into bales, stored at farm, and transported to final consumer.
PtE9	LCT3	Farmers, trader with transport, and end users	Pruning is manually windrowed and harvested (chipped) with machine, stored at off-farm storage, and transported to end user for power generation.
PtE10	LCT4	Farmers, pellet manufacturing plant, and final consumers (multiple)	Pruning is collected, stored, shredded at on-farm storage, and transported to where it will be processed into pellets.
PtE11	LCT3	Farmers, trader with transport, storage, and final consumer	Pruning is windrowed, raked and stacked manually, transported to off-farm storage where it is screened and chipped to be used for pellet production.
PtE12	LCT2	Farmers, trader with transport, and final consumer	Pruning is windrowed (by farmers), harvested (integrated harvesting/pre-shredding (by trader)); and completely shredded on-site and transported to power plant for electricity generation.
PtE13	LCT2	Trader, farmer, reseller, and final consumer	Raking of pruning is done using tractor with fork; pruning is piled, stored, and chipped (at on-farm storage site) with forestry chipper, and transported to the final consumer.
PtE14	LCT2	Farmers, service company (with transport), processing plant, intermediary, and final consumers	Pruning is collected, stored at side of farm and transported (bulk branches) to the pellets producing plant which produces pellets and distribute to the final consumers.
PtE15	LCT3	Farmers, service company/trader, and final consumers	Pruning is collected (picking and chipping), stored at off-farm storage, and transported to the final consumer to be used for heating purposes.
PtE16	LCT1	Farmer	Pruning is collected and shredded using own machine and the chips are used for heating purposes (own consumption).

Table 3. *Cont.*

PtE	LCT	Majors Actors	Logistics Activities
PtE17	LCT5	Farmers, trader with transport, and end consumer	Pruning is collected in an integrated windrowing/chipping system, and the chips are transported to the end users with heating plants.
PtE18	LCT5	Farmers, cooperative, transport company, and final consumer	Pruning is collected in an integrated windrowing/chipping system, and the chips are transported to the end users for production of thermal energy.
PtE19	LCT5	Farmers, cooperative, trader with transport, and final consumers	Pruning is collected in an integrated windrowing/baling system, and the bales are transported to the end users with boilers that can consume (burn) pruning bales.
PtE20	LCT4	Farmers	Pruning is collected manually and chipped with a machine, partly used for own consumption, and the rest is transported to the end user (plant nursery) to be stored and used.
PtE21	LCT3	Farmers, service company (trader), and final consumer	Pruning is windrowed and harvested in the form of bales (integrated system), stored and shredded at off-farm site, and transported to end users to produce heat and power.
PtE22	LCT1	Farmer	Pruning is harvested (chipped) and stored on-site for own consumption by the actor.
PtE23	LCT3	Farmer, fruit cooperative, trader (with transport), and final consumer	Pruning collected, shredded, stored at off-farm storage, and transported to the end user in the form of chips.
PtE24	LCT3	Farmer, cooperative, trader, and final consumer	Pruning collected, shredded, stored at off-farm storage, and transported to the end user.
PtE25	LCT2	Fruit cooperative, traders, and final consumers	Pruning is collected, stored on site by fruit cooperative, chipped on site, and transported to the end user for heat and power generation.

3.2. Pruning Activity and Characteristics

In the investigated PtE value chains, the pruning activity is carried out in almost all of the cases, using the manual pruning method with a chainsaw or scissors. In some cases, it is done with the support of lifts (Figure 4). The pruning frequency is mostly annual pruning, while it is biennial for some olive tree prunings. The execution of the pruning operations extends for most of the PtEs between November and March (Figure 5). The period of time that the farmers leave the pruning residues on the soil (before collection/harvesting) varies between 1 to 60 days. In most cases, it stays more than a week. Before the introduction of PtE initiatives, the traditional handling of pruning residues was similar in almost all of the cases (i.e., pruning was piled and burned at the side of the field, mulched, and left on the soil as organic fertilizer, or used partly for local firewood). Branches with larger diameters are all harvested to feed the local fireplace [15].

Figure 4. Pruning activity: assisted manual pruning (**left**) and mechanical pre-pruning (**right**) [25].

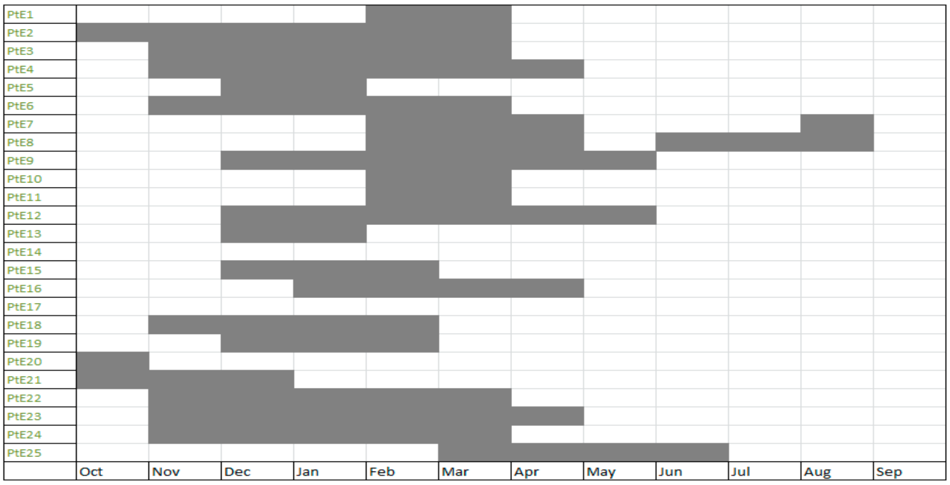

Figure 5. The time duration and season of pruning activities in the investigated PtE value chains (source: authors own illustration).

3.3. Pruning Collection/Harvesting

The collection (harvesting) of pruning residues can be done manually or with machines (Figure 6). It can be collected and hauled to the farm side, where it can be chipped and transported to the final user. Where harvesting machines are used, the pruning can be collected in the form of bales or chips. In some cases, integrated windrowing–harvesting/baling systems or windrowing–harvesting/chipping systems are applied. There is an interest in actors to implement the improved and integrated harvesting systems. But this could be constrained by high investment and logistics costs as well as the availability of end users (biomass consumers).

The utilization of the harvesting machine depends on the biomass availability and the energy demand. From the limited information regarding the minimum required plantation cover required to initiate an attractive PtE, it varies from 2 ha to 1000 ha depending on fruit tree type, age, and pruning productivity. Similarly, the minimum required plantation area to purchase a baling/chipping machine varies from 5 ha to 1000 ha. However, to purchase a new harvesting machine (baler or chipper) and organize an effective PtE value chain, the minimum plantation cover of 100 ha can be recommended, based on the result of this study.

Figure 6. Examples pruning harvesting with chipping and baling systems: pruning chipper (**left**) and pruning baler (**right**) [25].

3.4. Storage Characterstics and Activities at Storage Level

In the investigated PtEs, the pruning biomass could be harvested and directly transported to the end users (without using storage) or could be stored for a limited time. The storage location differs in the different chains. In some cases, both the on-farm storage and off-farm storage facilities have been used. The pruning biomass can be stored in the form of branches, bales, or chips (see Figure 7). About 9 of the investigated PtEs use on-farm storage, while about 12 PtEs use off-farm storage facilities. The storage at the farm site is often exposed for contamination with impurities, as it uses mostly agrarian soil floor. As on-farm storage is used in many cases, attention should be given to improve handling at on-farm storage and improve biomass quality. The intermediate storage and a storage adjacent to the final consumer facilities use mostly either paved floor or compacted earth floor, which could reduce impurities such as soil and stones.

The size and capacity of the storage depends on the amount of biomass handled and the available storage area. In the investigated PtEs, the storage area varies from 30 m^2 to 9000 m^2, while the capacity (in terms of biomass handled) varies from 40 m^3 to 90 m^3 annually. Regarding the cover of the storage, about 24% of the PtEs use roofed or closed bay storage, while about 52% have open air storage. In some cases, although the storage is roofed, the material remains uncovered, and this may expose the biomass to deterioration and limit the reduction of moisture.

Figure 7. Examples of storage of pruning biomass in the form of bales (**upper**) and chips (**under**) [12].

3.5. Transport

Different transport distances have been identified for different PtE cases. In the existing 16 pruning chains, the farm-to-consumer distance varied from 2–60 km (4–120 km round trip), while the average value is about 43 km (Table 4). For comparison purpose, the pruning transport distances considered in project demonstration activities are provided here. In case of Germany, the round trip from farm-to-consumer was about 171 km, while it was about 679 in Spain. The higher values in these two cases of demonstration indicate that long distances have been considered during the demonstration cases when compared to the distances recorded during the data survey from the existing pruning biomass supply chain. The PtE systems could be economically more attractive if there are end users in the vicinity of the planation area.

The farmers usually own tractors and small vehicles with trailers for inside farm transport activities. The pruning transport to the storage, and from the storage to consumption site, is often carried out by transport companies or service providers who also organize the PtE systems. In the case of short distances of farm-to-storage transport, the trailers with a smaller volume (3–10 m^3) capacity are often used. For transport from storage-to-consumer or for long distance transport from farm to off-farm storage, vehicles used vary from 16–100 m^3 volume capacity. In more than 56% of PtE chains, vehicles with a capacity of more than 15 m^3 have been used. It was also noticed that it is difficult to get and assign appropriate trucks at required time to implement PtE value chains.

Table 4. Average transport distances (round trip) for different PtE information sources.

Description	Farm-to-Storage (km)	Storage-to-Consumer (km)	Farm-to-Consumer (km)
Data survey for 16 existing chains	15	28	43
Data survey for all 25 chains	14	116	130
Project demonstration activity in Spain	317	362	679
Project demonstration activity in Germany	48	123	171

3.6. Power Plant Characteristics

In this study, the focus was to investigate the pruning biomass logistics chain from the collection/harvesting stage to transport to the gate of the end user. The quality requirements in this project have been a starting and final point. The prunings can be used (in the form of bales or chips) by a boiler to produce heat or power (Figure 8), or can be processed into pellets. The use of the energy from PtE includes heating energy for household, offices, public buildings, swimming pools, and industries. Power plants that generate electric power consume more biomass. In the investigated PtE value chains, the plant size in terms of the energy capacity varies from 10 kWth (thermal kW of boiler/gasifier) to 95 MWth.

Figure 8. A boiler where a biomass bales are used in Spain [12].

In this study, it was noticed that many of final consumers have doubt regarding the quality of pruning biomass (for instance, how free is it from impurities, such as soil, metals, and stones; how appropriate is the size of chips or bales; and how sustainable is the pruning biomass supply). Therefore, in initiating new PtE value chains, the consultation with potential final consumers is very essential.

3.7. Information Flow along PtE Value Chain

As biomass products flow along the logistics chain, an appropriate information flow is important. This facilitates the interaction between different actors in the PtE value chain, the management of logistics operations, and quality control, so as to reduce the biomass loss and damages on power plant facilities (due to impurities like metal and stones). From this point of view, the information flow and biomass quality control characteristics have been assessed in each of the 25 PtEs. The main means of communication among the different actors of the PtE value chain include personal communication, workshop, phone, internet, email, and meeting. However, there is no pruning biomass labelling and traceability system in almost all of the existing PtE chains. On the other hand, in the implementation of the PtE value chain, traders pinpointed that there is a need to have a certification system for wood as biomass, to track their origin and for pruning quality identification.

The biomass quality parameters such as moisture content, chips size, and bale size should be available and communicated appropriately among the chain. Out of the studied 25 chains, about 75% have information on the moisture content. Other information such as the blending of the pruning biomass, the chips size, and the bale size are mentioned, in most cases. Out of the 25 PtEs, about 16 PtE value chains have limited quality control activity. The major biomass quality control method is visual inspection, in order to reduce the contamination with soil and other impurities. Some end consumers have moisture content and ash content and chip size requirements. Regarding biomass quality issues, major concerns are how to reduce impurities (soil particles, stones, plastics, and metal wires), how to avoid stones and earth materials during loading, how to reduce the excessive heterogeneous nature of the material, and how to remove some large pieces from the pruning biomass.

The result of the study indicated that, for the continuous traceability information flow with adequate biomass quality parameters, effective and well-organized information flow along the PtE value chain should be developed. Appropriate information is also required to start the PtE initiative and to implement it effectively. In this regard, the main sources of information are identified as websites, magazines, conferences, advice from other actors, and companies. However, there was no clear information found regarding the appropriate training programs that could be provided to main actors, especially for PtE value chain organizers.

3.8. Purchasing and Procurement of Biomass

The PtE could be for self-consumption by the farmer (or company owning the yard), or for processing and trading pruning products for renewable energy. If the traders (service providers) organize and manage the PtE system, farmers allow other actors to harvest and take the prunings for free in most cases. In some cases, the traders may purchase the pruning for lower prices. The traders sell the processed products (chips and bales) to the final users. In such cases, the agreement with farmers is often simple; the farmers would only have to place the pruning aligned in the rows to facilitate the harvest while the service provider should harvest, process, and sell it. When the procurement agreement between farmers and service providers, as well as between service providers and final consumers, is well-coordinated, the service providers could execute the harvest sufficiently fast, so that the prices in the market allow a reasonable profit margin for them. In this regard, the reliability of the agreement between the PtE organizer and the final consumer is very important for the initiation and sustainability of a PtE system. The biomass product (chips or bales) selling price in the region and the expected revenue by the respective actors impacts the procurement and marketing of the pruning biomass for energy use. The product selling price and expected revenue information are presented in Table 5, together with the logistics operational costs estimated for each PtE value chain. Table 5 presents the product selling price for 15 PtE value chains, and it ranges from 45 €/t to 70 €/t for the chips and from 37 €/t to 73 €/t for the bales (however the number of PtE chains with bales is few in this case). However, when the data in Table 5 is used, the region (country) of each PtE should be taken into consideration, because the biomass prices and/or the PtE based renewable energy price varies in different countries or regions.

3.9. System Cost

The cost of the PtE system varies because of different factors, such as the biomass productivity of the area, performance of machineries (used to collect and process the pruning biomass), species and age of fruit tree, biomass storage and handling conditions, and the transport distance. The cost related data gathered at different stages of the logistics chain in each PtE has been compiled. The investment cost information was not exhaustive and was difficult to use for comparison analysis. However, the available investment cost data for each PtE was also gathered and used as a relevant reference for further economic analysis. Vineyards, olive, and fruit tree pruning operation costs were also was gathered, where available. From the available data, the agricultural pruning activity costs were from 80 €/ha to 7100 €/ha, depending on age and species of trees, the frequency (annual, biennial, every 10 years etc.), experience of worker, and equipment used.

As agricultural tree pruning is a regular activity of farmers, it is mainly a product orientated work, not being included in the costs for obtaining the pruning biomass. Therefore, in the assessment of the PtE system cost, the focus was on the investment and operational costs at the harvesting, storage, and transport stages. Accordingly, estimated total operational costs for each PtE have been presented in Table 5. For the PtE where the biomass is supplied to final consumer in the form of bales, the total operational cost varies from 27 €/t to 149 €/t. One of the major reasons for this variation is transport distance. For example, for PtE3, the final consumption site is at about 5 km from farm site, while for PtE19, the consumption site is about 280 km far away from the farm site (Table 5). Similarly, for supplying the biomass in the form of chips, the estimated operational cost varies from 32 €/t to 123 €/t. In this case, the distance from the farm to consumption site is about 20 km (for PtE12) and 140 km (for PtE18), respectively. It is important to notice that, in addition to transport distance, the operational cost depends on specific logistics conditions in each PtE value chains and also on quality of data obtained from actors.

From the literature, the operating costs at the machine-based harvesting stage of pruning varies and could be as high as 60 €/t [9,26–30]. Considering the harvesting (and moving to roadside) of prunings from apple, pear, and vineyards, at moisture content from 37% to 48%, Magagnotti et al. [30] estimated the operating cost to be between 11–60 €/t^{-1}.

When compared with the selling price information, the logistics operation cost is greater than the product selling price by about 17% on average. On top of this, there are costs due to biomass loss (during handling after collection/harvesting) and investment costs (for harvesting, storage, and transport operations), which increase the costs of processing and supplying pruning biomass products. This indicates that the PtE value chain organizers need to introduce improved processing and supply systems of the pruning biomass. On the other hand, regarding the information on the minimum expected revenue (Table 5), the value ranges from 30 €/t to 80 €/t. This indicates that the available pruning biomass selling price is good, so as to fulfil the expectation of the biomass suppliers. However, the operational and investment costs are found to be high, and need to be reduced in order to make PtE initiatives sustainable.

It is worth adding to this discussion the fact that service providers (traders) make a profit, as they often take prunings for free or buy from farmers for a lower price (farmers want to avoid prunings from the farm area). The farmers benefit from saving money or time and reducing their efforts of pruning wood management. A pruning wood value chain to be set-up successfully requires that the actors involved have a gain, either in economics or in other benefits, such as saving time. A point to be always observed is the avoided cost (i.e., farmers save cost of pruning management when they join PtE initiatives).

Energy policies should promote the utilization of renewable raw materials such, as pruning biomass, in order to address the environmental concerns [27]. This needs the design of cost-efficient biomass supply chains, because, these chains involve the supply and processing of a large volume of biomass, which could lead to a higher financial cost and environmental cost [31].

Table 5. Estimated total operational cost considering the harvesting, storage, and transport stages, in comparison with the product selling price and minimum expected revenue.

PtE Value Chain	Logistics Configuration	Country	Species	Operational Cost (Harvesting, Storage, Transport)	Minimum Expected Revenue from PtE	Selling Price (Related Product Type in Next Column)	Product Type (Related to Indicated Selling Price)	Affordable Energy Price (% More Than Fossil Energy)
				€/t	€/t	€/t		
PtE1	LCT3	Germany	Apple, cherry, pear, and plum with age of 50 years.	53	na	60	chips	na
PtE2	LCT2	Germany	Apple and pear trees of 50–60 years age	95	62	63	chips	na
PtE3	LCT4	France	Grape (merlot 95%, cabernets francs 3%, and cabernets sauvignons 2%)	27	na	na		na
PtE4	LCT3	France	Grapes for wine from tree; age 4–35 years.	51	na	na		na
PtE5	LCT3	Italy	Grapes from vineyards	114	50	70	chips	na
PtE6	LCT1	Italy	Vines, apricot, and olive trees, age 4–20 years	40	na	na		na
PtE7	LCT1	Poland	Apple, pear, peach, cherries, and nuts; age 1–25 years	101	na	na		na
PtE8	LCT2	Poland	Apples of 1–20 years old	44	75	73	bale	15
PtE9	LCT3	Spain	Olive trees of 100 years	55	80	55	chips	10
PtE10	LCT4	Spain	Olive of 70 years	54	50	na	chips	10
PtE11	LCT3	Spain	Cherry, almond, carob, olive, vineyard, orange, and lemon tree	76	na	na		25
PtE12	LCT2	Spain	Olive trees	32	na	37	branch	5
PtE13	LCT2	Spain	Olive tree	46	na	45 *	chips	20
PtE14	LCT2	Spain	Vineyards	26	na	65	chips	na
PtE15	LCT3	Spain	Vineyards with age 2 to 30 year	102	50	70	chips	10
PtE16	LCT1	Denmark	Apple, pears, and plums of 12–14 years old	44	na	na		15
PtE17	LCT5	Germany	Apple, 15–20; cherry, 30–40; plum, 20–25; and peach, 15–20 years old	73	na	70		na
PtE18	LCT5	Spain	Almond of 30 years old	123	na	70	almond shells	5
PtE19	LCT5	Spain	Vineyard of 5–15 years age	149	na	60	straw bale	
PtE20	LCT4	Spain	10 years old peach and 1 year old almond	56	30	58	chips	na
PtE21	LCT3	Spain	Peach of 8–12 years	80	na	58	chips	na
PtE22	LCT1	France	Grapes for wine	44	na	na		na
PtE23	LCT3	France	Vineyard of 20 (years).	152	na	na		10
PtE24	LCT3	France	Vineyard of 20 years old (40 years of typical renovation age).	68	na	na		15
PtE25	LCT2	Poland	Apple of 35–40 years old	31	70	70 **	chips	15

* When the chips are classified, their price is about 65 €/t; ** for the branches it is 5.25 €/t; na—not available.

3.10. Sustainability of PtE System

3.10.1. Biomass Losses along the PtE Chain

Excessive biomass losses along the logistics chain compromise the sustainability of PtE initiatives. In the investigated 25 pruning chains, the maximum total biomass losses along each supply chain could be as high as 37% (in case of chips) and 32% (in case of bales). The highest loss occurred at the collection (harvesting) stage and storage stages. The losses during transport are not significant and, if any, are mainly related to the handling during loading activities. Therefore, in Table 6, the loading/handling loses are included in the losses at harvesting/collection and storage stages for simplicity. The average loss along the chain (harvesting, storage, and transport) is 12% for chips and 16% for the supply in the form of bales.

Table 6. Summary of average biomass losses for identified PtE value chains.

Average Losses	Chips (%), Range	Bale (%), Range
Harvesting	9.22 (0.2–27.0)	9.42 (1.0–22.00)
Storage	6.7 (0.3–15.0)	2.84 (0.2–10.00)
Total chain	12.39 (0.50–37)	15.45 (1.20–32.00)

3.10.2. Major Constraints and Knowledge Gap Identified along the PtE Value Chain

In order to propose necessary interventions, it is important to identify constraints along the logistics chains. The major barriers hindering the implementation of PtE initiatives include a lower awareness level of farmers and end users regarding the PtE value chain; a lack of well-established model (experience) to follow; uncertainty in the pruning supply and its profitability (high cost of the system especially initial investment cost but lower energy price on market); and losing the opportunity to use pruning as an organic fertilizer on the soil. Table 7 presents a comprehensive summary of the identified constraints at each logistics stage, along with the proposed action measures to improve the system. These constraints were identified based on the information gathered from the data survey.

In addition to the barriers mentioned above, which hinders the implementation of PtE initiatives, there are major knowledge gaps that have been identified while investigating the 25 PtE chains. There is a lack of adequate knowledge on the profitability of the PtE system. Especially, it is a difficult task for farmers to make cost calculations. Many actors need to know profitability before investing in the PtE value chain. Therefore, a rigorous economic analysis is required, taking into consideration the different geographical areas. The profitability related analysis results should be communicated effectively. There is only limited awareness of people regarding the economic and environmental values of the PtE system. Therefore, awareness creation should be planned and implemented in the regions where good pruning biomass potential exists.

Reliable information on the pruning biomass quality parameters and the availability of biomass is not easily available for potential actors to use during decision making, in order to start aPtE initiative. Especially for farmers who want to join the PtE initiative and sell pruning biomass, but they do not know how to calculate their biomass potential. Therefore, more research should be conducted and such reliable data should be compiled and made available in local languages to promote the use of renewable PtE. There is no well-organized information flow and system to manage the PtE value chain effectively and efficiently. Therefore, where an improved pruning processing and distribution system is planned, it should be augmented with an efficient management system in which the traceability of information can be integrated effectively [32].

It is difficult to know if leaving pruning on soil as an organic fertilizer has more value than the PtE value. According to the experiences of some actors in the PtE value chains, leaving pruning on the soil could spread tree diseases, while some respondents disagree regarding the spread of fruit tree diseases. In addition, the consequence of the storage on the quality of the biomass is not well known by many actors of PtE. These issues should be addressed by conducting an in depth scientific analysis.

Table 7. Major constraints and proposed action measures.

Stage Along Chain	Major Constraints	Proposed Action Measures
Entire PtE chain	• Traditional handling of pruning is non-competitive. • Biomass quality and quantity problems. • Cost of developing the entire PtE logistics system. • In some cases, there is lack of real market, and local administrative offices are not really interested and not ready to promote the initiative. • Farmers need to get rid of pruning as fast as possible. On the other hand, pruning should stay in the field to lose moisture content. • There is a PtE management problem.	• Introducing improved distribution/transport system, pruning and harvesting, and storage systems in order to improve the whole supply chain. • Introducing effective harvesting machineries, storage, and transport systems. • Improving the biomass quality to produce quality fuel and be competitive. • Awareness creation about the benefits of the PtE value chain.
Harvesting	• Difficulty in identifying appropriate harvesting machineries for each pruning supply chain. • Pruning collection (windrowing and baling/chipping activities are costly and time consuming). • Harvesting operation can be affected by on farm structures, such as irrigation ducts. • Lack of getting enough areas for compiling piles in some cases. • Soil irrigation systems may be damaged during on-farm activities. • Operating harvesting machines is not easy in some cases. It is not possible to collect the product with the same system for all fields. • High biomass loss. • Harvester may have loud sound.	• Employees should use hearing protectors. • Improvement of harvesting operation can be done via some modification to the machine (e.g., modifying knives). • There should be enough space at the end of the field in order to facilitate pruning and harvesting.
Storage	• Chips could be contaminated with impurities like soil, stone, and metals. • Pruning biomass damage and loss (e.g., wet bales could decay if remained on soil for long time or deterioration of biomass due to lack of appropriate cover during storage). • Risk of fire. • Inadequate space for the piles and distance to the stockpiles. • Wide occupied area (e.g., due to inappropriate packaging). • Lack of adequate space for the piles and distance to the stockpiles. • Dust problem during chipping process at storage. • Problems of rabbit proliferation occur when the storage time is longer.	• Designing storage with appropriate floor, adequate space for piles, appropriate storage cover, and roofed area. • Collecting bales at the field side to reduce possibility of decay due to contact with soil. • The biomass storage should be under a cover, preferably with side walls allowing ventilation, in order to reduce losses and facilitate a reduction of moisture. • Increasing safety measures to reduce the risk of fire

Table 7. *Cont.*

Stage Along Chain	Major Constraints	Proposed Action Measures
Transport	• Pruning transport is costly due to inappropriate packaging (less weight per unit volume), high cost of loading and long-distance transport. • In transporting bales, difficult to optimize the number of tons transported in each truck. • Location of power plant (i.e., if power plants are far from field and production is low, the transport cost will be high). • Inefficient on-farm transport; Problem of access to the plots for the collection of pruning. • Difficulty to get and assign appropriate trucks and loading/unloading related problems. • Inaccessibility to the field where the biomass is placed.	• Introducing appropriate packaging system to increase weight per unit volume of biomass and reduce transport cost and space for storage (e.g., introducing baling system). • To optimize the transport, crushed biomass is best carried in bulk, and the transport distance (farm-to-consumer) should be reduced (i.e., identifying more end users in vicinity of biomass field).
End user	• Traditional use for fire wood has high emission and low efficiency. • Unavailability of many final consumers with appropriate boilers for pruning biomass consumption. Available boilers might not be designed (prepared) for chips or bales combustion. • Uncertainty in pruning biomass quality and quantity. • Convincing consumers to start using a PtE energy source is not easy. • Problems with the boiler efficiency due to the presence of impurities in the biomass and/or moisture content related problem. • Chip size might not be to the required size (there may be difficulty to get pruning products with characteristics that fit to the existing consumers biomass characteristics).	• Introducing effective boilers that can use pruning biomass products. • Improving pruning biomass quality and encouraging power plants (end users) to join PtE value chain.

3.10.3. Benefits of PtE and Opportunities to Promote Sustainability of PtE Initiatives

From the investigation of the PtE value chains, there are benefits recognized by different actors of the PtE value chains. These are important to develop more effective PtE systems with increased sustainability. The major perceived benefits of PtE include the followng: PtE has commercial and environmental values (e.g., burning of pruning on field is avoided and the risk of fire is minimized); the PtE concept is considered as a good idea that has commercial and environmental value; some actors perceive that PtE could reduce the spreading of fruit tree diseases; PtE initiative enables farmers save time and money since they do not involve in further pruning handling and management activities (e.g., avoiding mulching and/or burning of pruning in open air); and the PtE initiative also enables pruning biomass traders and cooperatives to create new business line and generate revenue. When used for self-consumption, it reduces the use of fossil fuels.

Additional opportunities to increase the sustainability of PtE initiatives include the following: the possible coordination among smallholders and between smallholders and other actors; high awareness of some stakeholders on environmental sustainability; satisfaction of some actors with PtE initiative they have involved by proving that it can be profitable and leads to sustainable PtE value chain; in some PtE chains, there is interest of the major actor and farmers to establish effective PtE system and commercialize it; there is interest of research institutes and agrarian consultants to involve in investigating and promoting PtE value chain; opportunity to generate employment opportunities and diversify the income of the stakeholders; the possibility of using existing companies dedicated to managing forestry and agricultural residues; national funds may be acquired to support PtE initiatives; and the existence of satisfactory PtE value chains and the possibility of utilizing available information and experience for future PtE development.

3.10.4. Interventions Recommended to Increase the Sustainability of PtE Initiatives

In order to highlight how to use the available opportunities to develop an effective and efficient PtE value chain and increase its sustainability, the following recommendations are provided, based on this study.

- Encouraging the producers by designing competitive and cost effective PtE system that reduces biomass losses, mainly at the collection and storage levels.
- Establishing a PtE initiative in the area where pruning biomass is available, to guarantee the pruning supply.
- Introducing a best system design for the PtE chain (i.e., integrated harvesting/chipping process and supply of chips instead of bales).
- A cooperative approach should be used, including many farmers, local administrators such as municipalities, and relevant companies, which are very important to establish sustainable pruning biomass to energy value chain.
- Creating network of similar PtE value chains and integrating the society as means of cooperation can promote the sustainability of PtE initiatives, where it is economically feasible.
- Involving the consumers at the initial stage of the PtE initiative so that it facilitates the implementation of the PtE initiative.

In general, pruning biomass can be produced for self-consumption or it can be commercialized. In the case of own consumption, there is no need for significant transport and more attention should be given to the improvement of harvesting and storage facilities. In the cases where many actors are involved in developing coordinated PtE value chains, an integrated harvesting system with appropriately designed intermediate storage is recommendable. This storage site can be used as a centre of management, where central information platform with smart logistics systems can be introduced to facilitate management of entire PtE logistics chains and reduce system cost. In order to set up an effective PtE initiative, it is important to identify and map optimal locations biomass potential, storage, and/or power plants, reducing the time, distance, and transport costs [33]. Performance measurement is important to understand the competitive status of firms [34], and this logistics audit analysis approach was found to be effective to evaluate PtE initiatives and can be used to promote the sustainable use of renewable energy resources.

4. Conclusions

The description of pruning biomass logistics chains has been carried out in order to identify the major logistics operations along the pruning supply chain from the field (farm) to the final consumer, and to identify the critical points for intervention. The assessment of the pruning-to-energy (PtE) value chain was done by conducting a literature-based description of the basic characteristics of the biomass supply chain; developing the logistics audit criteria; and conducting a logistics audit analysis to evaluate the performance of the PtE initiatives.

In general, 25 PtE value chains were identified (from Germany, Spain, Italy, Poland, France, and Denmark), and their logistics performance has been systematically analysed. The direct survey based on a comprehensive questionnaire was used to get the data for each PtE value chain. The surveying work targeted major actors such as farmers, traders and transporters, service providers (processing such as chipping and baling), relevant experts, and the end users of biomass. In this logistics audit analysis approach, the whole logistics chain, from fruit tree pruning to the final consumption, has been considered, with a main focus on harvesting, storage, and transport activities. The logistics audit check list was prepared to include the major characteristics of biomass to be assessed, namely: pruning biomass sources (species) and productivities, harvesting systems, storage characteristics and biomass treatment activities at storage, biomass transport, biomass quality and traceability information flow along logistics chain, biomass procurement and PtE system cost, and the sustainability of PtE initiatives.

Although the investigated PtE value chains have different logistics configurations and operate in different regions, which make it difficult to make general conclusions, the values of the important parameters can be presented in the following ranges:

- Biomass losses (at harvesting, storage, and transport) vary from 0.5% to 37% for chips, and 1.20% to 32% for bales.
- Estimated total operational cost (at harvesting, storage, and transport stages) ranges between 27 €/t and 149 €/t (wet base) when supplied in form of bales, and 32 €/t to 123 €/t for the case of chips.
- Pruning biomass selling price varies from 45 €/t to 70 €/t for chips and from 37 €/t to 73 €/t for bales.
- Expected minimum revenue from PtE business ranges between 30 €/t and 80 €/t.
- In order to purchase harvesting machines (baler or chipper) and initiate an attractive PtE value chain, at least about 100 ha of plantation size is recommendable.

The major identified constraints affecting the PtE chains include a difficulty in identifying a suitable harvesting, storage, and transport system, as well as the related high investment and operational costs; biomass losses at harvesting and storage site; contamination of biomass with impurities such as soil, stones, and metals; increased transport cost due to increased transport distance, lack of appropriate trucks, and/or loading/unloading systems; and less trust of final consumers on the quality and quantity of the pruning biomass supply for existing boilers or to invest in new power plants. The results of this study can be used as an important benchmark for conducting more investigations of PtE initiatives, and for creating an efficient pruning biomass value chain and trading systems. This enables us to promote the development and utilization of renewable energy sources.

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