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The Logistics of Bioenergy Routes for Heat and Power

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1. Introduction

This chapter aims to overview the logistics of bioenergy systems, focusing on the economic and sustainability implications of the different transport, processing and energy conversion systems for heat and power generation. The main research trends of biomass processing, decoupling of treatment and energy conversion, integration into existing infrastructures and energy systems, and optimal location and sizing of bioenergy facilities are reviewed. For this purpose, a description of supply chains modelling and research trends, technical options and related cost figures for the various steps of the biomass supply chains are overviewed. Moreover, the opportunities to integrate bioenergy into existing energy systems are explored, investigating the use of biofuels in combination with fossil fuels into existing plants and networks. Finally, the main research trends in the optimization of scale and location of the different steps of bioenergy routes are overviewed.

2. Biomass supply chains modelling and key issues

The term “biomass” includes several typologies of organic based materials that can be processed in a variety of methods to produce biofuels and bio-products suitable for several markets, such as energy, industry and food. An overview of bioenergy pathways is reported in Figure 1.

When evaluating bioenergy routes, a system perspective has to be taken, encompassing components such as biomass resource, supply management, processing and conversion systems, energy services. In fact, developing sustainable bioenergy from a economic, environmental and social point of view requires an optimization of the structure and functioning of the supply chain/networks, adjusted to the specific conditions of the production

systems (climate and topology, feedstock, technologies, infrastructures, energy end uses, etc). Steps such as biomass harvesting, storage, refining and transport are particularly relevant, and should be facilitated by suitable logistics of supply chains and operations management techniques.

Bioenergy models, as energy models in general, are useful in problems such as projecting future energy demand and supply, assessing the impacts of different energy technologies and energy efficiency measures, optimizing the operations of energy generators. In recent years, the total number of available energy models has grown tremendously, and various classification schemes that provide insight in the differences and similarities between energy models are available in literature, as reported in Table 1 [1-3]. One of the problems with classifying energy models is that there are many possible categories, while there are only few models that fit into one distinct category. In general, model design requires a trade-off between representational fidelity, model performance, and flexibility to multiple contexts. It is also evident that there is no energy tool that addresses all issues, but instead the 'ideal' energy tool is highly dependent on the specific objectives that must be fulfilled.

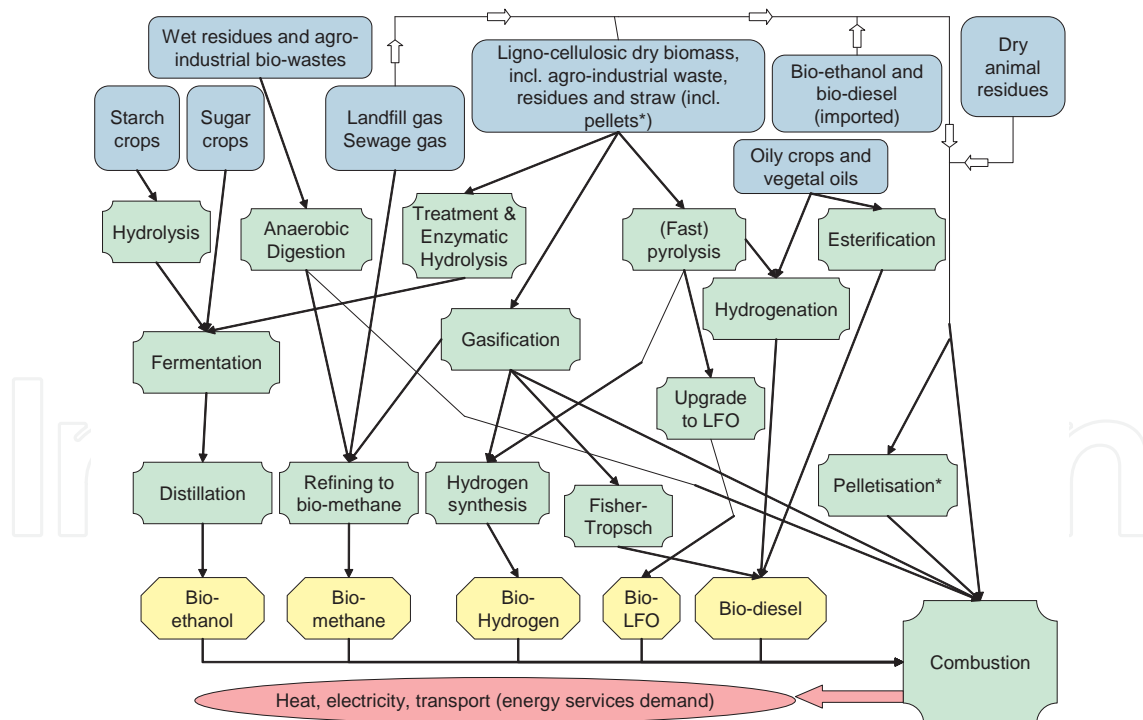


Figure 1. Simplified bioenergy conversion systems pathways

Classification criterion	Description
1. Purposes of Energy Models	General: potentials assessment, forecasting Specific: energy demand, biomass supply, impacts, appraisal, integrated approach, modular build-up
2. The Model Structure: Internal & External Assumptions	Degree of endogenization, description of non-energy sectors, description end-uses, description supply
3. The Analytical Approach	Top-Down or Bottom-Up
4. The Underlying Methodology	Econometric, Macro-Economic, Economic Equilibrium, Optimization, Simulation, Spreadsheet/Toolbox, Backcasting, Multi-Criteria
5. The Mathematical Approach	Linear programming, mixed-integer programming, dynamic programming
6. Geographical Coverage	Global, Regional, National, Local, or Project
7. Sectoral Coverage	Energy sectors or overall economy
8. The Time Horizon	Short, Medium, Long Term
9. Data Requirements	Qualitative, quantitative, aggregated/disaggregated

Table 1. Classification of energy models for bioenergy

In Table 2 the key factors in bioenergy modelling and biomass supply chains optimization are proposed. In particular, these factors include: (i) the biomass/biofuel chemical-physical properties (moisture, bulk density, LHV, ashes, metal contents, total solids and volatile solids percentages, etc), processing/handling properties (hydrofobicity, storability, grinding, odours, etc) and their influence on transport, storage, drying, conditioning and processing steps, (ii) the biomass seasonality and economic factors such as the relationships between quantity and timing of withdrawal and unitary supply costs. The integration of GIS based tools allows to assess the location over the territory of biomass potentials, transport, storage and processing infrastructures, and final energy demand sites. When estimating biomass potentials in bioenergy models, the factors that are commonly taken in account are the land uses, existing and competing uses of biomass, yield estimates and influence of environmental conditions (such as weather conditions). Moreover, sustainability issues such as direct and indirect land use change, energy inputs in biomass production, harvesting and processing steps and food vs no-food dynamics should also be accounted for. Logistics and infrastructure aspects are also crucial factors. In particular, both the various biomass/biofuel transport modes (ship, road, rail) and biofuel/energy distribution options (pipelines, networks, road) should be taken in account. Moreover, biomass storage and processing infrastructures should be considered, both in the case of existing and new facilities. In the processing and energy conversion steps, both the biomass to biofuel and the biofuel to energy technologies should be modelled. In order to take in account the trade-offs between large/small biomass supply radius (and related transport costs) and large/small biomass processing and conversion facilities, including the potentials of decentralized small scale plants, factors such as scale economies and influence of size on process efficiencies at various conversion technologies should be considered. Moreover, the presence of existing energy infrastructures and the options for biomass co-refining or biomass co-firing in existing fossil fuel plants should be considered, in order to evaluate the opportunities of integration of bioenergy into existing energy systems. Bioenergy modelling should also take in account

the options of coupling vs decoupling of processing and energy conversion plants, as discussed in next section. When investigating these integration opportunities, an accurate modelling of biofuel properties and their suitability for dual-fuelling in conventional plants is particularly important. Finally, in order to favourite bioenergy plants locations near to the energy demand, thus maximizing the energy, environmental and economic benefits of these routes, a proper modelling of the energy demand and its suitability for biomass/biofuel uptake is very important. The assessment of potential energy demand regards both stationary applications (heat/cool/power) and fuels for transports. In the first case, the optimization of biomass fired cogeneration or trigeneration (heat/cool/power) plants (in terms of size, locations and technologies) requires, other than the previously mentioned factors, a proper modelling of: (i) energy demand patterns (daily and seasonal variation of energy demand), (ii) quality of heat demand (temperature of heat/cool required), (iii) existing energy supply systems and related costs (baseline scenarios), (iv) subsidy regimes for bioenergy.

In order to address the specific issues of bioenergy, several methods have been used to model and analyse different aspects of the agricultural and forestry biomass logistics system. A number of basic models have been developed in literature to calculate the costs and compare different handling chains and strategies [4-6]. The recent development of advanced computational tools strongly contributed to the improvement of mathematical models for analysis and optimization of such complex supply and logistic systems [7-12], even if the contribution of these methods in biomass logistics could be limited by the high complexity and dynamic environment of bioenergy.

Biomass	Territory and potentials	Infrastructures and logistics	Processing-energy conversion	End uses
Temporal biomass availability (seasonality)	Biomass supply location over the territory	Transport systems	Biomass to biofuel technologies	End use typology
Biomass quality	Accessibility issues and available transport modes	Storage and processing infrastructures	Biofuel to energy technologies	Baseline energy scenario
Handling properties	Land uses and biomass yields estimates	Energy infrastructures and integration options (district heating, gas networks, pipelines)	Economies of scale, efficiencies	Energy demand patterns
cost vs quantity biomass	influence of environmental conditions		Processing-conversion coupling vs decoupling	Quality of energy demand
	Alternative and competing uses of biomass		Biofuel suitability for conversion processes	Subsidy regimes for bioenergy

Table 2. Classification of key factors in bioenergy modelling

Moreover, although many researches have an energy system approach, few actually use models that account for the many trade offs and the alternative handling options in the design of whole biomass supply chains. A detailed dynamic simulation program for harvesting, storage, pre-processing and transport of biomass, the IBSAL model, is proposed in [13]. It assumes time and space dependent availability of biomass under the influence of weather conditions and predicts the number, size and location of equipment needed to meet a certain demand. It also calculates the biomass supply costs, energy inputs and emissions, taking in account factors such as the operational parameters of the machines and storage constraints. One of the major innovations consists on the use of non-linear equations to describe these dependencies, e.g. a third-degree polynomial to represent the moisture content as a function of number of days since the start of harvest, or a gamma distribution to simulate the time dependent biomass availability during the harvesting period. However, the methodology is applied to corn stover supply and the implementation to different typologies of feedstocks and agricultural machinery systems would require specific experimental data to inform the model. Moreover, the model is only focused on the supply side and does not include any biomass to energy conversion process or final end uses. To partially overcome these limits, an evolution of the IBSAL model is proposed in [14]. The improved model assesses the logistics of multi-biomass supply and related storage issues to feed a cellulosic ethanol production plant, by a stochastic model with variable input data, such as weather, yields and machine breakdowns. The specific research problem is, in this case, to evaluate how the feedstocks daily demand of the plant can be met throughout the year, what is the cost of the agricultural logistic system, and what are the possible bottlenecks of the supply chains. However, the research does not propose an explicit storage and transport optimization strategy, that could be useful in order to minimize the supply area to meet a given demand, define the optimal location and sizing of storage facilities or scheduling for transport operations. Moreover, the research is focused on a single end-user facility and tailored for a very large straw supply chain and ethanol plant (capacity of 70 million litres/year). Specific issues arising from dispersed and small scale farming techniques, tortuosity of transport networks, land accessibility and ground slope, different storage techniques or other techno-economic factors should be captured when implementing this approach in different agricultural scenarios.

In [12] the storage and transport issues of biomass are assessed and the application to relevant case studies is proposed. In particular, the storage problem and the advantages of a multi-biomass supply chain on the logistic costs are evaluated. The use of intermediate storage locations between the fields and the power plant is often required for several logistic, economic, agronomic and environmental reasons. On the other side, the option of settling the storage facility next to the biomass power plant requires a storage layout with biomass drying capability using dumped heat from the power plant. This concept aims at reducing faster the biomass moisture content and prevents material decomposition as well as fungus and spores formation. In [12] three biomass storage solutions are compared, in terms of total system cost. The concept of multi-biomass is adopted in its simplest form, since two locally available biomass types are considered. The biomass supply chain modelling considers the seasonal availability of the resource, which requires very large storage of biomass for a sig-

nificant time period, if year-round operation of the power plant is desired. The limited time frame for collecting a large amount of biomass leads also to significant seasonal need of resources, both equipment and workforce. This seasonal demand may increase the cost of obtaining these resources, while leading to suboptimal utilization of resources, particularly of the storage space. The multi-biomass approach may reduce these problems significantly, if the biomass availability is properly shifted over the time. Another characteristic of the biomass supply chain is that it has to deal with low-density materials. As a result, there is increased need for transportation and handling equipment, as well as storage space. This problem is enhanced by the low heating value, which is partly due to the moisture of most agricultural biomass types. The low density of biomass increases further the cost of collection, handling, transport and storage stages of the supply chain. Finally, several biomass types require customized collection and handling equipment, leading to a complicated structure of the supply chain.

In [15], a linear mixed-integer model is proposed, that includes resources, handling/processing, storage and end uses. It is based on the wider *eTransport* model [16], developed for expansion planning in generic energy systems where several alternative energy carriers and technologies are considered simultaneously. The model is based on a network-node system approach, where both the topology and geographic distance of multiple energy infrastructures and the technical and economic properties of different investment alternatives are considered. The model minimises total energy system cost (investments, operation and emissions) of meeting predefined energy demands of energy (electricity, gas, heating) within a geographical area and over a given planning horizon, including alternative supply infrastructures for multiple energy carriers. The model is based on a nested optimisation, calculating both the optimal diurnal operation of the energy system (operational model) and the optimal expansion plan over a 20–30 years horizon (investment model). In the specific case of bioenergy flows, the amount of energy (and specific operating cost) at any point in the supply chain depends both on the volume and the moisture content in the biomass, and can be defined as a function of two main properties of the biomass [17]: the appearance (biomass in chips, pellets, logs) and the quality (moisture content). Since the moisture content has large influence on the efficiency of various biomass conversion processes, one of the main focus of the research is to represent the relationships between moisture and energy content of various biomasses and to handle long-term processes in the optimization, such as passive drying effects. As an example, the model allows choosing between cheap/free long-term passive drying during storage or spending fuel for forced and fast drying. Biomass density and heating value are also influenced by the processing and storage technologies.

In [17] another methodology for optimization of agricultural supply chains by dynamic programming is described, to find the lowest cost from harvest to end use. The model explicitly deals with the product properties (quality and appearance), which are influenced by handling, processing, transport and storage actions. In particular, agricultural commodities are described according to the appearance states (describing if a product is (un)packed, (un)wrapped, (un)labelled or cut into pieces) and quality states (describing the quality which can be expressed as microorganism infestation, ripeness, moisture content, colour,

taste). The types of actions in agrichains are thus: i) handling (actions which modify the appearance states of a product, such as wrapping, cutting and labelling); ii) processing (actions which modify the quality states of a product, such as cooling and drying); iii) transport and storage (actions which alter the quality states of a product. Chain optimisation refers to the construction of routes defining which actors should perform which actions (handling, processing, transportation and storage) at which process conditions, in order to achieve minimum total chain costs while achieving targets.

Another MILP model for the optimal design and operation of biofuel supply chains is proposed in [18] and applied to biodiesel supply chains in Greece. The model incorporates both the optimization of raw materials-feedstocks and biofuel production plants location. It includes the possibility to choose between the domestic biomass production and the import of biomass and-or biofuels to meet given bioenergy targets. However, the model is tailored for a single biofuel production process, it does not take in account storage, transport and environmental issues and costs and it represents the demand side as a fixed quantity of biodiesel to be produced in the whole investigation area.

The work presented in [19] describes an environmental decision support system based on three modules: a GIS-based interface for the characterization of the problem and for the determination of the parameters involved in the formulation of the problem; a database where data characterizing the problem is stored; the optimization module, subdivided into strategic planning, tactical planning and the operational level. The necessity of taking into account different levels derives from the different time scales to be considered and from the different decisions to be performed. Long-term decisions refer to plant sizing, location, and selection among the various technology options. Tactical level decisions refer to planning over a medium- short-term horizon, and are generally considered within a discrete-time setting, with the assumption that the plant capacity and the facilities are known. Finally, the operational level is based on the explicit modelling of the supply-chain process as an ordered sequence of the operations that should be performed from biomass collection to energy conversion. In this case, a non-linear mixed-integer programming optimization is proposed. The main focus is the optimal planning of forest biomass use for energy production.

Another non-linear decision support model is proposed in [20]. The problem considered is optimal exploitation of biomass resources with several harvesting sites and a few centralized combustion plants on a regional level. The aim is to find the optimal capacity of heat and power generation as well as the optimal utilization of biomass resources and transport options. The time horizon considered is one year so that the model is capable of giving long-term decision support.

Another decision support system (DSS) for bioenergy applications, with special reference to harvesting wood for energy from conventional forestry and short rotation forestry, is proposed in [21]. In particular, the work addresses the calculation of delivery costs for wood fuel from conventional forest in the UK. Moreover, an exhaustive review of topics related to the problems of modelling bioenergy supply systems is provided. The same research group proposed other DSSs: the Coppice decision support system (CDSS), a spread- sheet model that can be used to model the costs of growing short rotation coppices under UK conditions,

and the Coppice harvesting decision support system (CHDSS), which models the supply chain from the standing Coppice crop through harvesting, storage and transport. These DSSs, as well as other models, have been linked together to produce a bioenergy assessment model (BEAM), which is a comprehensive biomass to electricity model.

3. Bioenergy transport systems

Biomass transport modelling is essential to optimize bioenergy supply chains, plant size and locations. Various typologies of biomass transport models are available in literature. A first type is a simple continuous model [22,23], which is suitable for idealized situations; a second type is a discrete model with defined grid road systems [24,25]; a third type is a complete discrete model incorporating GIS [26,27]. Road tortuosity in the first and second type of models are generally based on assumptions without carrying out road system evaluations. In the last type, the road network is rasterised and then continuous grids of distance and transportation costs to the plant sites are computed using functions of Euclidean distance and allocation. Moreover, in case of on-farm biomass transport, previous studies [28] show that the haulage cost is also dictated by farm landscape attributes and infrastructure. This section overviews the biomass and biofuel transport systems and related costs with different supply route scenarios. The available handling, loading and transport technologies for the various categories of biomasses are assessed. The selection of transport modes is influenced by the typology of biomass feedstocks and supply chain dimension, and a possible biomass/biofuel classification for this purposes can be as follows: (i) forestry products and urban green; (ii) agricultural energy crops and by-products, (iii) urban and agro-industrial bio-wastes with high moisture content; (iv) waste vegetable oils and liquid biomass; (v) long distance transport of solid and liquid biomass; (vi) gaseous biofuels, including biogas, syngas, biomethane. The main trade-offs of road, rail, ship, pipeline transport systems are investigated in the following, and the key factors influencing the optimal choice of the transport mode are discussed.

3.1. Transport systems for solid biomass

Transportation is a cost element in any energy project, but this is especially true for biomass because of the lower energy and bulk density compared with fossil fuels. Several studies have shown that truck transport cost of agricultural residues biomass ranges from 20% to greater than 40% of total delivered cost, depending on distance traveled and mode of transportation [22]. Long-distance transport of biomass including the use of trucks and ships has been addressed in literature [23,24], proving that, despite the long shipping distance, the costs of Latin America wood chips in the receiving European harbour can be as low as 40 Eur/ t or 2.1 Eur/GJ, and the crop's costs account for 25–40% of the delivered costs. The relatively expensive truck transport from production site to gathering point restricts the size of the production area, so that a high biomass yield per hectare is vital to enable large-scale systems.

Many studies have shown that the optimum size of biomass processing and conversion plants is large when abundant biomass is available, and low-cost transport systems are

used; on the contrary, when the specific biomass transport cost increases, because of low energy density of the feedstock and long transport distances, and scale economies and conversion efficiencies are less influenced by the size, the optimal plant size tends to be lower [25-29]. In addition, many field sources of biomass are, by their nature, remote from the population centers that will use the produced energy. Thus, developers of such biomass projects will have the alternative of moving the biomass to a plant near the energy consumer, or moving the produced energy from a remote biomass processing plant, and the selection of optimal plant location is based on the relative costs and energy losses of biomass, biofuels and energy transport and intermediate storage. Moreover, both at a large scale and in urban areas, biomass transport by truck may not be physically possible owing to traffic congestion and resulting community opposition. Rail transport of biomass reduces the frequency of loads and offers better environmental performances in comparison to road transport. A specific comparison of rail vs truck transport of biomass is proposed in [30], and the minimum shipping distance for rail transport above which lower costs/km offset the incremental fixed cost in comparison to truck is estimated in the range of 145-170 km for wood chips and straw in a North American setting. Pipeline transport would deliver biomass with minimum ongoing community impact, but is feasible only for liquid and gaseous biomass [31], and will be discussed in the next section.

In [32] the relative cost of transportation by truck, rail, ship, and pipeline for three biomass feedstocks, by truck and pipeline for ethanol, and by transmission line for electrical power is assessed, for various plant sizes. Distance fixed costs and distance variable costs (including power losses during transmission), are calculated for each biomass type and mode of transportation. The results show that pipelining is competitive only at large scale, while transshipment is feasible for distances higher than 1,000-3,000 km, on the basis of the typology of biomass.

In [33] the delivery cost of different combinations of multiple forms of lignocellulosic feedstocks including agricultural and woody biomass is analysed. In particular, three types of biomass i.e., wheat, straw, corn stover and forest biomass were considered in different forms such as loose biomass, bales/bundles, chopped/chipped and pellets. It was found that the delivery cost of a combination of woody and agricultural biomass feedstocks is lower than that for a single type of biomass, and traffic congestions resulting from biomass supply to a large facility could be significantly reduced by increasing the density of biomass.

However, selection of a transportation mode cannot be based on only one issue. Economical, environmental, social, and technical parameters should be integrated to select the best system [34].

Transportation costs for biomass and its products have a distance fixed component (DFC) that is incurred regardless of the distance travelled, and includes loading-unloading costs depreciation, insurance, interests and the administrative cost of biomass transport, and a distance variable component (DVC) that includes costs of fuels, repair, tire, lubrication and labor. DFC depends on the type of biomass being transported and the equipment and contractual arrangements involved, which are both case specific, and vary based on the specific form of biomass to a far greater extent than DVC. For example, large round bales of stover or straw would require different treatment for transshipment from truck to rail than woodchips or pellets. The impact of DFC on overall transportation cost diminishes with increasing distance. Moreover, biomass

transportation costs are often referred to the total number of actual metric tons as road limits, and in this case the calculated transport cost per dry metric ton will vary for every biomass source. For truck, rail, and ship transport, mass is the primary factor setting the cost of shipment, although for low density loads volume can become the limiting factor. For pipelines transporting a single phase liquid, for example ethanol, liquid volume is the primary factor, whereas for two-phase slurry pipelines carrying biomass the amount of dry matter is the primary factor, because moisture level reaches equilibrium during transport. For both ship, road and rail transport modes, the DFC for low density biomass (straw) is significantly higher than for chips, pellets or TOP. Infact, chips and pellets lend themselves to bulk handling by methods such as conveying or pneumatic transfer, whereas straw/stover is moved as a large bale.

	Transport mode	Fuel	Capacity range	Capacity range	Fixed cost	Variable cost	Main drawbacks	Sources
1	Truck-small	Solid-liquid	15 m ³	5 t	2-4 Eur/t	0.2 Eur/km m ³	emission levels, traffic congestions, road suitability (for large trucks)	[23,24,30,32, 35]
	Truck-medium	biomass	35 m ³	25 t		0.15 Eur/km m ³		
	Truck-large		100 m ³	40 t		0.1 Eur/km m ³		
	Liquid-tank truck	Bio-oil	30 m ³	35 t	5.7 \$/m ³	0.18-0.07 \$/km*m ³		[23,32,41]
	Liquid tank trailer		60 m ³	70 t	5.6 \$/m ³	0.15-0.05 \$/km*m ³		
2	Rail	Solid-liquid	2,500 m ³	1000 t	5-14 \$/t	0.02-0.03 \$/km t	Rail network availability	[30,32]
3	Ship	biomass	6,700-105,000 m ³	4,000-63,000 t	11-34 \$/t	0.01 \$/km t	Large scale storage capacity, long distance emission levels, ships availability	[23,24,32]
4	Pipeline-1	Bio-oil,	156 m ³ /day		0.1	0.29	Investment costs, refurbishment costs in case of existing infrastructures,	[41,42]
	Pipeline-2	biodiesel	469 m ³ /day		0.04	0.12		
	Pipeline-3		1000 m ³ /day		0.02	0.07	energy losses (DH)	[32]
	Pipeline-4	ethanol	1000 m ³ /day		0	4.13 C-0.5885 \$/km t		
5	Gas network	gas	Highly variable on the basis of		50-150 kEur/km			[61-63]
6	District heating	90° / 120° heat pipeline diameter			350-450 kEur/km			[43-46,50,64, 65,99,112]

Notes: Variable transport cost figures are composed by fuel cost, transport maintenance and spare parts costs, personnel costs; fixed costs are given by loading-unloading costs and all the other costs that are not dependent on the transport distance;

Pipeline-1: capacity bio-oil plant 250 t/day, density 1,2 t/m³, transport capacity 156 m³/day, pipeline diameter 5.1 cm, distance between booster 9.1 km; 65 MW capacity delivered energy; Pipeline-2: capacity bio-oil plant 750 t/day, density 1,2 t/m³, transport capacity 469 m³/day, pipeline diameter 7.6 cm, distance between booster 9.4 km; 195 MW capacity delivered energy; Pipeline-3: capacity bio-oil plant 1600 t/day, density 1,2 t/m³, transport capacity 1000 m³/day, pipeline diameter 9.9 cm, distance between booster 8.1 km; 416 MW capacity delivered energy; C = capacity of bio-ethanol pipeline t/day

Pipeline costs include installation costs

Table 3. Biomass, biofuels and bioenergy transport modes: technical parameters and cost figures

The techno-economic parameters reported in Table 3 are obtained from an overview of literature data on capacities and costs of various biomass, biofuels and energy transport routes. However, cost figures are affected by a relevant range of uncertainties. As regards truck transport of wood chips and straw, as an example, fixed and variable transport costs range between 3.8-4.9 \$/dry t and 0.11-0.15 \$/t km in the Northern America scenario, as discussed in [35], while data for wood chips in Brazil [36] and Sweden [37] and mixed agricultural and forest residues in Thailand [38] present cost variations in the range of 50%.

The truck operating cost can vary because most of the cost components are region specific, and influenced by fuel taxation. A small change in the equipment use would have large impact on the costs [39]. Driver and fuel costs have wider range of tolerance within them [40]. The firm size from where truck or trailer are rented also affect the cost. Some costs are lower for small farms (such as wages, administrative costs) but these are offset by economics of scales of costs for equipment, tire and consumables which lead to large variations of total costs. There are also many different sizes and types of trucks available. In the specific case of small transport distances, which is typical of the integration of bioenergy in urban areas, the data are obtained from official prices of transports from operators in Italy. The data for medium and large truck are also referred to the Italian scenario (fuel taxation level and fixed costs).

3.2. Transport systems for liquid biomass

Liquid biomass, both in the form of pyrolysis bio-oil, row vegetable oil, bio-ethanol, biodiesel or other BTL fuel, present an higher energy density in comparison to solid biomass and can be transported by trucks, rail, ship and pipelines. Specific transport issues arise in case of high viscosity and corrosive bio-oils, such as pyrolysis oils, that require stainless steel tanks with an average 14% increase in transport costs [23]. Transport of conventional liquid fuels (per tonne) is also assumed to be 25% higher than for solid fuels [23]. Costs for liquid biomass by trucks are reported in Table 3, according to [41] and considering pyrolysis bio-oil. In case of biodiesel and bioethanol these costs could be reduced, because of the lower viscosity (that means quicker loading/unloading rate) and absence of corrosive materials for tanks.

Pipeline transport can be an economically interesting option for large scale transport of bio-oil and over long distances. Today, most of the crude oil is transported by pipeline, and the transport costs benefit from economy of scale in capital cost. Traffic congestion problems are also mitigated. Pipeline transportation of liquid fuels has been used over several decades. Recently, several studies have been carried out on the pipeline transport of raw biomass in the form of a slurry [31,32,35]. Bio-oil and liquid biofuels in general can be transported by pipeline in larger capacities and over longer distances. Current practice is to transport bio-oil by trucks from the production plant. An important characteristic of bio-oils is their high viscosity, that decreases when increasing temperature. In the case of pyrolysis bio-oil, at about 45 °C, its viscosity for pipeline transportation is 15 cSt which is similar to crude oil. To maintain the bio-oil in the pipeline over 45 °C, the pipeline has to be insulated. In the case of low pH bio-oil, the corrosion to carbon steel requires the use

of high density polyethylene (HDPE). Similar to truck transportation cost, pipeline transportation cost has both fixed cost (FC) and variable cost (VC). Fixed cost of pipeline transport includes capital cost of inlet and outlet stations. Inlet station refers to the terminal where bio-fuel moves from the storage tank to the pipeline through pumps. Outlet station refers to the terminal where it moves from the pipeline to the storage tank. The inlet station costs include: capital cost of storage tank, building and foundation cost, fittings and valves cost, inlet pump cost and access road cost. Similarly, the outlet station costs include storage tank cost, fittings, valve and small distribution pump cost and building cost. In [42], investment cost figures for inlet and outlet station for a bio-oil pipeline at a transport capacity in the range of 156-2,000 m³ per day (corresponding to a bio-oil plant using 250-3200 dry tonnes of biomass per day and a pipeline energy transport capacity of about 65-830 MW) are reported. Variable cost of pipeline transport includes capital cost of pipeline, installation and construction cost, operating cost of pipeline, booster station cost, maintenance cost of pipeline and pumps, communication line cost, insulation costs and road access cost. Operating cost of the pipeline includes labor required for running the system and electricity required for pumps. For transport of bio-oil over longer distances, booster stations are required to overcome the frictional losses during the transport. The variable cost for the same bio-oil pipeline capacity range, including the booster station and a length of 100 km are proposed in [42]. These cost figures have been used to inform a detailed techno-economic model based on discounted cash flow analysis, in order to calculate the cost of pipeline transport (\$/m³) of bio-oil for different capacities of pipeline (m³/day) at various lengths of pipeline. These cost figures are reported in Table 3. The results report that the pipeline transport cost decreases with the increase in capacity of pipeline and is directly proportional to the distance of transport. Although the pump power increases with the increase in the capacity, the total cost of pipeline transport of bio-oil (\$/m³) decreases with the capacity, predominantly due to the benefits from the economy of scale in the capital cost of pipeline. Because of the lower fixed transport costs of pipeline in comparison with truck systems, for short distances and large quantity of delivered fuels, the pipeline option could be more promising. For long distances, the bio-oil heating requirements to maintain the viscosity and the power consumption of the pumps due to the friction losses should be carefully assessed. However, it should be noted that pipeline costs are highly influenced by the specific installation area, since in densely populated urban areas, where most of the energy demand is concentrated, the costs can be even 5 times higher than in rural areas.

In [43] the life cycle assessment of transportation of bio-oil by pipeline and by truck are compared. The scope of the work includes the transportation of bio-oil by truck or pipeline from a centralized plant to an end-user. Two cases are studied for pipeline transport of bio-oil: the first case considers a coal based electricity supply for pumping the bio-oil through a pipeline; the second case considers an electricity supply from a renewable resource. The two cases of pipeline transport are compared to two cases of truck transport (truck trailer with capacity 30 m³ and super B-train truck with capacity 60 m³). The results report values of 345 and 17 g of CO₂/m³ km, respectively in the case of coal based and renewable electricity, and similar values for transport by trailer and super B-train truck are 89 and 60 g of CO₂/m³ km,

respectively. Energy input for bio-oil transport is 3.95 MJ/ m³ km by pipeline, 2.59 MJ/m³ km by truck and 1.66 MJ/ m³ km by super B-train truck.

In the case of liquid biofuels, other than the previous transport systems, pipelines can be used. In the case of high viscosity bio-oils, the pipelines should be probably heated in order to achieve acceptable transport yields. The advantages of pipeline systems are in terms of avoided congestion during delivery, avoided air emissions from trucks, and reduced operational costs. However, sometimes it is not possible to install pipelines, in particular in urban areas with planning constraints or high refurbishment costs. The solution of centralized biomass processing facilities and decentralized energy conversion plants is based on the concept that the high density biofuel can be easily stored and transported to the CHP plants near to the loads by means of efficient distribution systems as pipelines, eventually integrated into existing ones. The costs and the energy losses of biofuels distribution networks would be in most cases lower than that one of district heating networks.

4. Biomass storage, drying and pre-treatment systems

The biomass handling, storage and pretreatment are crucial steps for an optimal development of bioenergy supply chains. Different biomasses require specific treatments and the seasonality of supply increases the complexity of dimensioning and optimal operation of these facilities.

The storage requirements of various biomass and biofuel typologies and the technical options currently adopted are reviewed in the following, together with cost figures of different storage systems. These costs could be particularly relevant when low energy density biomasses, with high seasonality and particularly complex storage requirements have to be stored.

The biomass supply chain presents several distinctive characteristics that diversify it from a typical supply chain. One of them is the need to store the biomass in a proper way, because of its seasonal availability and the necessity of continuous operation of biomass conversion plants. Moreover, in case of imported biomass (wood chips, bio-oils) the transport logistics constraints and the possibility to purchase and hence store large quantities of biomass are crucial issues in order to favourite trading and achieve good market prices. The biomass storage is a particularly important task, both for the relevant investment costs of some storage technologies and for the biomass and energy losses and safety issues related to the selection of poor storage systems. Since most of the biomass-to-energy applications to date concern single biomass use, there is a need of storing very large amounts of biomass for a significant time period, if year-round operation of the power plant is desired. The limited time frame for collecting a large amount of biomass leads also to significant seasonal need of resources, both equipment and workforce. This seasonal demand may increase the cost of obtaining these resources, while leading to their suboptimal utilization, particularly as regards storage space. The problems introduced by the seasonality of biomass availability may be avoided, if a biomass that is available year- round is used, which is very rare in prac-

tice. The multi-biomass approach may smooth significantly these problems and is quite often applied in real cases. Another characteristic of the biomass supply chain is that it has to deal with low-density materials. As a result, there is increased need for transportation and handling equipment, as well as storage space. This problem is enhanced by the low heating value, which is partly due to the increased moisture of most agricultural biomass types. The low density of biomass increases further the cost of collection, handling, transport and storage stages of the supply chain. Finally, several biomass types require customized collection and handling equipment, leading to a complicated structure of the supply chain. For example, there are different requirements on handling and transportation equipment and storage space configuration if biomass is procured in the forms of sticks, chips, round bales, plastic bags, etc. Moreover, in case of wet biomass for biogas plants, storage issues are particularly relevant since the mass and energy losses during a not accurate storage can be very relevant. Other typologies of biomass can not be easily stored without a preliminary pre-treatment (drying), because of odour problems and health and safety regulations (i.e. wet olive cake). Liquid biomass (bio-oils) should be also stored in a proper way in order to avoid acidification and deterioration of the biofuel. Therefore, the typology of biomass and the form in which the biomass will be procured often determines the investment and operational costs of the respective bioenergy exploitation system, as it affects the requirements and design of the biomass supply chain.

In case of solid biomass for thermochemical applications, on-field storage is a low-cost option, with the drawback of high biomass losses, difficult control of moisture content, risk of auto-ignition, health and safety issues, and finally land occupation that can hinder next cropping. The use of intermediate storage between field and energy conversion plant is also an option, that implies double biomass transport and often higher total delivery costs [57]. In case of long distances, the use of road-rail transport systems could be integrated with intermediate storage [22]. Storage location at the premises of biomass upgrading and biofuel conversion plants could facilitate the drying process, by means of dumped heat from the process plants, thus preventing material decomposition and health and safety risks.

As regards solid biomass for thermochemical conversion systems, three typologies of storage are assessed in [11]: i) closed warehouse with biomass drying capability, by hot air injection generated by dumped heat of the CHP plant which helps to avoid quality degradation of the biomass while simultaneously increasing the energy content of the biofuel; ii) covered storage facility of a pole-frame structure having a metal roof without any infrastructure for biomass drying where a 0.5% material loss/month rate has been assumed; iii) ambient storage of biomass, covered only with a plastic film presenting the highest material loss rate, which is assumed to be 1% material loss/month.

In Table 4 the main characteristics and costs of the available storage systems are described.

Biomass drying provides significant benefits in case of thermochemical conversion systems, such as increased boiler efficiency, lower air emissions, improved boiler operations. The three main options for lignocellulosic biomass drying are rotary dryers, flash dryers and superheated steam dryers. The first types of dryers are less sensitive to biomass size and are the most common option, even presenting the greatest fire hazard. Flash dryers are more

compact and easier to control, but require small particle size, while superheated steam dryers present the best energy efficiency performances with very low air emission levels. The dryer selection is dependent on the biomass typology, opportunity of integration into biomass processing systems, required air emission levels, availability of waste heat. The biomass drying technologies required in case of thermochemical energy conversion processes are reviewed in [66-68]. In particular, in [66] a detailed description of dryer technologies and heat recovery systems for biomass drying are provided. Guidelines about optimal selection of drying technology and size on the basis of the specific process and feedstocks are also provided, including cost figures, environmental performances and safety issues for each option under investigation.

Storage typology	Material loss (%/month)	Investment cost	O&M costs (% investment/yr)	Maximum height (m)	Suitable biomass	Note
Open storage	1-3%	20-50 Eur/m ²	4	3-4	Solid biomass	Risks of ignition
Covered storage	0,5-1%	100-150 Eur/m ²	4	6-8	Solid biomass	
Closed warehouse	negligible	200-300 Eur/m ²	5	6-8	Solid biomass	Possible integration with drying systems and biomass treatments
Plastic covered storage	0,5-2%	50-100 Eur/m ²	4	6-8	Wet biomass for biogas	
Depressurized warehouse	negligible	300-500 Eur/m ²		6-8	Solid biomass	Required to minimize odours emissions of biomass
Silos	Negligible	25-35 Eur/m ³		6-8	Liquid-solid biomass	
Storage tank	negligible	40-50 Eur/m ³		6-8	Wet solid-liquid biomass	Required to minimize pre-fermentation of wet biomass in biogas plants

Table 4. Main characteristics of biomass storage [11, 58-60]

In case of wet biomass, overall efficiency can often be improved by dewatering prior to thermal drying. On the downside, mechanical dewatering equipment itself can consume a large amount of energy and have high maintenance requirements, which must be weighed against the reduction in drying energy. Dewatering equipment includes drying beds, filters and screens, presses, and centrifuges. Depending on the material and the specific type of equipment, mechanical dewatering equipment may reduce moisture content to as little as approximately 50% [67]. Passive dewatering methods, such as using filter bags that are impervious to rain but allow moisture to seep out, can achieve moisture contents as low as 30% at low cost, but long periods of time – on the order of two to three months – may be required. An overview of dewatering and drying technologies on the basis of biomass properties is proposed in [67,68], including cost analyses, energy performances, health and environmental issues.

Technologies such as natural drying, solar drying, gas or biomass fired rotating kilns, drying systems coupled to CHP plants with heat recovery systems are compared.

The biomass treatment and upgrading processes are required to obtain high energy density biofuels, which can be easily transported, stored, and that are suitable for high efficiency energy conversion processes, possibly at the premises of the energy demand. In Table 5, the commercially available and the most promising biomass treatment processes are described, to produce solid, liquid and gaseous biofuels. In most cases, these processes are implemented near to the biomass production sites, in order to minimize the transport costs, facilitate the trade on the market and the storage issues. However, when integrating biomass routes into existing energy systems, the specific logistics, economic and environmental constraints of energy demand in tertiary and residential sectors imply the necessity to locate these processing facilities in industrial areas, eventually decoupling them to the final energy conversion of biofuels near to the loads. Moreover, locating these processes in industrial areas could facilitate the implementation of biorefineries approaches and the integration of multiple processes.

The most promising biofuels are pellets (and in particular torrefied pellet with higher LHV), bio-oils (both from FAME and 2nd gen thermochemical processes on lignocellulosic biomass) and bio-methane (from AD biogas upgrading or 2nd gen FT processes on lignocellulosic biomass).

n	Biofuel	Treatment	Input biomass	References
Solid biofuel				
1	Pellet	Chipping-drying-pelletization	Lignocellulosic biomass	[69-71]
2	TOP (torrefied pellet)	Torrefaction-pelletization	Lignocellulosic biomass	[24,72-74]
3	Chip	Chipping-drying	Lignocellulosic biomass	
4	TOP (torrefied pellet)	Hydrotreatment-drying/dewatering	Wet lignocellulosic biomass	[75-77]
Liquid biofuel				
5	Bio-oil	Mechanical or chemical refining / oil hydrotreatments	Vegetable oils and fat oils	[78-80]
6	Pyrolysis oil (BTL)	Pyrolysis and thermochemical processes on lignocell biomass	Lignocellulosic biomass	[47,81-83]
7	Biodiesel	Esterification of FAME (fatty acid methyl esters)	Vegetable oils and fats	
8	Biodiesel-FT	Gasification coupled to FT biodiesel process	Lignocellulosic biomass	[84-86]
9	Bioethanol	2 nd gen process from lignocellulosic biomass	Lignocellulosic biomass	[87-89]
Gas biofuel				
10	Syngas	Gasification of lignocellulosic biomass	Lignocellulosic biomass	[90-92]
11	Biogas	Anaerobic Digestion	Wet fermentable biomass	[93,94]
12	Biomethane-AD	AD and biogas upgrading	Wet fermentable biomass	[95,96]
13	Biomethane-FT	Gasification+syngas upgrading	Lignocellulosic biomass	[97,98]
14	Bio-hydrogen	Dark fermentation-AD processes	Wet fermentable biomass	[89,100-102]
15	Bio-hydrogen-FT	Catalytic synthesis from FT processes	Lignocellulosic biomass	[103-106]

Table 5. Biomass processing technologies for heat and power generation

5. Energy conversion and integration with existing infrastructures

The biofuels can then be converted into energy for stationary applications by means of several technologies. The heat generation is the cheapest and most profitable conversion system for solid biomass and in absence of specific incentives for bio-electricity. The district heating (DH) option is interesting in case of high heat demand density (i.e. new buildings or refurbishment of existing ones), and possibility to increase the networks load factor by district cooling with adsorption chillers. The CHP option with solid biomass can be attractive in case of high electricity costs, incentives for biomass electricity, favourable rules for on-site generation and net metering, presence of suitable heat/electricity demand and possibility to manage the logistic constraints of the biomass transports and storage. The technological options are ORC plants up to 1-2 MWe [107, 108] and ST, possibly in cofiring, for higher size [109]. In the case of liquid and gaseous biofuels, the options of internal combustion engines (ICE) and gas turbines (GT) [46], also in cofiring with natural gas, are available and allow minimizing the biomass transport, storage and air emission constraints which are typical of large solid biomass boilers and make their diffusion difficult in urban areas. In perspective, the use of small scale ICE, but also microturbines (MT) [110] and fuel cells (SOFC) [111], fired by high quality biofuels (bioethanol, biomethane, biohydrogen [89,106]) for heat and power, could be a very promising option, in particular if connected to a centralized biofuel distribution network, and integrated with the gas network.

One of the key issues when implementing competitive and sustainable bioenergy routes is the integration with existing energy systems and infrastructures.

In this context, there are several promising opportunities of repowering existing fossil fuel plants (brownfield plants) for biomass cofiring, both in the case of CHP and district heating systems [113-115]. Moreover, new power plants can be installed in dual-fuel configurations, in order to increase plant operation flexibility, reduce the problems of biomass storage, handling, seasonality, transport of relevant quantities of biofuels, that are typical of single fuel plants. On the contrary, when a power plant is designed to fire both biofuels and fossil fuels, the typical technical and economic problems of only biomass-fired power plants can be drastically reduced, and large scale (and hence higher conversion efficiencies) can be achieved avoiding the use of huge quantities of biomass. ICEs are typical technologies that can be fed by multi-fuels; in particular Diesel engines are suitable for diesel/gas operation with a maximum gas (or biogas) quantity of 75% [116] and a slight efficiency reduction. Also gas turbines can be fed by natural gas in combination to bio-oils, biodiesel, or bio-ethanol. As an example, GE's LM6000-PC aeroderivative gas turbine can be fired by natural gas, ethanol, biodiesel fuels size 35-60 MWe.

Another interesting energy systems integration opportunity regards the use of existing infrastructures for biofuels and fossil fuels processing (co-refining) and the transport. In the latter case, the potentials to use existing natural gas to transport biomethane from thermochemical synthesis or anaerobic digestion processes are particularly promising.

6. Decoupling of biomass processing and optimal sizing

The biomass processing and pre-treatment facilities are influenced by scale economies and in most cases large processing plants can minimize the biofuel production costs, in particular when efficient biomass transport systems are implemented and the variable component of transport cost (dependent on the biomass collection distance) is not dominant. Moreover, biomass processing plants require large sites for biomass storage and handling, and the amenity issues related to the presence of these industrial facilities are often not compatible with residential areas. On the contrary, the final biofuel energy conversion should be located at the premises of the energy demand, and in particular where it presents the highest costs, such as in residential areas, in order to minimize the energy distribution costs. This is particularly relevant in the case of heat (and eventually combined cool generation by adsorption chillers) or CCHP plants. For this reason, several researches on bioenergy are focused on decoupling of biomass processing and biofuel energy conversion, to favourite the integration of bioenergy into urban and peri-urban energy systems.

As an example, in [47] it is described how systems de-coupling applied to fast pyrolysis and diesel engines can distinguish itself from the other conversion technologies, since several remote generators are much better served by a large fast pyrolysis plant that supplies fuel to de-coupled diesel engines than by constructing an entire close-coupled system at each generating site. Another advantage of de-coupling is that the fast pyrolysis conversion step and the diesel engine generation step can operate independently, with intermediate storage of the fast pyrolysis liquid fuel, increasing overall reliability. Peak load or seasonal power requirements would also benefit from de-coupling since a small fast pyrolysis plant could operate continuously to produce fuel that is stored for use in the engine on demand. A similar approach, but related to Fisher-tropsch liquids production at a centralized catalytic synthesis facility with the two options of direct biomass transportation and gasification to centralised plant or preliminary distributed processing of biomass by fast pyrolysis to bio-oil is proposed in [27]. The results show that, for large biomass collection radius, the intermediate and distributed processing of biomass to bio-oil presents lower total production costs, because of the lower biomass delivery costs that offsets the higher operation and biomass costs. A similar approach, related to torrefaction vs fast pyrolysis bio-oil vs wood pellets pre-treatment and long distance transport to FT liquid or power plants is proposed in [24], including a detailed assessment of overall chain efficiency in long distance biofuel transport, increased energy conversion efficiency of high quality biofuels, and sensitivity to the main techno-economic parameters. The results report that torrefaction coupled to pelletization to feed BIGCC or cofiring power plants allows minimizing the energy production costs. Another research proposed in [48] compares the production of wood thinning chips, pellet, fast pyrolysis bio-oil and bio-methanol with the further options of cofiring or cogeneration, in order to define the best biomass conversion strategies, and the benefits of densification in case of long distance transport are enhanced. Finally, in [49] the options of HTC treatment of lignocellulosic biomass vs pelletization and coupling these facilities to CHP plants are investigated; the results show that HTC can be a very interesting option for wet biomass, competitive to drying-pelletization.

Bioenergy plants can be also conducted at a wide range of capacities. The problem of optimal size calculation of biomass-to-energy conversion plants has been widely addressed in literature, on the basis of the trade off between the high conversion efficiencies and economies of scale of large size plants and the low biomass collection radius, transport costs and feedstocks collection and management requirements of small size plants [27, 29,51-54]. Factors such as feedstock availability and spatial distribution, terrain and road conditions, biomass transport specific costs, storage costs, existing energy infrastructures, biomass seasonality issues, conversion plant scale factors and efficiencies influence this optimization problem. Logistic aspects are particularly relevant when low energy density and highly dispersed feedstocks are used. Moreover, small scale plants can facilitate the use of excess heat generated, that can match local loads, if a cogeneration configuration is selected. In [55,56], two generic analytical frameworks are proposed, to calculate the optimal conversion plant size for biogas plants.

7. Conclusions

This chapter overviewed the logistic issues of bioenergy routes for stationary applications, discussing the supply chain modelling approaches proposed in literature, the various options for storage, transport, processing and energy conversion of the biomass, and the research trends in order to improve the sustainability and economics of biomass for heat and power.

One of the most interesting research areas regards the optimal location and sizing of biomass processing and conversion facilities, on the basis of the biomass resource, the logistics of supply and conditioning, the final energy end-user typology and existing energy infrastructures for bioenergy integration.

The following main considerations can be drawn: i) high quality biofuels (pellet, bio-oils, biomethane) should be used in order to minimize transport, storage and environmental issues and facilitate the energy coinversion of biomass at the premises of energy loads by CHP plants; ii) decoupling of biomass upgrading and biofuel energy conversion near to the loads is a very promising option; iii) small boilers are suitable for rural areas and low heat density zones, while DH is feasible with high energy density loads or when cooling distribution can be introduced to increase the network load factor; iv) integration into existing infrastructures is a key factor (i.e. possibility to use existing gas networks for bio-methane); v) solid biomass CHP implies large storage, transport and air emission issues, should be integrated into DH schemes and localized where space and logistics of transport are not a constraint; vi) large CHP plants should be integrated as possible into brownfield plants and using cofiring options to maximize energy conversion efficiencies while limiting the amounts of biomass required; vii) the most reliable technological option currently available for small scale biomass CHP in urban and periurban areas are ORC plants fed by solid biofuels and ICE fed by liquid or gaseous biofuels, while promising technologies for small scale on site biofuel CHP are microturbines and fuel cells. In conclusion, the economic competitiveness of

bioenergy routes in CHP schemes is strongly influenced by the subsidies available for bioelectricity, while biomass heating and cooling can be, at some extent, competitive with fossil fuels even without incentives.

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