

Competitive priorities to address optimisation in biomass value chains: The case of biomass CHP



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ABSTRACT

Policy and industry decision makers place high priority on the contribution of biomass to the emerging low carbon, circular economy. Optimisation of performance, from the perspectives of environmental, social and economic sustainability and resource efficiency, is essential to successful development and operation of biomass value chains. The complexity of value chains, which comprise interrelated stages from land use to conversion and multiple end products, presents challenges.

To date, decision makers have approached from the viewpoints of single market sectors or issues, such as market shares of bioeconomy and reduction of carbon emissions to mitigate climate change. This approach does not achieve a full understanding of value chains and their competitive priorities, limits consumer awareness, and poses risks of sub-optimal performance and under-development of potential local capacity.

This paper presents a conceptual framework that combines value chain analysis and competitive priority theory with indicators suitable to measure, monitor and interpret sustainability and resource efficiency at value chain level. The case of biomass Combined Heat and Power (CHP) is used to illustrate how optimisation strategies can be focused to address challenges in value chain stages which will lead to better performance and uptake of sustainably sourced, widely accepted biomass options.

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1. Introduction

Policy and industry decision makers place high priority on biomass as a significant resource for the emerging low carbon, circular economy. Biomass based value chains can offer opportunities to reduce use of petrochemicals, mitigate climate change [1–3] and contribute to local economic growth including the creation of skilled employment opportunities [4]. Worldwide, decision makers are nowadays increasingly exploring varied, innovative value chains that can supply and use biomass sustainably and efficiently [2]. They face a number of challenges: the imperative to comply with resource efficient and sustainable practices;

inadequate data due to use of complex, open-ended or inconsistent metrics [5] and; the lack of coherence in systems thinking [6] to incorporate challenges and develop optimisation strategies that create value based on competitive priorities. Moreover, the individual stages within biomass value chains have complex interrelations of physical assets (land, soil, water, air, climate) with market attributes (displacement of other land based activities, competition for raw materials, innovative technologies and valorisation of co-products) which cannot be fully addressed by single target optimisation [4]. A systemic approach is required to evaluate how physical and market related challenges can be articulated with relevant competitive priorities fit to address the main decision concern in each stage of the biomass value chain and deliver optimised performance [7].

Biomass value chains for bioenergy and biobased products have been extensively studied in literature [2,3]. This paper builds on it as well but goes beyond and expands the analytical scope of the approach to define challenges within the individual value chain stages and specifically select indicators that can interpret performance for relevant competitive priorities, improve competitive advantages and as such foster the development of resource efficient

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and sustainable value chains. Competitive priorities in this analysis signify a strategic focus on building specific operational capabilities that can improve the value chain's position in the market. Decision makers can select a mix of competitive priorities and combine them to inform future decisions not because one priority is more important than the other but because the optimal choices are selected in the given context (socio-economic, environmental and political) to translate the prevailing challenges across the value chain and turn them to opportunities.

Value chain analysis was initially introduced by Porter [8] to represent internal activities involved with producing goods and services. The approach applies a systemic strategy to analyse internal value chain activities, understand challenges and identify competitive advantages and disadvantages. It can be used to understand a production system and focus assessment on stages, activities and competitive priorities. It can identify challenges that trigger major uncertainties and articulate strategies to overcome them, define competitive advantages and incentivise development [9].

In this paper, we apply value chain analysis to biomass production for bioenergy and biobased products accounting for a combination of metrics reflecting performance for resource efficiency, economic, environmental and social sustainability [10]. This is especially important because of the potential for these value chains to ameliorate many challenges economies face struggling to deal with their carbon budgets. Whilst conventional value chain analysis emphasises the value creation from a financial point of view [11] the recent increased concerns for 'green value-added pathways' in which not only the economic value creation but also the environmental and the social contributions can be accounted for necessitate a more rounded use of this method. The biomass value chain comprises all stages and activities in the flow from natural assets and raw materials to products, and it can be analysed in such a way that all important joints are balanced out of a combination of resource efficiency and sustainability aspects all the way from cradle to grave.

Competitive priority theory is usually applied to individual firms but, in this paper, we combine it with value chain analysis and adapt it to explore wider physical and market biomass value chain attributes. Lee [12] and Torjai et al. [13] used competitive theory to address uncertainties across supply and demand interactions in value chains. Further research in this field [14] acknowledges that competitive priorities can be used to articulate improved organisational performance in a value chain and that they should be measured with consistent and suitable indicators [5,12,13].

In the field of biomass as a resource for the bioeconomy, there have been several initiatives that addressed suitable indicators which interpret performance and can be used in decision making and monitoring by government and industry. These include among others:

- "Bioeconomy Knowledge Centre" by its Joint Research Centre (JRC). The work assesses a set of socioeconomic indicators for different bioeconomy sectors (number of persons employed, turnover, value added, labour productivity), and estimates country performance [15].
- BioMonitor project aims to establish a sustainable and robust framework that different stakeholders can use to monitor the bioeconomy and its various impacts in relation to the EU and its Member States. The project is ongoing [16].
- BERST project [17] developed a set of quantitative and qualitative indicators to understand and to estimate the potentials and challenges of sub-national bioeconomies (clusters or regions).
- SAT-BBE project [18] has designed a systems analysis tools framework to monitor the evolution of the bioeconomy in the

EU, and to analyse the socio-economic and environmental impacts of the bioeconomy and its relevant policies.

- Biomass Policies project developed a set of criteria and indicators that address resource efficiency and sustainability in biomass value chains.
- S2Biom project (2013–2017) has developed "Sustainability Criteria and Indicators for the Bioeconomy" [19].

A recent study by FAO [20] which reviewed bioeconomy indicators at territorial and product/value chain level concludes that the main challenge for monitoring sustainability performance for biomass is the lack of methodologies for attributing specific impacts to the biomass value chain stages, that also leads to fragmented data collection. The study advises that the combination of the value chain approach with competitive priority theory can be helpful to assess the impact and performance since it is suitable for identifying challenges within individual stages and facilitating suitable optimisation to overcome them at value chain level.

The work presented here combines value chain analysis and competitive priority theory with consistent, performance based [21] indicators interpreting attributes that are important but challenging for both the establishment and operation of individual value chain stages. The combination of both methods can help identifying challenges that hinder performance in individual value chain stages and at the same time steer optimisation of relevant competitive priorities that can overcome them and turn them to competitive advantages. Thus, decision makers can be enabled to focus policy and support [22,23] from the perspectives of environmental, social and economic sustainability and resource efficiency [24].

The purpose of the paper is to present a conceptual framework that allows looking into optimisation possibilities along the given value chain. It is structured in three sections. The first section describes the conceptual framework to develop optimisation strategies by using value chain analysis and competitive priority theory together with indicators that are fit to address challenges in the establishment and operation of biomass value chains. The second section uses the case of biomass-based Combined Heat and Power (CHP) to illustrate how the method can be applied in each value chain stage to develop optimisation strategies that could overcome challenges and foster opportunities for optimal performance, increased consumer awareness and development of potential local capacity. Finally, the third section provides conclusions and discusses how this approach can enable decision makers to focus strategies and improve overall performance of value chains.

The paper aims to address the complexity, open-ending and inconsistency in metrics and does not include a comprehensive analysis of all available indicators. It suggests a potential approach that combines the value chain analysis with the competitive priority theory as well as narrows down indicators to ensure there is a meaningful selection that interprets challenges and allows comparisons. The actual quantification of the metrics of the indicators as well as any possible combination of indicators to be used depends largely on the availability and validity of transparent data sources.

2. Conceptual framework

The earliest use of competitive priorities, by Hayes and Wheelwright [25], described how individual manufacturing companies compete in the marketplace by focusing on quality, lead-time, cost and/or flexibility. Many authors and practitioners have added to and adapted this list over the years { [13,26–28]} for example adding transferability and innovation.

This paper combines value chain analysis and competitive

priority theory with the selection of consistent, performance-based indicators in value chain stages to understand challenges and focus optimisation strategies to improve sustainability and resource efficiency. It includes three sequential, linked steps (Fig. 1):

- 1. System design.** This step aims to understand the system. It defines key stages and underlying activities within biobased value chains, identifies challenges that trigger major uncertainties and explores competitive priorities that are essential for the development of sustainable and resource efficient biobased value chains.
- 2. Selection of indicators.** This step focuses the assessment by suggesting indicators that are suitable for the main principles of sustainability and resource efficiency and fit to measure performance, overcome challenges and steer focus on the competitive priorities within individual value chains. This paper uses a mix of indicators focusing on functions, products and components, energy and composite indicators. The list of indicators is indicative and should always be adjusted depending on the physical assets and market attributes of the value chains addressed and the region of implementation.
- 3. Optimisation strategies.** This step builds on the indicators suggested in the previous one and explores how they fit in each competitive priority and what evidence they can provide to focus optimisation strategies at value chain level.

This framework provides a means for decision makers to turn challenges into objectives of future optimisation strategies that, despite uncertainties, can positively influence attitudes, behaviors and decision making [24]. Results are presented for an application to biomass CHP, to illustrate how this approach can assist in strategy development.

2.1. System design

System design in the value chain theory [11] recognises which stages and activities are the sources of cost or differentiation and which ones could be improved through competitive priorities [7,8]. In other words, by looking into internal activities, the analysis reveals where a value chain’s competitive advantages [7] or disadvantages are. If the value chain aims to benefit from cost advantage strategy, optimisation should focus on activities contributing the most to the achievement of cost reductions. The value chain that

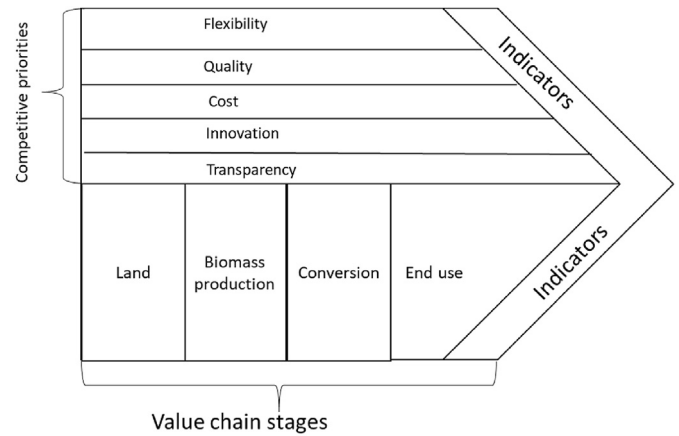


Fig. 2. Basic value chain flow chart for biobased value chains (adapted from Porter, 1985).

competes through differentiation advantage will try to perform its activities better than competing ones would [29].

The main stages in biomass value chains, which include land use, biomass production, conversion and end use, require optimisation for both cost and a variety of differentiation advantages that are linked to physical assets and market attributes. This is in agreement to research from Fisher [23] and Torjai [13] who state that biomass value chains have a dual function combining physical and market assets. The physical function refers to specific activities such as land use, biomass production and delivery to the conversion plant [13]. As such the supply chain involves physical attributes and needs to be designed with focus on minimising physical challenges throughout raw material production and conversion. This type of value chain is described as physically efficient. The market assets refer to the delivery of biobased products to end users and this adds an innovative nature to the biomass value chains. The selection of competitive priorities must therefore ensure that both physical and market assets are represented in the analysis.

Strategic decisions for biomass value chains at policy and industrial level to date have been based on using the resource to deliver sector specific targets (e.g. climate change, energy, transport fuels, bioeconomy, etc.) rather than providing integrated support

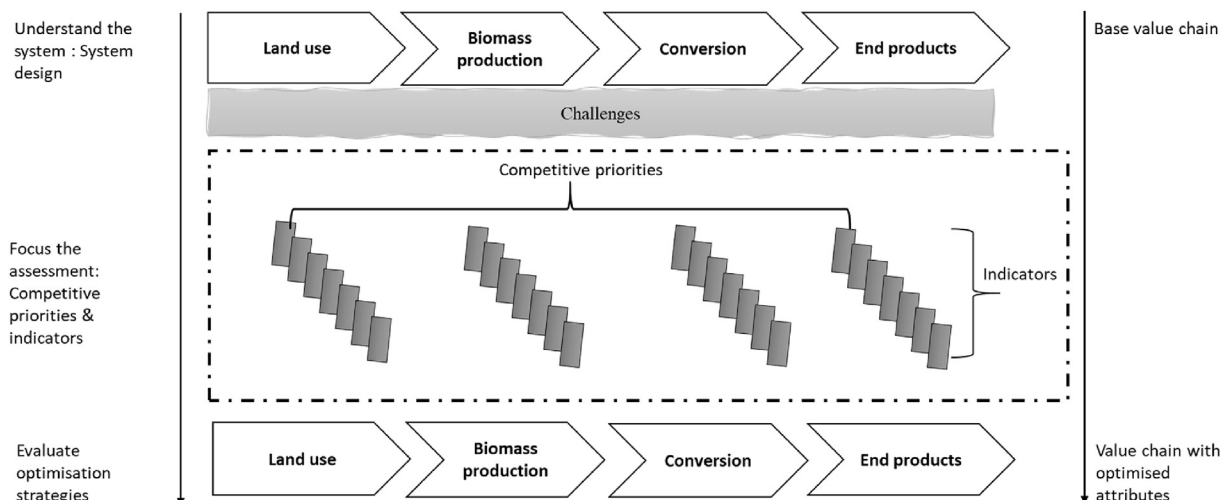


Fig. 1. Outline of methodological steps for optimisation strategies through value chain analysis and competitive priority theory.

across the different stages of biomass value chains and exploiting competitive advantages within the value chain stages and specific regional settings. Strategy formation to date has therefore resulted in fragmented, sub-optimal biomass use. The use of value chain analysis will allow identification of activities causing uncertainty and focus optimisation of competitive advantages through suitable competitive priorities.

This step uses value chain analysis to understand the system by defining key stages and underlying activities [20] within biomass value chains. Following it applies the competitive priority theory to identify challenges that trigger major uncertainties and explores competitive priorities that are essential to foster competitive advantages for the development of sustainable and resource efficient biobased value chains.

Biomass value chains for the bioeconomy need to exhibit improved performance in terms of flexibility of raw material provision and conversion technologies that can allow valorisation of both main products and co-products in order to deliver high quality outputs at a cost-efficient manner. Moreover, highly innovative techniques and practices are required to improve performance of the increasingly varied value chains being explored and implemented. This paper applies a set of five competitive priorities, matching both the physical assets and market attributes within the value chain stages and explores how the biomass value chains can be differentiated to achieve marketplace competitiveness [12,13] as well as functional efficiency in a sustainable and resource efficient manner. These are: flexibility, quality, cost, innovation and transparency.

- Flexibility is the ability to expand or adjust capacity volume and adjust product design, range and variety [27]. Flexibility is essential firstly to ensure a broad, year-round biomass supply that can be adapted to local ecology and climate and secondly to adjust conversion pathways and scales of implementation to convert raw materials with variable qualities to energy, fuels and biobased products.
- Quality is defined as improving process and product performance and adherence to quality standards [27]. Quality of raw materials, practices and end products are important for successful establishment and uninterrupted operation throughout the value chain lifetime [6].
- Cost addresses the reduction of production costs of goods sold as well as generating added-value [28]. The competitiveness of biomass value chains relies on the costs of the individual stages with land use and biomass production accounting for almost half of the total [6]. Creating value and improving costs along the chain is important for the viability and commercial implementation especially when highly innovative components are involved [12].
- Innovation addresses the development of innovative equipment and processes [13]. With biomass being one of the key resources for the low carbon circular economy [19], innovation is the cornerstone defining which value chain configurations perform best technically whilst being sustainable and resource efficient [6].
- Transparency is defined as current information about status of system and immediate notification of unexpected events [13]. Sustainability [20] and avoidance of displacing other activities or product sectors is of paramount importance to any development in the biomass sector. Including transparency in the competitive priorities of biomass value chains is therefore essential to improve clarity and awareness of the benefits from their implementation as well as create trust among society.

The section below discusses major challenges within individual

value chain stages and suggests relevant competitive priorities that can help overcome them.

Land use: Most biomass feedstocks are land-based, being sourced from agriculture and forest systems. The main activities in this stage are land acquisition and soil management. Decision makers face challenges including the need to avoid displacement of other land-based activities and the need to ensure sustainable practices that improve soil quality. The competitive priorities examined in this paper for this stage are quality, cost, innovation and transparency.

Biomass production includes the following activities: crop establishment and management, harvesting, pretreatment (chipping, drying, milling, briquetting, etc.), storage and transport.

Crop establishment and management practices must recognize and enhance biodiversity, enable low input cultivation systems, and minimise intensity of the applied practices. The competitive priorities examined in this paper for this stage are flexibility, quality, cost and innovation.

Conversion pathways of biomass to biobased products include biochemical,¹ thermochemical² and physical or chemical depolymerisation.³ The main activities are the construction and operation of conversion installations. Challenges with regards to construction include site selection and access to technology. With regards to operation, challenges include low emissions performance, handling mixed volumes of feedstocks and improving synergies for valorisation of residues and co-products.

The competitive priorities examined in this paper for this stage are flexibility, quality, cost and innovation.

End use of biomass-based products includes activities related to distribution and consumer use. Products should be compatible with existing infrastructure, standards and distribution channels. Furthermore, both consumer acceptance and successful market uptake will be subject to their fitness to substitute existing products and commodities in sectors as chemicals, food, energy, fuels, etc. The competitive priorities examined in this paper for this stage are quality, cost and transparency (see Table 1).

Table 2 below outlines the challenges within value chain activities and suggests competitive priorities that can help overcoming them by optimising sustainability and resource efficiency. It also categorises them based on their ability to interpret the physical and market driven attributes of the chain and the type of optimisation strategies (cost and/or differentiation) that they can inform.

Each of the competitive priorities presented in this section requires comprehensive metrics that are fit to clearly measure the priority, improve understanding on requirements to overcome this challenge as well as interlink across the value chain stages to advance the overall performance.

¹ Small to medium scale installations (residential) will focus on the production of heat, as well as some industrial installations (producing process heat). From a certain scale - in particular when passing 1 - 5MWth - electricity production will come into focus, first in combination with heat (heat driven CHPs). Typical fields of applications for biomass CHP plants are wood processing industries and sawmills, district heating systems (newly erected or retrofitted systems) as well as industries with a high process heat and cooling demand. Installations focusing on only electricity production generally start from 20 MWe and bigger. These require large amounts of biomass. In Scandinavia also large-scale CHP is applied, reaching higher overall efficiency than condensing power plants.

² These conversion processes tend more towards biorefineries, producing fuels and/or chemicals (potentially also heat and electricity as side product or to feed into the internal process). Pyrolysis oil production can also be combined in a CHP plant. Fischer-Tropsch synthesis needs to have large scale to be commercial. The other processes can be medium scale.

³ Physical or chemical treatment is required to remove lignin from biomass and deconstruct cellulose to make it more accessible for further microbial conversion. <https://www.scitecheuropa.eu/bioeconomy/93538>.

Table 1
Competitive priorities that can lead to sustainability and resource efficiency within biobased value chains and challenges they can address.

	Challenges that trigger major uncertainties for sustainability and resource efficiency	Relevant competitive priorities
Land use	Minimising competition with current land uses	Quality Innovation
	Avoid displacement of other land-based activities	Transparency Cost
	Improve land quality and maintain soil organic matter	Quality Innovation
Biomass production	Year-round, sustainable biomass supply	Cost
	Competition for biomass feedstocks	Innovation
	Biodiversity loss	
Conversion	Maintain low input and less intensive cropping practices	Flexibility Quality Quality
	Safeguard low soil compaction and soil carbon	
	Maintain low emission levels or pollution discharge from pre-treatment	
	Reduce the carbon footprint of storage & transport	
	Site selection for the plant location	Innovation
	Access to technology	Quality Flexibility Cost
End use	Low emissions performance,	
	Handling mixed volumes of feedstocks	
	Optimising synergies for valorisation of residues and co-products.	
	Compatibility of the bio-commodities with existing processes and standards	Quality Cost
End use	Replaceability and competition with existing infrastructure and distribution channels	Transparency
	Awareness	
	Public perception	

2.2. Competitive priorities and indicators

Biomass value chains involve dynamic processes that necessitate system-based assessments covering land use, biomass production, conversion and end use [21]. The previous section detailed competitive priorities, in which value chains must operate well to achieve performance-based competitive advantages in a sustainable and resource efficient manner. These competitive priorities can be articulated with indicators that fit to the function of the value chain.

This step of the methodology suggests a set of indicators that are relevant to the main principles of sustainability and resource efficiency,⁴ can address competitive priorities, and can be used to measure, monitor and interpret performance, overcome challenges and facilitate opportunities within individual value chains. Detailed definitions of indicators, data sources and limitations are provided in Annex 1.

Resource efficiency [6,30,31] implies reducing the amount of resources used to meet our needs. But it also relates to the environmental aspects – on water, air, soil and biodiversity – that result from extracting resources from natural systems and emitting wastes and pollution, thus making environmental sustainability an inherent part of resource efficiency [32]. Resource efficiency is essential when addressing competition of food and non-food sectors for specific biomass feedstocks. This competition can be leveraged through optimisation strategies for feedstock provision that include among others competitive priorities such as flexibility and innovation.

Sustainability however is a broader concept and beyond targeting environmental values focuses on the triple bottom line approach which contributes to environmental integrity, social well-being and economic resilience [33]. In this definition of sustainability, the actors or stakeholders of the value chain focus on minimising environmental burden, maximising social prosperity and maintaining economic advantages.

Indicators are quantitative or qualitative variables providing means to help assess performance or compliance in the areas of concern, to reflect changes and to measure achievement. Resource efficiency in this paper is addressed with four indicators: i) bio-energy carriers and biomaterials per unit of cultivated area is used to define land productivity; ii) direct and indirect land use change [33] refers to the conversion of land from one purpose to another; iii) primary and secondary product outputs [32]; iv) conversion efficiency [32] compares the energy content of inputs and outputs of the value chain.

Sustainability includes environmental, economic and social dimensions. Environmental sustainability is addressed with the following indicators related to climate protection, biodiversity, soil, water use and air: i) life cycle greenhouse gas (GHG) emissions; ii) sustainable harvest levels; iii) conservation of areas with both high biodiversity and carbon stock [32–34]; iv) soil organic carbon and nutrients [6,35]; v) water use efficiency; vi) acidification and vii) particle pollution [36,37].

Economic sustainability is determined by the ‘value’ created along the stages of the value chain criteria. The indicators suggested in this paper are related to costs and market readiness and include: i) levelised life cycle costs and ii) Technological Readiness Level (TRL), both for feedstock production and conversion stages.

Social sustainability defines how the value generated by the biobased value chain is shared among stakeholders. The indicators suggested in this paper are related to jobs and local economy: i) full time equivalents (FTE) along the full value chain [41,42] and ii) contribution to local economy.

Table 2 presents the suggested indicators and their relevance to measure, monitor and interpret performance of competitive priorities in the individual biomass value chain activities.

2.3. Optimisation strategies with competitive priority indicators

The theory of using competitive priorities to optimise strategy formation has been addressed primarily in business development. Plott (1996) [43] defines competitive strategy as being different by choosing a different set of activities to deliver the company’s mix of value to the customers. Markides (2003) [44] argues that the essence of developing a strategy is to select one strategic position

⁴ Nitrogen oxides (NOx) act as indirect greenhouse gases by producing the tropospheric greenhouse gas ‘ozone’ via photochemical reactions in the atmosphere. The impact of NOx gases on global warming is not all bad though.

Table 2
Suggested indicators to measure, monitor and interpret performance for competitive priorities in individual biomass value chain activities.

	Indicators	Main activities								
		Land use		Biomass production			Conversion		End use	
		Land acquisition	Soil management	Crop establishment & crop management	Harvest	Pre-treatment Storage Transport	Construction	Operation	Distribution	Consumer use
Resource efficiency	Bioenergy carriers & biomaterials per unit of cultivated area (tonne per ha or GJ/ha/yr)	Innovation								
	Direct/indirect land use change	Transparency								
	Primary & secondary outputs	Flexibility								
Environmental Sustainability [38,39]	Cumulative energy demand (GJ input/GJ output)/non-renewable energy requirement (GJ input)	Flexibility; Innovation								
	Life cycle GHG emissions (gCO ₂ eq/MJ)	Quality; Transparency								
	Sustainable harvest level (% of net annual growth)	Flexibility; Quality								
	Conservation of land with significant biodiversity	Quality								
	Cultivation practises in line with biodiversity	Quality, Innovation								
	Soil carbon & nutrients (tonnes/ha)	Quality, Innovation								
	Acidification (g SO ₂ eq/MJ); particulate matter (g PM ₁₀ /MJ); NO _x , ^a etc.	Quality								
Water use efficiency (m ³ /tonne outputs)	Flexibility; Quality									
Economic Sustainability	Levelised life cycle costs (€/tonne outputs)	Cost								
	Technology readiness level for feedstock 1–9 ((CAAFI) ⁷ [32,35,40])	Flexibility; Cost; Innovation								
	Technology readiness level for conversion 1–9 ([24,34])	Flexibility; Cost; Innovation								
Social Sustainability	FTE along the full value chain (number of full-time jobs/tonne or GJ of end products)	Cost								
	Contribution to rural economy (€/tonne product)	Cost; Transparency								

^a http://caafi.org/tools/docs/Path_to_Aviation_Alternative_Fuel_Readiness_v24.pdf accessed on 23rd October 2019.

that a company or value chain can claim as its own and pursue it. This will help focus the strategy with competitive priorities that differ from that of its competitors [45] and optimise the key stages towards achieving it. In biomass-based value chains the strategic position accepted by key initiatives [20,46] is that they should be sustainable and resource efficient to deliver benefits for the low carbon, circular economies of the future [20].

Optimisation strategies require detailed understanding of how competitive priorities in value chains can be used as means to convert challenges to competitive advantages. The term competitive advantage [7] refers to the capabilities which allow a value chain to differentiate itself from its competitors [9]. It is defined in literature [47] as the differential in any attribute or factor that allows a value chain to create better value and achieve superior performance [48–52]. Competitive advantage, is also linked to

various sources of innovation [53], such as new technologies; the modification of demand or the emergence of new demand; the emergence of a new segment; changes in costs or the availability of means of production; and changes in regulation.

In a similar line of thinking, Beams et al. [26] define biomass use for the bioeconomy as a shift towards differentiated sustainable production practices that use sources of innovation in the form of new technological processes or biotechnology. Ideally, the bioeconomy should emerge from the modification of demand to steer better use of resources [27], the emergence of new biobased segments that aim to replace the use of fossil and mineral materials, but also from the changes in flexibility and quality of raw materials and technological pathways that can valorize feedstocks and promote resource efficiency without depleting natural capital [2]. This definition complies with the ones other researchers suggested and

justifies the need to optimise future strategies using the respective value chain advantages (e.g. sustainability, resource efficiency [28,29,54], reduction in use of resources to meet societal needs [2,30,55], etc).

This step builds on the indicators suggested in the previous one and explores how they fit in each competitive priority and what evidence they can provide to focus optimisation strategies at value chain level. Understanding how indicators can be used to measure, monitor [14] and interpret performance within the value chain stages allows informed decision makers to develop focused strategies that foster relevant competitive priorities and identify options that create sustainable and resource efficient opportunities.

Flexibility offers opportunities for value chain configurations [56,57] with high performance in terms of sustainability and resource efficiency. This priority applies within biomass production and conversion stages and can be accomplished through selection of suitable biomass feedstocks, types and scale of conversion technologies. Indicators that can address flexibility include:

- *primary and secondary product* inform on flexibility in production of biomass to generate or incorporate different practices, reduce competition for feedstocks and adapt to various conversion technologies or changing markets;
- *cumulative energy demand and non-renewable energy requirement* inform on the flexibility of overall value chain to allocate energy inputs and outputs strategically;
- *sustainable harvest level* is calculated through activities in biomass production (crop establishment, management and harvest). It informs on harvesting techniques and allowable harvest levels and assists in designing flexible biomass production schemes and adjusting harvesting techniques to incorporate long-term sustainable management;
- *water use and water efficiency* are calculated through biomass production and conversion, and inform on flexibility in strategies based on the balance between efficiency and sustainability of production;
- *technology readiness level for feedstock and for conversion* is evaluated for the biomass production and conversion stages. It facilitates optimisations in flexibility by informing on scales of application [40,58] and value chain configurations that allow reaching optimal performance.

Quality aims to improve process and product performance and adherence to quality standards and certification schemes. Physical assets – soil, water and air – must be safeguarded throughout the biomass value chain establishment and operation while the quality of the end-product is critical for consumer confidence and successful market uptake. It applies across all value chain stages [59,60] in soil preparation, pre-treatment, storage and harvest, operation and distribution. Indicators that can measure quality performance and optimisation include:

- *life cycle greenhouse gas emissions* can inform on limitations for land use change, soil quality, crop input requirements, management practices, process inputs and energy efficiency, sustainable distribution channels, end use, etc.;
- *conservation of land with significant biodiversity* informs on the selection of low-impact crops [61,62] for the native environment as well as suitable cultivation practices [63];
- *sustainable harvest levels* can inform on the quality specifications for the harvested biomass and ensure the quality of soil throughout the process operations;
- *soil carbon and soil nutrients* indicators inform on standard values for maintenance and improvement of soil quality;

- *air quality* informs on specifications for air emissions throughout the value chain;
- *water use efficiency* informs on suitability of water for irrigation purposes, when and if required during the land use and biomass production stages;

Cost as a competitive priority which aims to create highest added financial value and lowest costs across value chain stages. Indicators that can measure performance and optimisation include:

- *levelised life cycle costs* inform on the overall cost of the value chain as well as costs within individual stages and respective activities;
- *technology readiness level for feedstock and for conversion* informs cost by level of maturity
- *FTE along the full value chain* informs on labor costs;
- *contribution to rural economy* informs on the economic growth (e.g. induced investment, capital and material expenditure benefitting local businesses, etc.) [64,65] caused by the development of biobased value chains in a specific region.

Innovation is defined as the development of innovative cultivation techniques in line with biodiversity conservation as well as use of innovative equipment and processes. The development and efficiency of converting biological raw materials to a series of commodities depends in large part on technological innovation. It is calculated in the land use, biomass production, conversion stages, including notably soil management, crop establishment and management, pre-treatment and construction activities and processing efficiency. Indicators used to measure performance include:

- *bioenergy carriers and biomaterials per hectare* of cultivated area can inform on innovations required in terms of land use productivity, new crop species and novel management practices;
- *soil carbon and nutrients* can inform on innovations required to rehabilitate unused or degraded land;
- *cumulative energy demand and non-renewable energy requirement* can inform on innovations required in terms of conversion efficiency; proximity to grid, maturity of technologies, etc.
- *technology readiness level for feedstock and for conversion* informs on innovative breakthroughs of the value chain;
- *contribution to local economy* can support the development of new knowledge-sharing and education schemes, training capacity and partnerships to improve acceptance and perceptions.

Transparency reflects current information about status of system and immediate notification of unexpected events. It is addressed in the land use and end-product stages through land use change and emissions. Relevant indicators to measure performance include:

- *direct/indirect land use change* informs at the initial development stage about the land use patterns and potential displacement effects or novel developments;
- *life cycle greenhouse gas emissions* inform on compliance with the prevailing certification and standardisation schemes throughout the operational lifetime of the value chain.

Table 3 describes how indicators illustrate competitive priorities, address challenges and provide evidence for resource efficiency and sustainability in each value chain stage.

3. The case study: Biomass Combined Heat and Power

There is a rich body of knowledge [7] on the use competitive

Table 3
Use of indicators and competitive priorities to provide evidence and address challenges in biomass value chains.

Value chain stage	Indicators	Competitive priorities	Evidence provided by indicators to overcome resource efficiency and sustainability challenges	Challenges
Land use Biomass production	Bioenergy carriers and biomaterials per hectare of cultivated area	Innovation	Evaluation of land and biomass feedstock; cultivation inputs, management practices and inform on innovations required in breeding/genetics to achieve further optimisation of the value chain. Innovations are required in terms of new crop species and novel management practices	Year-round sustainable provision of biomass Maintain low input and less intensive cropping practices
	Direct/indirect land use change	Transparency	Information at the initial planning stage of any biobased value chain about the land use patterns, potential displacement effects or novel developments	Minimising competition with current land uses, avoid displacement of other land-based activities or create value through land regeneration
	Sustainable harvest level	Flexibility Quality	Flexible biomass production schemes Harvesting techniques to incorporate long-term sustainable management Quality specifications for the harvested biomass and soil	Safeguard low soil compaction and appropriate soil carbon levels
	Conservation of land with biodiversity	Quality	Quality specifications to ensure biodiversity is preserved and enriched	Loss of biodiversity
	Soil carbon and nutrients	Quality Innovation	Standard values for maintenance and improvement of soil quality Recommendations for innovations are required to rehabilitate unused or degraded land	Improve land quality and maintain soil organic matter
Biomass Production	Water use efficiency	Flexibility Quality	Flexibility in strategies based on the balance between efficiency and sustainability of production Suitability of water for irrigation purposes	Maintain low input and less intensive cropping practices Improve land productivity
Biomass production Conversion	Primary and secondary products	Flexibility	Flexibility in production of biomass to generate or incorporate different practices, reduce competition for feedstocks and adapt to various conversion technologies or changing markets	Maintain low emission levels Reduce the carbon footprint throughout the value chain
	Cumulative energy demand; Non-renewable energy requirement	Flexibility Innovation	Optimisation of overall value chain to allocate energy inputs and outputs strategically Innovations required in terms of conversion efficiency; proximity to grid, maturity of technologies, etc.	Maintain low emission levels Reduce the carbon footprint throughout the value chain
	Technology readiness level for feedstock and for conversion	Flexibility Cost Innovation	Optimisations in flexibility by informing on scales of application and value chain configurations that allow reaching optimal performance Cost by level of maturity Evidence on the commercial maturity of feedstocks, cultivation practices and conversion technologies	Achieve optimal performance Evolution from demonstration to commercialisation
Land use Biomass production Conversion End use	Life cycle GHG emissions	Quality Transparency	Limitations for land use change, soil quality, crop input requirements, management practices, process inputs, sustainable distribution channels, etc. Compliance with the prevailing certification and standardisation schemes throughout the operational lifetime of the value chain	Maintain low emission levels or pollution discharge Reduce the carbon footprint of the storage and transportation of the feedstock Awareness & Public perception
	Air quality Levelised life cycle costs	Quality Cost	Specifications for air emissions throughout the value chain Overall cost of the value chain as well as costs within individual stages and respective activities Informs on investment required throughout the value chain lifetime to maintain process and product quality	Maintain low emission levels or pollution discharge Optimising synergies for valorisation of residues and co-products Compatibility of the bio-commodities with existing processes and standards Replaceability with existing infrastructure and distribution channels Awareness & public perception
	FTE along the full value chain	Cost	Labour costs across value chain	Year-round employment in rural agricultural regions
	Contribution to rural economy	Cost Transparency	Informs on the economic growth caused by the development of biobased value chains in a specific region Supports the development of new knowledge-sharing and education schemes, training capacity and partnerships to improve acceptance and perceptions	Rural development Rehabilitation of unused, abandoned and degraded land Quality of life

priorities in the strategy literature, ranging from the industry positioning approach, the resource-based view and the dynamic capability approach [53]. It is widely agreed among researchers that the concept needs to be tested empirically to determine the competitive priorities which create a value chain's competitiveness. This section uses the case of biomass CHP to illustrate how decision making can use competitive priority indicators in each value chain stage and focus optimisation strategies to overcome challenges and foster opportunities that lead to optimal performance, increased consumer awareness and development of potential local capacity.

The rationale of the system and the analysis of indicators have been presented to 30 stakeholders (one workshop with twenty stakeholders and selected interviews) in total and they have selected the challenges which require improvements within the value chain stages.

3.1. System design

Small and medium scale combustion is typically within the range 0.5 MW–10 MW and is heat-led. Applications include forest

and agricultural processing industries and district heating systems for urban areas. The main biomass feedstocks which can be used are primary forest residues, prunnings and landscape care wood, agricultural residues (e.g. straw) and woody perennial crops (e.g. poplar) [54]. The rationale for selecting this value chain is that it can use a variety of feedstocks including residues and dedicated crops, it is commercially mature and exhibits high market diversity within the industry and district heating sectors.

- *Ability to use a variety of feedstocks* that can facilitate managing competition and addressing resource efficiency. Agricultural, forest residues, landscape care wood and woody crops are promising feedstocks which have the potential to reduce pressure on the forest biomass [55].
- *Technology is commercially mature*
- *Market diversity*: Combined Heat and Power has a diverse portfolio of applications. Usually the biomass feedstocks that are used derive as secondary products, residues or wastes from the main processing activity of the respective industries. By further exploiting them for energy contributes to low carbon and circular economy using renewable (biomass) raw materials.

Moreover, CHP is considered an important pathway to increase the efficiency of the energy system and to reduce global CO₂ emissions [56]. The system design of the value chain is presented schematically in the following figure:

3.2. Competitive priority indicators addressing challenges in value chain stages of biomass Combined Heat and Power

The use of competitive priorities in individual value chain stages enables understanding of the factors that should influence decision making of biomass CHP operations (see Fig. 3) [13]. Extending the respective indicators beyond single-cost or GHG saving ones avoids limiting the scope and brings to surface important value chain characteristics [5,13,25]. This section discusses the challenges in decision making for each value chain stage of biomass CHP and suggests competitive priority indicators next to each decision-making issue in order to focus future optimisation strategies.

Land use is the first decision making step at the initial planning of biomass value chains. Decision making at this stage needs to consider the quality of soil, the cost of land acquisition and the public perception regarding direct and indirect land use that may cause displacement of the existing land-based activities. In the case of biomass CHP, both activities in this stage (land acquisition and soil preparation) are relevant only if the biomass feedstock (all or a part of it) derives from woody crops. If biomass sources are only residual streams, then the first decision making step is biomass production. For woody crops the selection of suitable land to use for bioenergy poses challenges in terms of competition with other

land-based activities, soil disturbance and deterioration of quality (e.g. loss of soil carbon).

Relevant competitive priorities to inform the development of future strategies are quality, cost, innovation and transparency. Suitable indicators that can be considered are:

- **Quality**: i) conservation of land with significant biodiversity to maintain high carbon stock and species diversity and ii) soil carbon and soil nutrients to inform on standard values for maintenance and improvement of soil quality.
- **Cost**: i) levelised life cycle costs-the cost of land (purchase or rent) and costs occurring through soil management practices and ii) employment in FTE for these activities during the lifetime of the project.
- **Innovation**: i) Bioenergy carriers and biomaterials per hectare of cultivated area to define what type of innovations are required in terms of land use productivity and measure their effectiveness to land productivity and ii) soil carbon and nutrients to decide what innovations are required to rehabilitate unused or degraded land.
- **Transparency**: Direct/indirect land use change to appreciate land use patterns and design the woody crop plantation in a manner that reduces potential displacement effects.

The respective mapping of competitive priority indicators across the activities and the evidence they can provide is illustrated in Fig. 4.

Biomass Production: In common with all biomass value chains, medium scale biomass CHP applications face challenges to secure year-round feedstock supply that is sustainable and resource efficient. Decision making at this stage needs to consider how to secure flexible feedstock supply with quality that meets the conversion technology specifications and at the same time keep costs throughout the year at reasonable level [59]. Specific challenges by biomass feedstock type include:

- **Agricultural residues**: i) potential biodiversity loss when over-harvesting, ii) risk of loss of soil organic carbon and nutrients when over-harvesting, iii) stover and stubbles are difficult to harvest and there is no common practice and iv) there are competing markets for animal bedding (in case of straw).
- **Forest residues**: i) biodiversity loss when harvesting forest residues through loss of dead wood and stumps which is negative for forest plant species diversity and soil fauna, ii) increased fertilisation (N and wood ash) may have negative impacts on vegetation, iii) increased risk of soil erosion, in particular when stumps are harvested, iv) risk of loss of soil organic carbon and nutrients when over-harvesting, v) risk of reduced soil fertility and soil structure when harvesting stumps and vi) leaching of

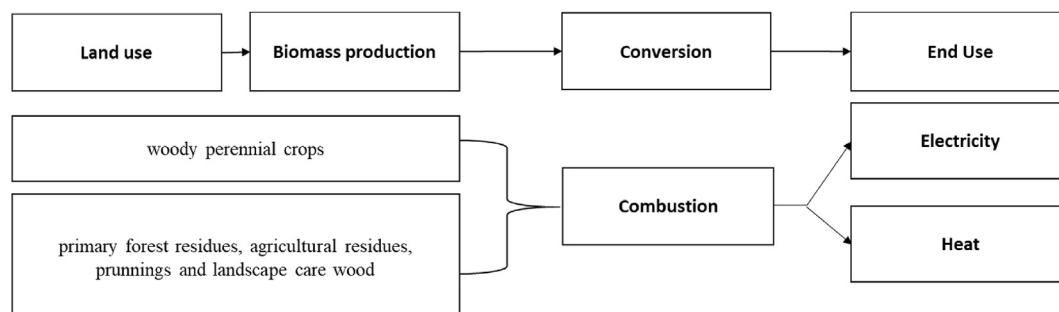


Fig. 3. Schematic representation of biomass CHP value chain.

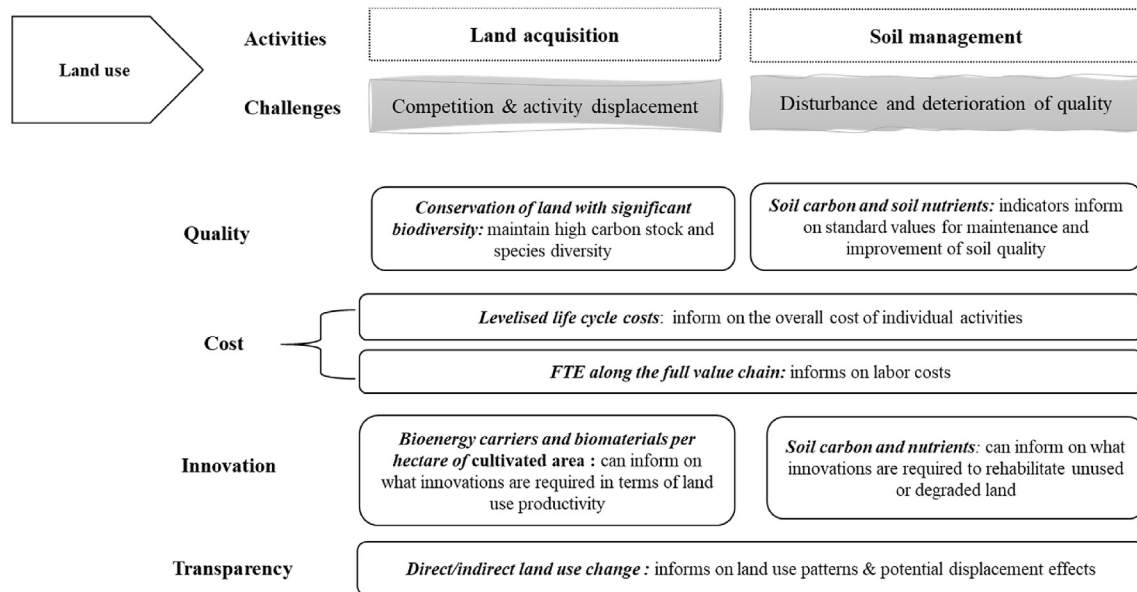


Fig. 4. Competitive priority indicators for optimisation strategies in the land use stage.

nitrogen to water may increase if residue removal causes higher rates of application of fertiliser.

- Landscape care wood: i) biodiversity loss when over-harvesting and habitat disturbance when harvested regularly, ii) potential soil erosion caused during harvesting, according to practices, iii) removal of prunings from permanent crops may reduce soil carbon when overharvested and iv) dispersed availability of biomass may limit application scale.
- Woody crops: i) potential competition with food and feed crops, leading to indirect land use change, ii) risk of loss of sensitive habitats (e.g. stepic habitats, High Nature Value farmland, biodiversity rich grasslands) when introduced, iii) potential damage to soil structure (e.g. harvesting, root removal after 20 years), iv) in arid circumstances ground water abstraction and depletion is possible because of deep roots, v) use of fertilisers and pesticides which can be leached to ground water and pollute habitats, vi) limited financial attractiveness for farmers, vii) farmers unfamiliar with these types of crops and viii) potential competition with food production in terms of land use (not in case of marginal land).

Relevant competitive priorities to inform the development of future strategies include flexibility, quality, cost and innovation. Suitable indicators that can be considered are:

- Flexibility: i) primary and secondary product to select suitable feedstock types, practices and inputs and ii) Technology Readiness Level to optimise sustainable productivity on a year-round basis.
- Quality: i) water use efficiency to balance between efficiency and sustainability of production, ii) sustainable harvest level to minimise soil compaction and iii) life cycle GHG emissions to inform on adherence of the planned biomass production activities with standards and certification.
- Cost: i) levelised life cycle costs-the costs occurring through crop establishment and annual crop management practices as well as harvest, pre-treatment and transport and ii) FTE employment for these activities during the lifetime of the project.

- Innovation: i) bioenergy carriers and biomaterials per hectare of cultivated area to define the type of innovations required for optimised feedstock productivity and to measure their effectiveness to the value chain efficiency and ii) cultivation practices in line with biodiversity: selection of low-impact crops for native environment.

The respective mapping of competitive priority indicators across the activities and the evidence they can provide is illustrated in Fig. 5.

Conversion: Medium scale combustion (industry level) ranges from a few hundred kilo Watt up to a few Mega Watt. They are mainly heat-led. Typical fields of applications are CHP plants in wood processing industries and sawmills, district heating systems as well as industries with a high process heat demand. These value chains offer important advantages for resource efficiency when they are developed and operated in a sustainable manner. These include [66]:

- Electricity is generated next to the base heat production; the overall energy conversion efficiencies range from 65 to 85%.
- Low input of fossil fuels with high GHG savings.
- Better control options for PM emissions compared to small scale installations.
- Positive when full year industrial heat demand. In the case of industrial residues, the business case for the industry itself can be very strong since it will include avoided costs for disposal.

Decision making at this stage needs to facilitate the resource efficient valorisation of main product and co-products. Relevant competitive priorities to include in optimisation strategies are flexibility [67], quality, cost and innovation. Suitable indicators that can be considered are:

- Flexibility: i) primary and secondary product to select appropriate conversion pathways for the available feedstocks, ii) cumulative energy demand and non-renewable energy requirement to allocate energy inputs and outputs and iii) Technology Readiness Level to design scales of application and value chain configurations.

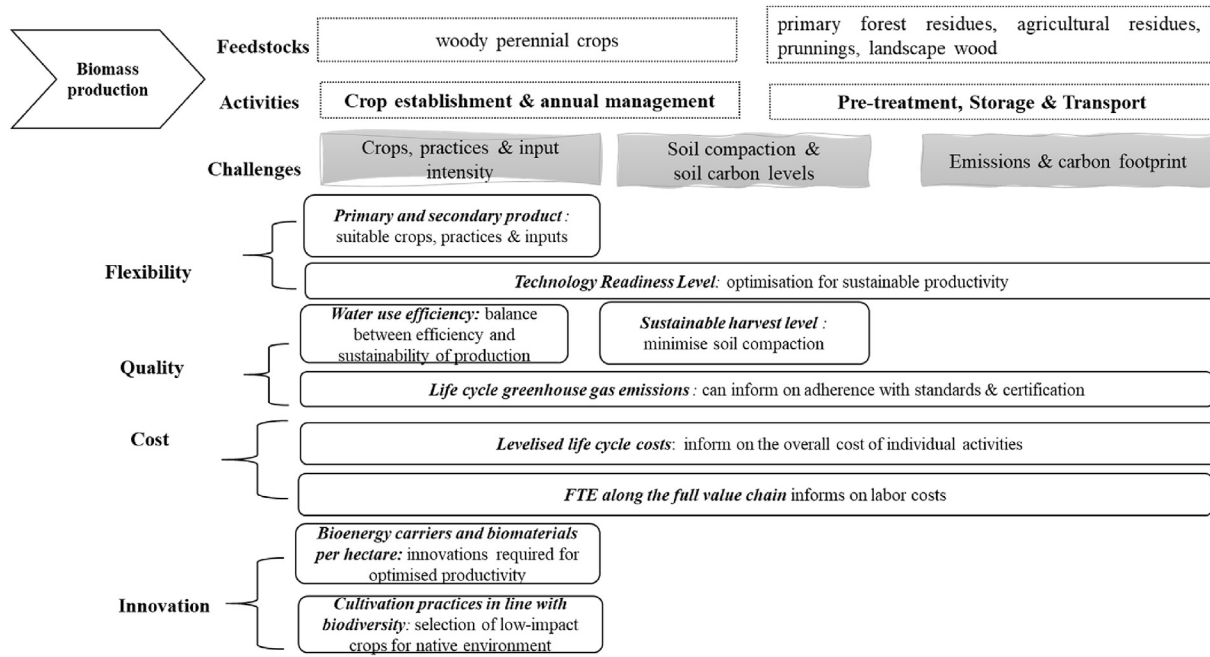


Fig. 5. Competitive priority indicators for optimisation strategies in the biomass production stage.

- Quality: i) life cycle GHG emissions to inform on adherence of the planned biomass conversion activities with standards and certification and ii) air quality to inform on the overall impact to air.
- Cost: i) levelised life cycle costs-the costs occurring through construction and operation and ii) FTE employment for these activities during the lifetime of the project.
- Innovation: i) Technology Readiness Level defines the appropriate scales of application and ii) cumulative energy demand and non-renewable energy requirement informs on the low carbon potential of the conversion pathway through circularity.

The respective mapping of competitive priority indicators across the activities and the evidence they can provide is illustrated in Fig. 6.

End use- Heat & electricity for industry: Decision making at this stage should consider how to generate sustainable heat and electricity and distribute at competitive prices [68,69]. The main challenges for distribution are compatibility with existing processes and standards and ii) replaceability with existing infrastructure and distribution channels [70] while consumer awareness and acceptance are the main challenges for end use. Relevant competitive priorities to include in optimisation strategies are quality, cost, and transparency. Suitable indicators that can be considered are:

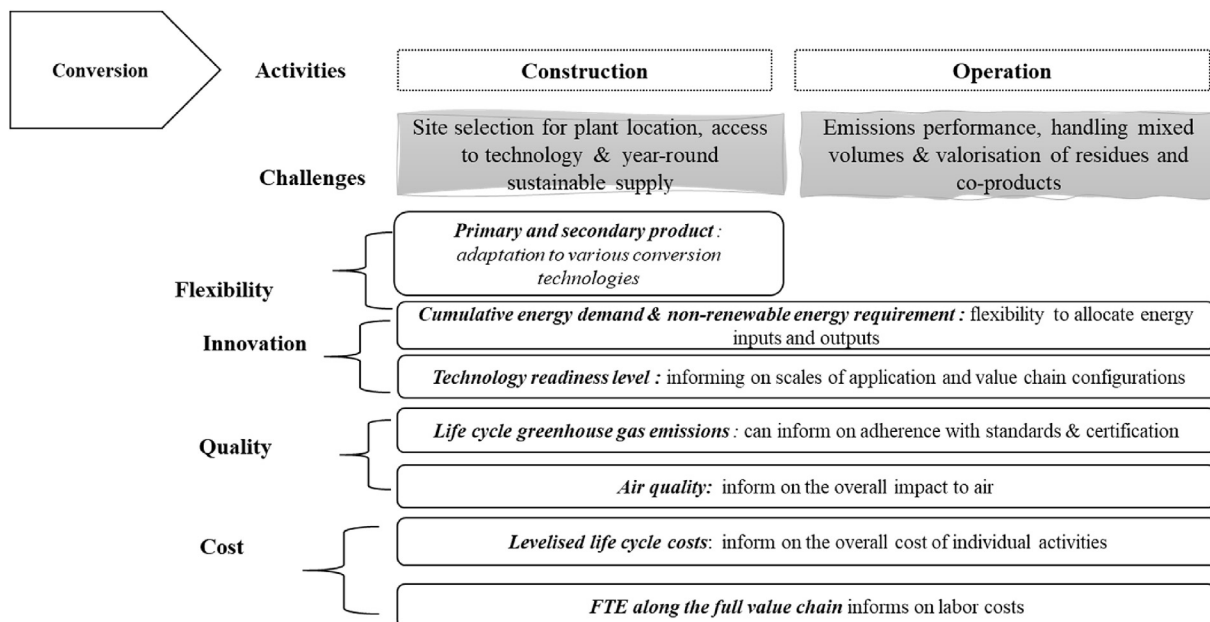


Fig. 6. Competitive priority indicators for optimisation strategies in the conversion stage.

Cost: i) levelised life cycle costs inform on the costs for biomass-based heat and electricity and allow for comparisons with fossil and other renewables and ii) FTE employment for the generation of biomass heat and electricity during the lifetime of the project.

Quality: life cycle GHG emissions which can inform on adherence of the generated heat and electricity with standards and certification.

Transparency: contribution to rural economy informs on the economic growth caused by the development of biomass CHP in a specific region.

The respective mapping of competitive priority indicators across the activities and the evidence they can provide illustrated in Fig. 7.

3.3. Optimisation strategies for medium scale biomass Combined Heat and Power with residues and woody crops

Regardless of the aim of a political or industrial activity or aspiration, decision makers should consider the relevant competitive priorities [13] at each value chain step and formulate suitable objectives to boost their effectiveness. This section suggests focused objectives for future optimisation strategies that can overcome challenges in each value chain stage and discusses how they can lead to better performance and uptake of sustainably sourced and widely accepted biomass options. Fig. 4 below provides an overview of the focused objectives across the value chain stages and individual activities.

Optimisation strategies in the land use stage of biomass CHP should improve the feedstock mix in order to secure year-round supply with minimal direct and indirect land use change while protecting soil quality with the use of sustainable practices. The following objectives can be considered:

1. Rehabilitation of unused, abandoned and degraded land for productive systems. A future strategy could include, among others, the following issues:
 - Potential use of marginal lands with woody biomass crops [71] must be prioritised to increase soil quality and soil carbon stock [72], where suitable.

- Woody biomass crops can be introduced in land rehabilitation as means to provide winter shelter and birds nesting inside plantations [73,74].

These will foster uptake of unused natural assets [75], improve land quality and water use [76] and at the same time reduce competition and displacement of other land-based activities. They will also diversify options for locally sourced feedstock supply, improve cost and increase uptake of innovative practices in options for the cultivation of woody crops.

2. Implementation of soil remediation or revitalisation practices. This objective will improve soil quality and facilitate the application of innovative practices for soil rehabilitation. A future strategy could include, among others, the following issues:
 - Residual feedstock types have priority as they do not cause any land use change.
 - Both in residual and woody feedstocks soil management should follow sustainable practices to improve soil conditions and increase productivity.

These will lead to uptake of locally source material and security of year-round supply.

3. Design public awareness campaigns and training activities for the local community where the biomass CHP will be established and where feedstock is produced. This objective will increase transparency and build trust for the benefits of the biomass value chain.

These will increase knowledge in the local community and improve acceptance of the biomass CHP value chain establishment and operation.

Indicators that can facilitate measuring, monitoring and interpretation in the land use stage include: i) bioenergy carriers and biomaterials per ha, ii) direct/indirect land use change, iii) sustainable harvest level, vi) conservation of land with biodiversity, v) soil carbon and nutrients, vi) life cycle GHG emissions, vii) air quality, viii) levelised life cycle costs, ix) FTE employment along the full value chain and x) contribution to rural economy.

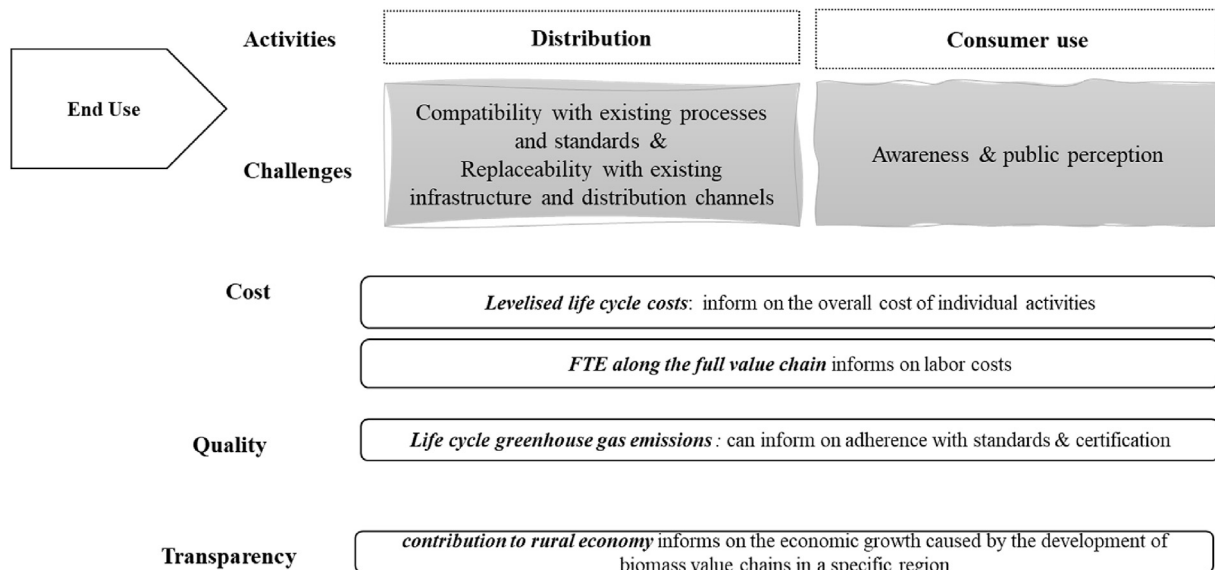


Fig. 7. Competitive priority indicators for optimisation strategies in the end use stage.

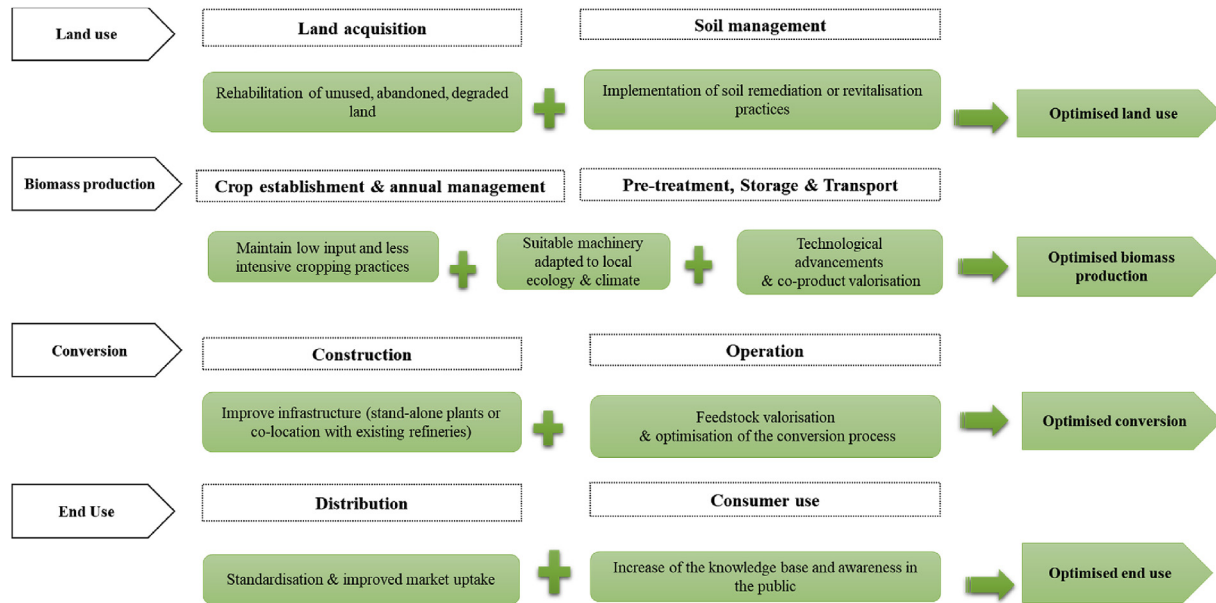


Fig. 8. Focused objectives for optimisation strategies in biomass CHP across value chain stages and activities.

In the biomass production stage, optimisation strategies must ensure year-round supply of good quality feedstocks that are produced, harvested and handled following the resource efficiency and sustainability principles. Crop establishment and management practices must recognize and enhance biodiversity, enable low input cultivation systems, and minimise intensity of the applied practices. The following objectives can be considered:

1. Apply low input and intensity cropping practices. A future strategy could include, among others, the following issues:
 - Select crop species and varieties that are adapted to local climate and ecology.
 - Woody biomass crops like poplar must ensure low pesticide and nitrogen applications so that they have no direct negative impacts on habitat quality.
 - Mixed cropping patterns to ensure soil coverage during winter months can reduce soil erosion and improve soil carbon.

These will improve flexibility for feedstock production, quality of raw materials by reducing chemical inputs and biomass production costs.

2. Use of suitable machinery adapted to local ecology and climate. The following issues can be considered in a future strategy:
 - Harvesting time both for residues and woody crops must be optimised based on climate and crop physiology.
 - The choice of machinery should account for soil and crop types.

These will foster application of innovative machinery and practices and increase flexibility in the type of feedstocks.

3. Use of technological advancements and co-product valorisation.

This will improve quality of end products and foster the application of innovative techniques.

Indicators that can facilitate measuring, monitoring and interpretation include: i) bioenergy carriers and biomaterials per ha, ii)

direct/indirect land use change, iii) sustainable harvest level, iv) conservation of land with biodiversity, v) soil carbon and nutrients, vi) water use efficiency, vii) primary and secondary products, viii) cumulative energy demand and non-renewable energy requirement, ix) technology readiness level for feedstock and for conversion, x) life cycle GHG emissions, xi) air quality, xii) levelised life cycle costs, xiii) FTE employment along the full value chain and xiv) contribution to rural economy.

In the conversion stage optimisation strategies should target improvements in infrastructure both for stand-alone plants and for co-location with existing refineries [77]; and valorising feedstock and optimising conversion processes. The following objectives can be considered:

1. Steer biomass CHP applications in industries with proximity to feedstock.

This will improve flexibility for energy generation options for the industry [78], quality of conversion performance with reduced emissions and foster the application of innovative technologies.

2. Improve feedstock valorisation. A future strategy could include, among others, the following issues:
 - Implement conversion pathways which can handling mixed volumes of feedstocks.
 - Optimising synergies for valorisation of residues and co-products.

These will foster application of innovative pathways and cost effectiveness with the added value of the sales of valorised co-products [79].

Indicators that can facilitate measuring, monitoring and interpretation include: i) primary and secondary products, ii) cumulative energy demand and non-renewable energy requirements, iii) technology readiness level for feedstock and for conversion, iv) life cycle GHG emissions, v) air quality, vi) levelised life cycle costs, vii) FTE employment along the full value chain and viii) contribution to rural economy.

Optimisation strategies in the end use stage include

standardisation, improved market uptake [80], increase knowledge and public awareness. The following objectives can be considered:

1. Improve compatibility of the bio-commodities with existing processes and standards [81].

This will improve quality of biomass heat and electricity.

2. Facilitate smooth operation of heat and electricity markets for renewables and biomass.

This will improve costs through favourable taxation, feed in tariffs and premiums.

3. Develop promotion campaigns for biomass heat and electricity.

This will increase transparency and increase of the knowledge base and awareness in the public [82].

Indicators that can facilitate measuring, monitoring and interpretation include: i) life cycle GHG emissions, ii) air quality, iii) levelised life cycle costs, iv) FTE employment along the full value chain and v) contribution to rural economy.

4. Conclusions

Biomass is considered a key component to meet targets in most policy and strategic documents dealing with low carbon and circular economy. Decision makers are increasingly exploring varied, innovative value chains with high complexity. They face challenges to comply with resource efficient and sustainable practices, interpret fragmented, inconsistent metrics, and decisions often lack coherent systems thinking. This prevents understanding challenges within value chain stages and developing focused optimisation strategies to overcome them and create value at local level.

The conceptual framework presented in this paper combines value chain analysis and competitive priority theory and aims to allow comprehensive assessment of performance, from the perspectives of environmental, social and economic sustainability and resource efficiency as well as enable decision makers develop optimisation strategies based on competitive priorities.

The approach can be easily tailored/adapted to local conditions and value chain specificities and addresses three important challenges decision makers face when prioritising policy and support for biomass in low carbon and circular economy:

Imperative to comply with resource efficient and sustainable practices: The work focuses on value chain approach [45] because such system thinking would allow biomass value chains to adhere to the sustainability criteria through all stages of the value chain from production of feedstock to biomass supply to conversion to end-use. Besides, resource efficiency can be achieved when all stages in the value chain are optimised. For example, the feedstock quality can be tailored according to the need of the biorefineries and conversion technologies. A value chain approach can track the feedstock flow which will allow planning of optimal use of feedstocks, conversion to main products and co-products, and recycling of wastes.

Inadequate data due to use of complex, open-ended or inconsistent metrics: The work presented in this paper suggests tailored indicators which can inform decision making at the value chain level as well as within individual stages. They can measure, monitor and interpret important aspects of environmental, economic and social sustainability as well as resource efficiency. The information provided by each indicator can be used to improve the performance of the value-adding activities along the value chain and focus future support on their respective competitive priorities. The suggested

indicators are:

- appropriate to explain performance of the value chain attribute;
- feasible to use for assessment because of quality and data availability;
- easy to understand by all stakeholders involved in the value chain and easy to interpret and communicate to the public;
- credible because they can be quantified and supported by high quality data and judgment from the scientific community;
- clear because they can be measured, traced and replicated; and
- sensitive to both natural and human activities in the biomass value chain.

Lack coherent systems thinking: Biomass value chains can achieve optimal performance when interfacing among stages and activities is well balanced. The conceptual framework examined in this paper follows systems approach and introduces competitive priorities measured by tailored indicators across all value chain stages and activities. This allows understanding of challenges and forming strategic objectives which will stimulate improve performance for value chain attributes that entail uncertainties and risk during the development and operational life of the value chain.

The challenges and indicators presented in this paper are indicative and aim to illustrate how the combination of value chain analysis and competitive priority theory can foster better decision making for biomass value chains. Future analysis and recommendations should always be subject to case and regional specific traits of the understudy value chains.

CRediT authorship contribution statement

Calliope Panoutsou: Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision. **Asha Singh:** Conceptualization, Validation, Investigation, Resources, Writing - review & editing. **Thomas Christensen:** Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Luc Pelkmans:** Conceptualization, Data curation, Formal analysis, Resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.glt.2020.04.001>.

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