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RESEARCH ARTICLE

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Method for assessing the potential of miscanthus on marginal lands for high temperature heat demand: The case studies of France and Belgium

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Abstract

Energy crops on marginal lands are seen as an interesting option to increase biomass contribution to the primary energy mix. However, in the literature there is currently a lack of integrated assessments of margin land availability, energy crop production potential and supply chain optimisation. Assessing the potential and the cost of these resources in a given region is therefore a difficult task. This work also emphasises the importance on a clear definition and discussion about marginal lands and the related ethical issues embedded in the concept to ensure positive societal impacts of the results. This study proposes a methodology to estimate and analyse, in terms of economic costs, the potential of miscanthus grown on marginal lands from the production to the final point of use. Different datasets are assembled and a supply chain optimisation model is developed to minimize the total cost of the system. Miscanthus is used as a representative energy crop for the Belgian and French case studies. High temperature heat demand is considered as final use. The miscanthus can be traded by truck either in the form of chips or pellets. The results show that the miscanthus on marginal lands could supply high temperature heat up to 38 TWh in France and 1.4 TWh in Belgium with an average cost of around 50 €/t. The different sensitivity analyses showed that the yield variation has the strongest influence on the final cost, together with the distances and the cost of production of miscanthus. The main pattern observed is the local consumption of miscanthus chips and export of the surplus (if any) to the neighbouring regions. Pellets are only of marginal interest for France and are never observed for Belgium. Distances and availability of sufficient feedstocks are the two main parameters impacting the production of pellets.

KEYWORDS

biomass potential, energy crops, high temperature heat, marginal lands, miscanthus, supply chain

1 | INTRODUCTION

Biomass plays a key role in the energy transition required to mitigate climate change (Chum et al., 2011; IEA, 2021). Indeed, this versatile resource can significantly contribute to the supply of the different energy needs: heat, transport and electricity, as well as to the non-energy demand (Daioglou et al., 2015). The bottleneck for a more extensive deployment of biomass in the energy transition is the availability of a sustainable feedstock and the development of the related supply chains (Alakangas et al., 2012; PricewaterhouseCoopers et al., 2017; Smeets et al., 2004). Therefore, it is important to carefully study the potential of biomass production considering sustainability aspects and the required supply chains. Among the different biomass production options, energy crops are considered as an important one to increase the current biomass production (European Commission, 2018; Material Economics, 2021). Indeed, energy crops cover a large share of the bioenergy potential in many studies (Faaij, 2018; Smeets et al., 2004; WWF, 2011). Beringer et al. (2011) have estimated that energy crops can represent between one-fifth to more than half of the global bioenergy potential depending on the assumptions of land management. However, concerns have been raised on the sustainability of energy crops, mainly in relation to the potential land competition with food crops (Beringer et al., 2011). To avoid this land competition, the concept of marginal lands has gained attention as a solution for growing energy crops (European Commission, 2018; Mehmood et al., 2017).

According to Elbersen et al. (2018), the EU28 has more than 60 MHa of marginal lands (i.e. ~21% of EU28 agricultural area). In the recent work of Vera et al. (2021), the authors estimated that around 20 MHa of marginal lands would be available in 2030 that respect the sustainability criteria of the Renewable Energy Directive from the European Commission (RED II), a three-fold reduction compared with the estimates of (Elbersen et al., 2018). The project S2biom estimates the European marginal lands available at around 25 MHa (S2Biom, 2016). In Gerwin et al. (2018) the marginal lands in Europe were estimated at around 58 MHa. This illustrates the large range of estimations for marginal lands, and this is even more pronounced on a worldwide scale with estimations from 200 up to nearly 1600 MHa (Dauber et al., 2012). In order to be able to discuss its limits and implications, it is important to be aware of the methodology and the definition considered for marginal lands. In this work, the definition of marginal lands will be clearly stated and briefly discussed in order to stimulate further debate.

Among the energy crops compatible with marginal lands, lignocellulosic crops usually represent good candidates due to low maintenance requirements and their ability to grow on poorer soils (Mehmood et al., 2017). Those energy crops include, among others, miscanthus, Reed Canary grass, switchgrass, Giant Reed, Willow or Poplar (Vera et al., 2021). They all present different characteristics for production and final uses. The specific choice of the crop should thus consider both the production characteristics (weather and soil conditions) and the final use (combustion, anaerobic digestion, oil extraction, etc.) (Vera et al., 2021). Currently, around 0.1 Mha are used for lignocellulosic energy crops in the EU (Bioenergy Europe, 2019). According to the different scenarios elaborated by the European Commission in the report "A clean planet for all", the land area dedicated to energy crops should represent between 9 and 29 Mha in 2050 (European Commission, 2018). Such an amount would increase local renewable energy sources and improve energy independence while developing rural activities and revenues (European Commission, 2018). However, it would also induce land-use changes leading to potential controversies. Therefore, energy crops represent an important feedstock to consider carefully and discuss in the definition of future energy scenarios.

Miscanthus is recognized to be one of the energy crops with the greatest potential especially for combustion as final use (Vera et al., 2021). Moreover, it is one of the most interesting crops to grow on the majority of the marginal lands in Europe (Elbersen et al., 2018). Still, in some regions Reed Canary Grass, Camelin, Willow or Poplar would probably be more adapted. To facilitate the analysis of this study, only miscanthus is considered. Miscanthus x giganteus, hereafter referred to as miscanthus, is a lignocellulosic perennial grass. It is a C4 plant with rhizomes, originating from Asia, that is cultivated over 15–25 years with an annual harvest from the second or third year (Gauthier & Somer, 2013; Pari, 2019). It has a large potential for producing biomass due to its good yield and low maintenance requirements (Jacobson et al., 2013), with no (or low) fertilisation requirements (Seutin & Stilmant, 2020), which makes it a good candidate for marginal lands cultivation. Miscanthus has also different environmental benefits. It can lower erosion risk, improve soil quality as it stores carbon in soil through rhizomes and leaf fall, and it has also positive effects on biodiversity by providing an environment for different species (birds, invertebrates or small mammals) (Murphy et al., 2013; Semere & Slater, 2007). The miscanthus can be harvested in autumn around September or in the following spring around March when it is dry and when the leaves have fallen on the ground. The spring harvest is more suitable for combustion applications while the autumn harvest is more suitable for anaerobic digestion in

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biogas production, due to its higher moisture content (Kiesel et al., 2017). The spring harvest has two main advantages: (i) there are fewer nutrients exported since the leaves stay on the field and (ii) the miscanthus is already dry with moisture lower than 20% (Gauthier & Somer, 2013). Considering those advantages and the fact that the overall efficiency is higher for miscanthus combustion (with spring harvest) than for biogas production (with autumn harvest) (Kiesel et al., 2017), this study considers only miscanthus from the spring harvest for combustion use.

In the literature, the studies on energy crops mostly focus on one single production field (Acaroğlu & Aksoy, 2005; Amaducci et al., 2017; Mantineo et al., 2009), which is interesting for the production of experimental data and analyses, but does not allow for broader discussion on a regional or (inter)national scale. Furthermore, studies on energy crops generally focus only on the production aspect (Acaroğlu & Aksoy, 2005; Amaducci et al., 2017; Dubis et al., 2020; Mantineo et al., 2009) without considering the post-processing and the analysis of the final use within the complete supply chain. Yet, some works consider the post-processing of the energy crops for the production of advanced energy carriers, such as liquid fuels, biogas or pellets (Fusi et al., 2021; Jankowski et al., 2016; Vera et al., 2021). However, only a few papers include the final use of those fuels in the scope of the study (Kiesel et al., 2019). Therefore, in this work, a methodology is proposed and illustrated to study the entire cycle of the energy crop, that is, from cultivation to the final uses at a national scale, including transport and potential post-processing steps. France and Belgium are used as case studies in order to have two countries with different size and thus different transportation distances. High-temperature heat is the final use considered in this study. Indeed, it is one of the most relevant uses for biomass in the context of the energy transition (Colla et al., 2022). Furthermore, handling miscanthus chips or pellets seems more feasible for industrial technologies rather than decentralised technologies (e.g. residential boilers or stoves) due to the specificity of the fuel (ash content and composition) (Daraban et al., 2015). Different datasets are used and assembled for the different steps of the methodology. A supply chain optimisation model is developed to determine the exchanges required between the points of production and consumption. A sensitivity analysis is performed to identify the key parameters that influence the total costs and the use of pellets. Thus, this work develops and demonstrates a replicable methodology to study the potential of energy crops on marginal lands from production to consumption. This allows a more complete and coherent analysis of the potential role of sustainable energy crops in the energy transition.

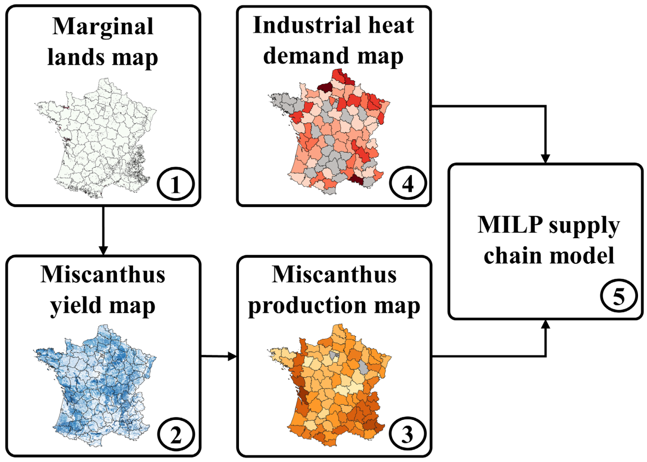

FIGURE 1 Flowchart describing the steps involved in the pre-process of the input data (1–4) fed into the optimization model (5). The optimization model aims at characterizing the exchanges in quantity, typology of carriers and associated final costs.

2 | MATERIALS AND METHODS

This section presents the methodology used, the different assumptions and the data considered. Figure 1 summarizes the five steps involved in the computation of the cost-optimal design of miscanthus supply chain. The analysis is achieved at the district level (named NUTS03 by the EU classification—Nomenclature of territorial units for statistics).

First, the marginal land considerations and data are presented in Section 2.1. The data related to miscanthus cultivation is presented in Section 2.2. The production is already an intermediary result used as input in the supply chain model, which is presented in Section 2.5. The final use of miscanthus chips for industrial heat is presented in Section 2.4. In addition, Section 2.3 presents additional data required for the supply chain model optimisation on the transportation costs and post-processing option (pelletisation). Finally, the uncertainty analysis is presented in Section 2.6.

2.1 | Marginal lands definition and data

Many definitions of marginal lands co-exist (Shortall, 2013). Indeed, different thresholds of "marginality" can be considered and thus affect the estimates (Khanna et al., 2021; Mellor et al., 2021). To ensure coherent discussion, it is therefore important to clearly state the definition and data considered. The data on marginal lands of this work are extracted from Vera et al. (2021) where the authors consider data from the EU MAGIC project which are based on six main biophysical constraints (Elbersen et al., 2020) and they added a further filter to comply with the RED

II sustainability criteria (e.g. excluding agricultural areas). In the initial EU MAGIC project, which aims to map marginal lands where energy crops can be grown (Elbersen et al., 2020), marginal lands are defined as

> Lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors (Elbersen et al., 2020).

In their work, Vera et al. (2021) add around 30 criteria to exclude from the evaluation all lands that would not respect sustainability criteria from EU Renewable Energy Directive II. Those criteria relate to land-use risk, greenhouse gas emissions savings, nature and biodiversity protection. According to those data (Vera et al., 2021), the marginal lands cover 1.4% of the total French area. A large part of marginal lands is located in the southeast part of France (Figure 2), mainly corresponding to shrublands and open space suitable for energy crops. On the West coast the regions with large marginal lands are regions with established energy crops according to the sorting of Vera et al. (2021). If the estimations of marginal lands used in the project EU MAGIC (Elbersen et al., 2020) are used without the additional sustainability filters from Vera et al. (2021), France would have 3.3 Mha of marginal lands, that is, 6% of the French continental territory which is around five times higher than the estimations

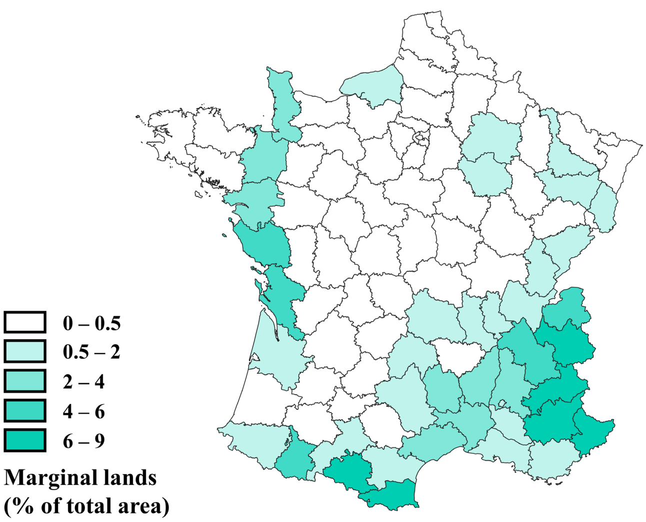

FIGURE 2 Map with the percentage of marginal lands per NUTS3 region in France. Data source: Vera et al. (2021).

from Vera et al. (2021). This would result in a much higher miscanthus potential with a major impact on the results in terms of production, total costs, and on the entire design of the supply chain. Therefore, preliminary work on a coherent definition of marginal lands is essential.

2.2 | Miscanthus data collection

In this section, the data on the cultivation of miscanthus are presented and discussed, that is, economic costs and yield distribution based on the MiscanFor model.

2.2.1 | Economic costs

The establishment/planting costs of a miscanthus crop represent an important part of the economic costs as illustrated in Table 1 (all costs are expressed in euro for the year 2018). However, as opposed to harvesting operations, those operations take place only once during the total cycle, so in total harvesting operations costs are higher. The costs related to the establishment of the plantation include the purchase of the rhizomes, the ploughing, the soil conditioning or disking, the planting and the weed control. Only Miscanthus × giganteus is considered in this work with rhizomes propagation, but some studies analyse the possibility of a different form of miscanthus hybrid with seed propagation (Hastings et al., 2017). Fertilisers are not used because they did not show any added value, while they implied additional costs (Seutin & Stilmant, 2020). The lifetime of the culture is considered to be 20 years even though some parcels are still productive after more than 20 years. An adapted potato planter is used for the planting. For the harvest, the miscanthus can be directly chopped with a self-propelled forage harvester as for maize, or it can be baled (Pari, 2019). In this study, the forage harvester was considered as it already produces chips that can be directly used for combustion or pelletisation without the primary grinder. The year of planting and the following year, the miscanthus is not harvested,

TABLE 1 Economic costs for miscanthus cultivation from (Winkler et al., 2020)

	Economic costs (€/ha)	Year of application
Rhizomes, planting, previous soil preparation and weed control	3743	1
Harvesting operations	451	2–20
Removals	115	20

but can be chopped and left on site to improve soil quality (Bombeck & Gossiaux, 2016). Harvest efficiency is assumed to be 90% (Styles & Jones, 2007).

2.2.2 | Yield distribution

The yield of Miscanthus x. giganteus for the geographic area of France was determined by using the MiscanFor model (Hastings et al., 2009) with a spatial resolution of 1 km × 1 km. MiscanFor is a plant growth model that uses genotype-specific parameters to predict yields of miscanthus (Miscanthus × giganteus or Miscanthus sinensis—with provision for other genotypes when data become available) or C4 grasses in a wide range of environments. The MiscanFor model was developed from the MISCANMOD model (Clifton-Brown et al., 2004) by improving process descriptions for light interception by the canopy and the impact of temperature and water stress on radiation use efficiency, genotype-specific process descriptions for the plant growth phase, photo-period sensitivity, thermal time, temperature-dependent radiation-use efficiency, drought and frost kill predictions, nutrient repartition to the rhizome, and moisture content at harvest are added. MiscanFor was successfully tested against yield observations ($R^2 = 0.84$) from across the United Kingdom (UK) and Europe (Hastings et al., 2009).

This model has identified photoperiod sensitivity in addition to drought resistance and frost tolerance as parameters for crop improvement to extend the range of climatic conditions under which this crop can be grown economically. It requires the soil parameters of field capacity and wilting point to calculate the soil moisture deficit from the balance between actual evapo-transpiration and rainfall and soil organic carbon to estimate the change in soil carbon. The plant growth module is driven by air temperature and incident photosynthetically active radiation (PAR). Changes in atmospheric carbon dioxide concentration are not considered for C4 grasses as the impact is minimal (e.g. Leakey, 2009) and no published experiments exist for miscanthus. The plant available water sub-model is based on the proposed model by Campbell (1985) and used soil physical and chemical data extracted from the Harmonized World Soil Data (HWSD; Fischer et al., 2008).

The climate data used was the CRU TS v 4.05 (Harris et al., 2020) from which the historical meteorological parameters of maximum and minimum temperature, precipitation, evapotranspiration and cloud cover were extracted from 2000 to 2016 on a half-degree grid. PAR was calculated using the meteorological parameters and latitude. The MiscanFor model calculated the yield and soil carbon change for each year at each HWSD grid point using the temperature corrected for altitude from the difference between the altitude of each meteorological grid and the soil grids. The mean and standard deviation of the yields from the period 2000–2016 were calculated for each grid point and all the outputs mapped using ArcGIS.

From the map (Figure 3), the marginal land parcels identified by Vera et al. (2021) were added and intersected with the yield raster on QGIS. When a marginal land parcel covers several modelled yields, the minimum yield was considered (conservative approach). Each marginal land parcel was characterised by the modelled mean yield for a well-established crop. From the fourth year after plantation, it is assumed that the mean yield is achieved, while yield is around 67% in the second year and 93% in the third year (Gauthier, 2013). The parcels where the mean yield is lower than 11 t/ha were excluded as the costs per ton would be too high. Indeed, the farm-gate costs would reach value higher than the lower range of the selling price referenced in Winkler et al. (2020) of around 70 €/t. Then, based on the combination of marginal lands and miscanthus yield data, miscanthus primary production is estimated and aggregated at NUTS03 level for the next steps of the study (supply chain optimization).

2.3 | Post-processing and transport of miscanthus

For post-processing of the miscanthus feedstock, two options were evaluated: (i) using chips directly as they are produced from the harvest, and (ii) producing pellets from the harvested chips. Pellets allow to increase the density of the feedstock and thus reduce the transportation costs. The cost of the pellet plant and the

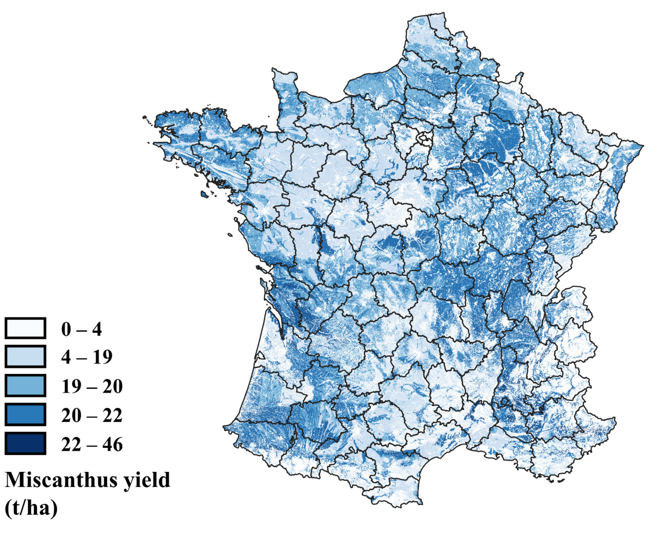

FIGURE 3 Map of miscanthus yield distribution, data are based on the MiscanFor results (average annual yield with 2000–2016 climatic data). Urban, forest and wet areas are excluded.

related scale effect due to size is illustrated in Figure 4. It integrates the capital investment (CAPEX) (Thek & Obernberger, 2012), the installation costs (33% of CAPEX) (Hoque et al., 2013), the maintenance costs (3% of CAPEX) (Sultana et al., 2010) and the operating costs (energy and labour) (Gauthier, 2013; Mupondwa et al., 2012). The related scale factor for the entire costs corresponds to 0.56, which is in the range presented by (Mupondwa et al., 2012). It is a pellet plant without dryer and primary grinder costs. Indeed, as the miscanthus feedstock is harvested as chips with low moisture content, those two steps can be saved theoretically (Fusi et al., 2021; Gauthier, 2013). This might be an optimistic assumption as drying is required if the moisture content of miscanthus feedstock is greater than 20% before pelletisation (Murphy et al., 2013). This needs to be kept in mind when analysing the results. From the miscanthus field and the pellet plants, transportation needs to be considered. Only road transportation is considered (Table 2).

2.4 | Final use—High-temperature heat

The distribution of high temperature (HT) heat demand per NUTS03 region was based on the relative repartition of the industrial CO_2 emissions used as a proxy from the European project "Hotmaps project" (Hotmaps project, 2019). The total HT demand was extracted from the European Union's projections for 2030 (Ragwitz et al., 2016). The estimation is presented in Figure 5. The two regions with high consumption correspond to the industrial zones of Le Havre and Fos-sur-Mer with high concentration of refineries, and production plants of chemicals, cement, iron and steel, refineries. Industrial pellet boilers and chips boilers are assumed to have similar efficiencies (around 86%) (Moret et al., 2017).

2.5 | Supply chain optimization

The map of France is divided in 94 cells corresponding to districts level (NUTS03 level) characterised by the parameters presented in Table 3. Based on the cost of production and transport of chips and pellets, the optimization problem minimizes the total cost of the supply chain. Accordingly, the exchanges of miscanthus between the cells, and the size and location of the plants for the production of pellets are identified. The distances are considered linear between cells' centroids but the impact

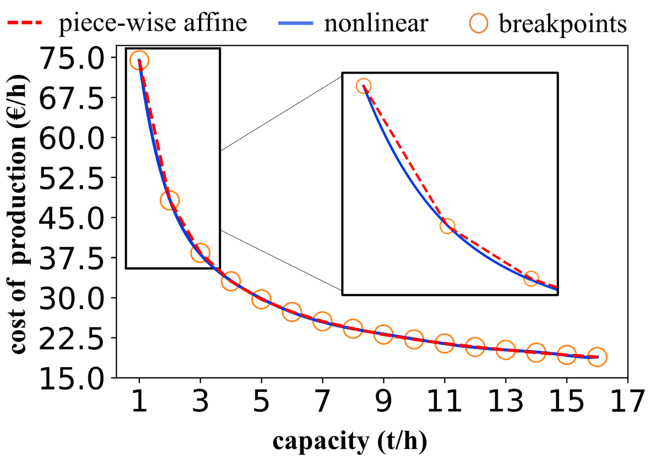

FIGURE 4 Variation of the cost of a plant for pellets production (independent of transport and feedstock costs) with the size of the plant.

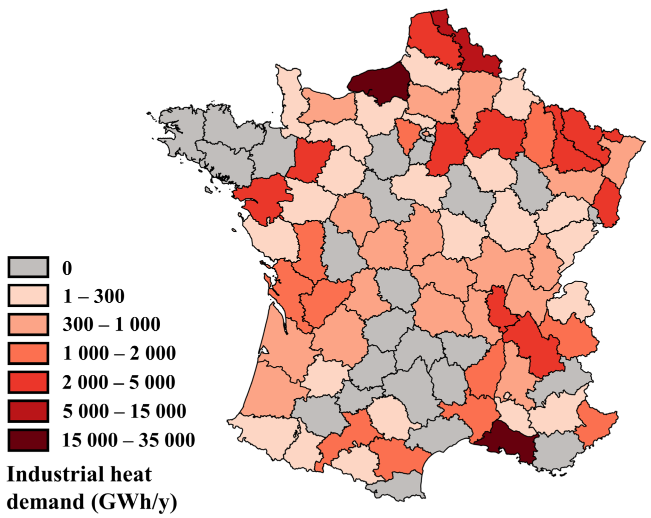

FIGURE 5 High temperature (HT) heat demand repartition in NUTS03 region.

TABLE 2 Road transport costs for pellets and chips

Feedstock	Value	Unit	Source
Pellets	0.082	€/km/t	Suurs (2002); Sikkema et al. (2012); Hoque et al. (2013)
Chips	0.22	€/km/t	Suurs (2002); Manzone and Balsari (2015); Yoshida and Takata (2019)

TABLE 3 Parameters for each cell in the supply chain optimisation model

Parameter	Unit
Area of marginal land	ha
Weighted average yield	MWh/ha/year
High temperature heat demand (as feedstock input to the boilers)	MWh
Radius (for internal transportation)	km
Centroid location	Geographical coordinates

of tortuosity and larger distance is analysed through the sensitivity analysis with a tortuosity factor. All the mathematical details of the model are provided in the Appendix, Equation (1) represents the objective function of the optimization problem: minimisation of total costs of the system (from production, post-processing and transportations)

$$\min \sum_{i \in \text{NUTS03}} \sum_{j \in \text{carrier}} \left(C_{j,i} + T_{j,i}\right), \tag{1}$$

with

- i is the cell among the 94 cells of the NUTS03 discretization,
- j the carrier, that is, chips or pellets,
- $C_{j,i}$ the total cost of production of carrier j in cell i,
- $T_{j,i}$ the total cost of transportation of carrier j in cell i.

For chips, the total cost of production depends on the costs of cultivation of miscanthus and on the marginal lands. For pellets, the total costs of production depend on the cost of the pellet plant and its size (depending on the availability of the feedstock as input). Note that all miscanthus is produced first in the form of chips; then, the model can decide to produce pellets from these chips or to transport them and use them as chips. The total cost of transportation depends on the quantity, the distances covered and the carrier transported (chips or pellets).

2.6 | Sensitivity analysis

The different parameters are characterised by uncertainties (or range of possible variation) for their deterministic value chosen for this case study. The purpose of the sensitivity analysis is to evaluate the impact of the variation of those parameters on the average prices of miscanthus and on the production of pellets. In Table 4, the different parameters are presented with their deterministic value and the range of variation based on the literature. The variation for marginal lands is based on the observation that the initial estimate does not consider any logistical

TABLE 4 Range of variation of parameters involved in the sensitivity analysis

Parameter	Reference value	Variation range	Justification and references
Chips transportation costs	0.22 €/t/km (cf. Table 2)	±18%	Based on variation observed in Suurs (2002); Hoque et al. (2013); Manzone and Balsari (2015); Yoshida and Takata (2019)
Distances	Euclidean distances (or radius for internal consumption)	±50%	Tortuosity factor taken from Fan et al. (2011)
Heating demand	Forecast for 2030 (cf. Section 2.4)	±20%	Chosen arbitrarily
Marginal lands	524,900 Ha for France (see Section 2.1)	−54%	Based on the range of variation if only parcels with a minimum yield higher or equal to 20 t/ha
Miscanthus production costs	Cf. Table 1	±15% (+10%)	Based on the range of variation presented in Winkler et al. (2020) and over-costs due to marginality conditions based on the costs presented in Soldatos (2015)
Miscanthus Yield	Based on yield modelling from MISCANFOR (cf. Section 2.2.2)	±20%	Interannual variation estimated by Hastings et al. (2009)
Pellet plants costs	See Section 2.3 (cf. Figure 4)	±20%	Based on distribution costs from Mupondwa et al. (2012) and the distribution estimated in Section 2.3
Pellets transportation costs	0.082 €/t/km (cf. Table 2)	±26%	Based on variation observed in Suurs (2002); Sikkema et al. (2012), Hoque et al. (2013)

or administrative hurdles, and thus represents the upper limit of marginal lands availability for energy crops. The range of variation in marginal land is therefore established on the basis of a restriction of available land considering a different minimum yield threshold required for growing energy crops, as explained in Table 4 and in Section 2.2.2.

A global sensitivity analysis (GSA) is performed to determine the main influencing parameters on costs based on Sobol indices that quantified the contribution of each parameter to the variance of the objective. The RHEIA package is used in order to study the uncertainty and sensitivity through a Polynomial Chaos Expansion surrogate modelling technique, of which a full description is provided in Coppitters et al. (2022). Secondly, a local sensitivity analysis is performed to assess the impact of parameter variation on the pellets production.

3 | RESULTS

By combining the different datasets, we estimated the potential of production and characterized it in terms of costs. Afterwards, we applied the supply chain optimisation model to determine the typology of feedstock consumed in each district and the typologies of exchanges. In this section, the results and the sensitivity analysis are presented and discussed to evaluate the contribution of miscanthus to the energy transition and the role of pelletisation in France. The results for Belgium (obtained with the same methodology) are presented and discussed in a second step in comparison with the results for France.

3.1 | Miscanthus production potential

The combination of the data of the marginal lands with the distribution of the miscanthus yield leads to the annual miscanthus potential per district, as illustrated in Figure 6a. The total potential of miscanthus on French marginal lands was estimated to 37.6 TWh/year on yield. Considering the boiler efficiency, this represents 27% of the process heat demand in 2030 for France. The costs of production vary from 28 €/t to 67 €/t maximum (Figure 6b) with a weighted average cost of 38 €/t. The highest costs are logically observed where the yields are the lowest and vice-versa.

From the production potential, the related production costs (Figure 6) and the map of the high temperature heat (Figure 5), the supply chain model can optimize the potential post-process (pelletisation) and transport from production to consumption points. The results are discussed in the following sections.

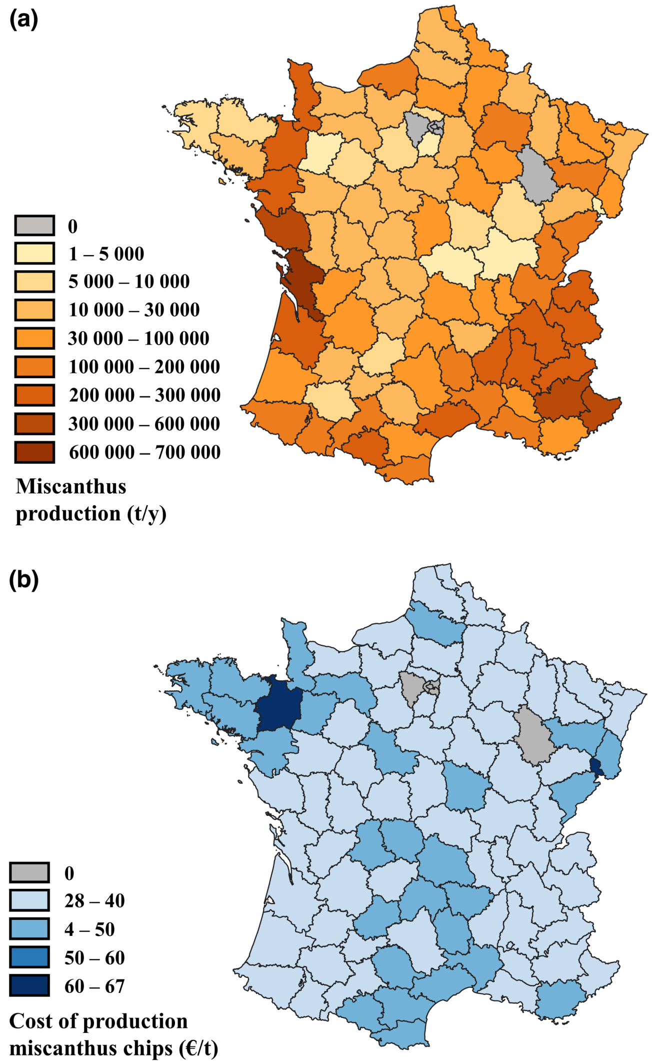

FIGURE 6 Miscanthus annual production in dry tons per NUTS03 region (a) and average miscanthus chips cost (b) in France with a NUTS03 discretisation.

3.2 | Miscanthus post-processing, transportation and total costs

The results of the optimization of the supply chain show that most exchanges are under the form of chips (Table 5). The main pattern observed is the following: the local consumption of chips is prioritised with an export of the surplus, in the form of chips, to the nearest neighbouring districts (average distances of 85 km for exchanges between districts). If there is no local demand, then all the production of chips is exported to the nearest district with a HT heat demand to be satisfied. Only one pellet plant is installed (Figure 7) and 119 kt of pellets are produced and exchanged (per year). The mean distance covered with pellets is more than four times higher than the one for chips (Table 6).

TABLE 5 Quantity of chips and pellets consumed locally (from internal production) or exchanged

Quantity (kt)	Chips	Pellets
Locally consumed	3927	—
Exchanged	4419	119

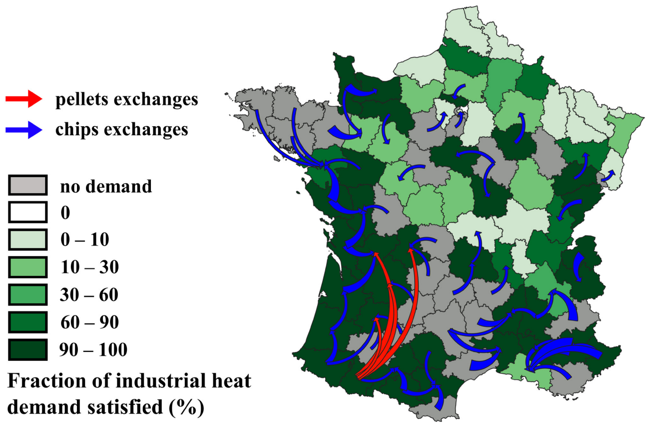

FIGURE 7 Industrial heat satisfied by miscanthus and exchanges of miscanthus chips and pellets between cells in France.

TABLE 6 Distances covered from production to consumption sites depending on miscanthus form

Distances (km)	Chips	Pellets
Mean	62	250
Min	20	148
Max	205	326

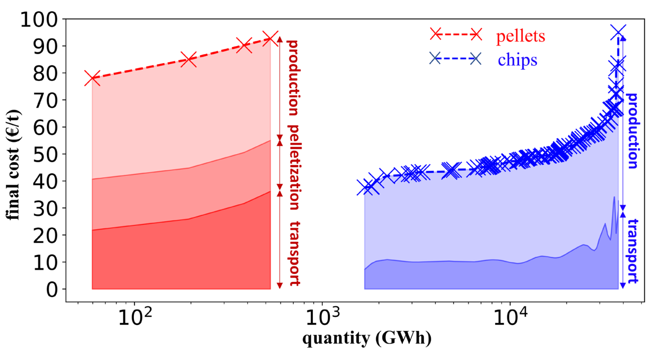

FIGURE 8 Costs distribution of the miscanthus potential in the form of chips or pellets and breakdown of the costs between production and transport.

The final cost of miscanthus chips ranges from 34 € to 95 €/t as illustrated in Figure 8 (transport to final point of use included). The weighted average cost for chips at the final point of use is of 50 €/t and production costs are around 38 €/t, with an average transport cost of 12 €/t.

TABLE 7 Sobol indices of the different parameters (quantifying the contribution of each parameter to the variance of the miscanthus average cost) and mean value and standard deviation of the average cost per MWh of miscanthus (from production to consumption points)

	Sobol indices
Yield	0.39
Distances	0.32
Miscanthus production costs	0.26
Chips transportation costs	0.02
Heating demand	~0
Marginal lands	~0
Pellets transportation costs	~0
Pellet plants costs	~0
Mean value for the average cost (€/t)	56
Standard deviation	7.1

The pellet cost ranges from 78 to 93 €/t, with the cultivation cost ("production" in Figure 8) being the major part, from 42% to 50% depending on the transportation distances. Due to the large capacity of the production unit, the cost of pelletisation is in the lower range (cf. Figure 4): around 19 €/t, counting for 20%–24% of the final pellet prices. Transportation costs count for the remaining parts (26%–38%). Pellets present higher prices than the average price for chips (88 €/t vs. 50 €/t) and it counts for a marginal part of the total miscanthus used (1.4% of all miscanthus produced). The sensitivity analysis of Section 3.3 allows for a deeper analysis of the relevance of pelletisation.

3.3 | Sensitivity analysis

Sensitivity analyses are presented in this section. First a Global Sensitivity Analysis (GSA) is performed to evaluate the main impacting factors on the average miscanthus costs. Secondly, sensitivity analyses are performed looking at the pellet production in order to assess the key factors that determine the suitability of pellets in the system.

3.3.1 | GSA on miscanthus average costs

The GSA is performed looking at the variation of miscanthus average costs. Running the first order GSA already results with a leave-one-out error below 0.05. The different Sobol indices are presented in Table 7. The standard deviation represents 13% of the mean cost (cf. Table 7). The variation of the average cost is thus quite limited. However, it is interesting to note that the total quantity of miscanthus produced varies twice more than the average costs: 26% of variation (from 17 to 42 TWh). Meaning that the total miscanthus quantity is more sensitive and thus more uncertain than the final costs.

3.3.2 | Sensitivity on pellet production

In addition to the costs, it is interesting to look at the total quantity of pellets produced for the sensitivity analyses, in order to determine in which conditions producing pellets is economically relevant. The following analyses was done considering the quantity of pellets as indicator. A local sensitivity analysis was run to evaluate the impact of each parameter on the total amount of pellets produced. Local sensitivity analysis is interesting to isolate the effect of each parameter variation. However, it does not capture the effect of combined variation for the different parameters. Therefore, we performed a brute force approach (1000 simulations) with random variations of all parameters based on their variation range (cf. Table 4 in Section 2.6) and the final quantity of pellets produced were analysed to spot the cases with or without pellet production.

For the local sensitivity analysis, the distances, the yield, the quantity of marginal lands and the chips transportation cost are positively correlated to the total amount of pellets produced (cf. Figure 9). On the other hand, the pellet plant cost, the pellet transportation cost and the heating demand are negatively correlated. With a higher heating demand, the ratio between miscanthus production and heating demand would be lower. This induces lower proportion of heating demand satisfied and therefore more for local consumption, thus less surplus to export and shorter transportation distances to cover. Therefore, in this case pellet production is less relevant. Inversely, with a smaller heating demand the ratio between miscanthus production and heating demand would be higher. This would induce a higher proportion of heating demand satisfied, thus more feedstock available for export and longer transportation distances, and thus potentially more relevance for pellet production. In general pellets production is quite sensitive to the heating demand scenario and the transportation distances, while in practice both relate to change in transportation distances. The miscanthus production costs do not impact the overall pellet production as it has similar influence on the total costs if the miscanthus is consumed as chips or pellets. In practice with a 20% variation in any of the parameters (excluding chips production costs), the pellets production falls to zero. The pellets production is thus quite sensitive to changes and its total share within the total miscanthus feedstock is quite small variating from 0% to 4%. This shows that the interest of pellet is quite marginal for this study case.

The analysis of the 1000 cases showed that the main impacting parameters are the yield, the marginal lands and the distances. Variations of those parameters create clear zones where no pellets are produced on one side, and where pellets are potentially produced on the other side. This distinction depends on different parameters combinations as illustrated in Figure 10 with distances and marginal land variations. The other combinations of parameters show a similar trend, that is, a large "no pellet zone" and a corner zone with potential pellet production. Interestingly, in Figure 10, with only the two parameters represented, there is no zone where pellets are automatically produced. This zone appears when the different parameters influencing the feedstock availability are combined (i.e. yield, marginal lands and heat demand) as shown in Figure 11. Figure 11 also shows that the specific combinations of those conditions are less likely to occur

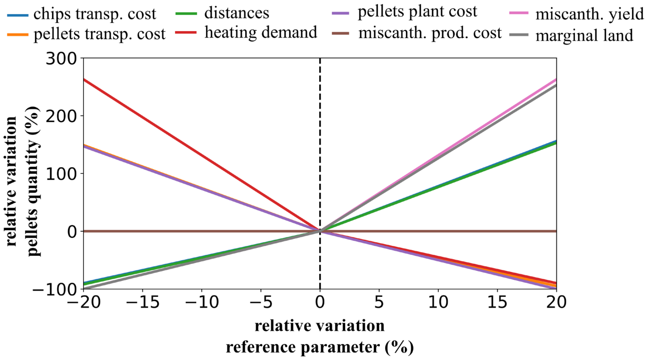

FIGURE 9 Pellets production relative change in response to local variation of each parameter compared with baseline scenario.

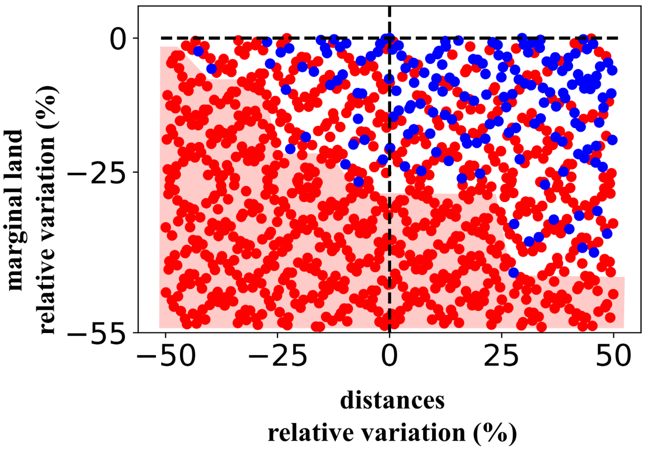

FIGURE 10 Plot of 1000 cases with random parameter variation based on variation range, highlighting the cases when pellets are produced (blue points) or not produced (red points) for the variation of distances and marginal lands. The conditions for which pellets are not produced are also highlighted with a red area ("no pellet zone").

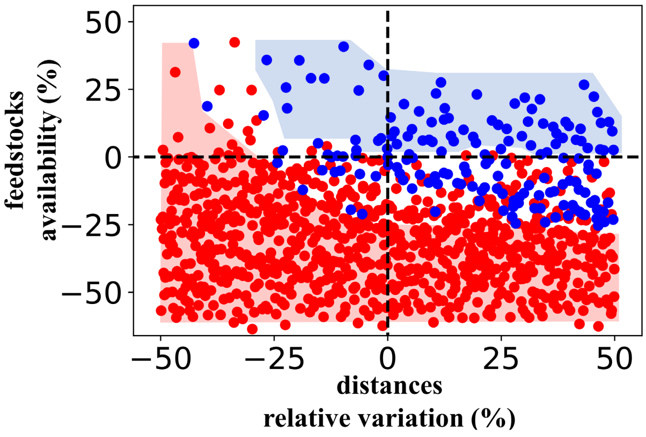

FIGURE 11 Plot of 1000 cases with random combinations of parameter variation highlighting the cases when pellets are produced (blue dots) or not produced (red dots). Red area of the plot highlights the conditions for which pellets are not produced ("no pellet zone") and blue area the conditions for which pellets are produced ("pellet zone"), based on the relative variation of distances and feedstock availability (combination of variation of yield, marginal lands and heat demand).

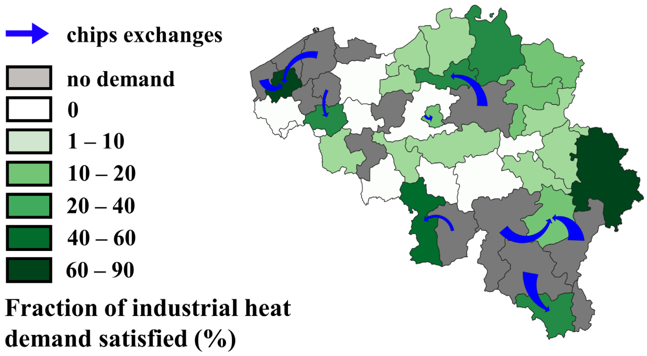

FIGURE 12 Industrial heat demand satisfied by miscanthus and exchanges of miscanthus chips between cells in Belgium.

considering the different ranges of variation: in 16% of the cases there is a small pellets production (up to 7% of total miscanthus production) versus 84% of the cases where there is no pellets production at all.

3.4 | Belgian case study

Belgium was tested as case study in order to have a representative case for a smaller country. In this case the miscanthus production could reach 1.4 TWh (cultivation on 0.7% of the Belgian area). This represents 2% of industrial heat demand in 2030. Belgium has high industrial heat demand when compared to its size: the average demand per unit of area is nearly nine times higher than in France. Therefore, local consumption is even more dominant and exchanges between cells are limited and in the form of chips exclusively (Figure 12). The average costs for the 1000 cases are estimated at 50.4 +/− 6.7 €/t, cheaper than for France because of smaller distances and no pellet production. Indeed, pellets were never observed for the 1000 cases of the sensitivity analysis.

4 | DISCUSSION

The production of miscanthus on marginal lands estimated by the methodology developed in this work should be considered as the upper bound values of what could be produced from marginal lands. Indeed, several aspects such as the specific logistic for each district (e.g. the exact shape and location of the parcels, etc.), or the administrative barriers, among others, are not considered and would tend to decrease the potential of production.

Regarding the supply chain analysis, the results logically showed that the distances covered are larger for pellets than for chips (Figure 7 and Table 6). However, the maximum distance travelled with chips is greater than the minimum distance for pellets, which shows that distance is not the only influencing parameter. Indeed, the need for large amount of feedstock is also important in order to set up a large pellet plant with lower costs (see Section 2.3). The availability of a large amount of feedstock is determined by two factors: (i) the potential of production of chips in the region (depending on the yield and the area of marginal land available) and (ii) the demand of high temperature heat that will induce the local consumption of chips. Thus, it is the surplus of feedstock available (i.e. local production minus local demand) that influences the availability of feedstock for pellet production. The importance of this availability in pellet production was confirmed by the sensitivity analysis (Figure 11).

Regarding the economic costs, the highest final costs observed for miscanthus chips are due to the cultivation of miscanthus on land with low yield and long transportation distances, thus less convenient in terms of final costs. This is observed in the Finistère district (extreme West of France in Brittany) which presents the highest costs at the final point of use. This is due to relatively low yield, but mostly to a large distance from the point of use (205 km) and insufficient feedstock to produce pellets with a reduction of costs. In this case, the costs due to transportation represents more than half of total costs. Transportation distances and yield are indeed the main factors influencing the economic performances as stated by Soldatos in Soldatos (2015) and this is verified in the sensitivity analysis in Section 3.3. The range of miscanthus costs are in line with other publications (de la Rúa & Lechón, 2016; Gauthier, 2013; Khanna et al., 2008; Soldatos, 2015; Wang et al., 2012). In the work of Wang et al. (2012) for example, the miscanthus farm-gate costs ranged in most of the cases between 43 and 68 €/t (with 2012 average exchange rate for GBP to Euro).

Discussing the profitability of miscanthus is always difficult as there is no reliable market price (Witzel & Finger, 2016). However, as in this study the miscanthus chips are used for industrial heat, the market price of industrial wood pellets could be used as an indicator. According to the Argus cif NWE, the wood pellet market price is varying between 120 and 210 €/t (EEX AG, 2018). Assuming that industrials will go for miscanthus chips only if it is cheaper than industrial wood pellets, this would mean that miscanthus chips could be competitive if market price is below 120 €/t which seems reasonable as the average final costs are around 50 €/t (transport included). In addition, in comparison with gas price for non-household consumers and excluding tax, miscanthus chips (considering average price) is 60% cheaper than gas (based on second-half of 2020 with data from Eurostat) (Eurostat, 2022). This would tend to make the miscanthus chips profitable, provided that the market conditions are reliable with sufficient supply for industrials which can be facilitated by appropriate policies (Stoof et al., 2015). Additionally, the quality difference with classical wood chips for combustion purpose might induce over-cost for the boiler operation and maintenance (Iqbal et al., 2017), and that should be considered in the market analysis which is not the aim of the current study.

Looking at the sensitivity analysis on the costs, the main influencing uncertainties are the yield, the distances and the production costs, which is coherent with results from Soldatos (2015). Having higher production costs (e.g. due to over-costs related to the marginality condition of the lands) increases the importance of the yield on the final costs per unit produced. The other parameters variations have only minimal influence on the average cost. The uncertainties on the parameters related to pellets have very low influence on average costs as pellets represent a small share of the total costs.

The sensitivity analysis shows that the uncertainty on the total amount of miscanthus is twice higher than the uncertainty on the average costs. This means that even if the final quantity is more uncertain, the final cost per unit produced is estimated within an acceptable cost range. Indeed, there is 98% of probability to have the miscanthus final costs lower than 71 €/t (or 16 €/MWh) which seems to be a reasonable cost for heating fuel. In comparison the natural gas price in France for non-household consumers in the second half of 2020 was of 28 €/MWh (Eurostat, 2022). However, having a large uncertainty on the total amount of miscanthus produced affects the results for pellet production as the availability of sufficient feedstock is a key factor for the installation of a pellet plant. This is confirmed by the sensitivity analysis that shows that considering the variation ranges of the different parameters (mainly related to distances and feedstock availability), it is more likely that no pellets appear in the system. Furthermore, if additional constraints on marginal lands exploitation are considered (e.g. logistics, administrative, etc.), this would decrease the feedstock availability and thus reduce further the pellet relevance.

In addition to the uncertainty on the relevance of pellet plants, the results clearly show that pellets, when present, keep a marginal role in the overall system, and with higher final costs. Therefore, one can question the interest of those pellets. In this modelling framework, all the miscanthus on marginal lands with yield higher than 11 t/ha was forced to be produced and to be used. However, one could decide not to produce miscanthus if final costs are higher than a certain value. This result would tend to promote the use of miscanthus as long as pellets are not needed, that is, for local uses with limited transportation distances. For the French case study, around 35 TWh of miscanthus chips could be produced and consumed for final costs lower than 70 €/t. Furthermore, avoiding miscanthus production on marginal lands where the final costs are higher than 70 €/t would even tend to decrease the average costs as it could reduce the transport needed to dispose of the total amount of miscanthus (i.e. more local consumption). This would further strengthen the general pattern of miscanthus production and consumption observed in this work. Indeed, for the different simulations, similar systems are observed: local consumption of chips, no (or small) pellets production, and exchanges between neighbouring regions with limited transportation distances.

Finally, the definition and considerations of marginal lands need to be discussed for ethical reasons and its implication on the quantitative results. Indeed, the definition of "marginal land" affect the availability of miscanthus feedstock and thus influence the final estimates as well as the relevancy of pellet production as discussed previously. As observed and discussed by Khanna et al. (2021) there is no consensus on one single definition of marginal lands. The concept of marginal lands is in some ways subjective as the name suggests. Marginal literally means "small and not important" or "not part of a main or important group or situation" (Oxford University Press, 2022). In the literature on marginal lands for bioenergy production, the term marginal refers mostly to the second meaning. Therefore, its quantification depends directly on what is considered the main part of the land and the indicators on which this view is based (e.g. agricultural production, biodiversity, landscape effect, etc.). In the literature, the marginality of lands is usually assessed based on a productivist vision (Shortall, 2015). As mentioned by Shortall (2015), the definition of marginal lands raises ethical issues that must be discussed and are notably dependent on one's perception of nature and its relationship with human society (land-use, natural resources management, etc.). Not taking these ethical issues into account in the definition and quantification of marginal lands would conceal the different societal impacts associated with the vision under consideration. This would thus be the opposite of the holistic and multidisciplinary analysis which is needed to study sustainable biomass production (López-Bellido et al., 2014). The definition from the EU MAGIC project (Elbersen et al., 2020) is based on a definition that focuses only on biophysical constraints with a productivist point of view, in the sense that the only goal and indicator considered is the production (of biomass). This productivist vision presents its limitations for including sustainability. Indeed, productivism presents inherent contradictions with ecological sustainability, particularly because of the vision of nature considered only as a set of usable resources (Anderson, 2009; Heikkurinen et al., 2021; Illich, 1983). This current study proposes a classical focus on biomass production but including sustainability criteria from Vera et al. (2021). With those criteria, it broadens the vision—adding some considerations out of the classical productivist spectrum (e.g. nature and biodiversity protection). Yet the main focus is still on the production simply restricting the eligible zones to limits the impacts without deep reconsideration of the vision considered of nature. The productivist point of view could be confronted with alternative visions that induce a thorough rethinking of the classical conception of bioenergy and agriculture as discussed in the thesis of Shortall (2015) or by Kazic and Dessendier (2022). This discussion goes beyond a purely technical discussion and adds philosophical, anthropological and political dimensions which are important (Anderson, 2009; Ayre, 2015; Illich, 1983; Levidow et al., 2012; Shortall et al., 2019; Wilson, 2001), and would surely have an impact on the study of bioenergy potential (Shortall, 2015).

The developed methodology is a practical tool to estimate at a macro-scale the potential, the cost range related to the whole supply chain and general patterns for production, transportation and consumption. However, it does not consider some specificities at the local scale, such as exact location of marginal lands and industries which reduce accuracy of transportation distances costs. Yet, the sensitivity analysis allows to compensate for this lack of precision. Additionally, the current study proposes a first theoretical analysis without any influence of the market dynamics while in practice it can influence the consumption pattern. Furthermore, the social, administrative, and environmental aspects need to be integrated to the evaluation. Those different aspects are highly case dependent, data intensive and required adapted analyses at higher geographical resolution (local scale). For example, it is relevant to evaluate the impacts on the greenhouse gas emissions (fossil fuel substitution and carbon soil sequestration), on the employment, on the biodiversity or on the transportation infrastructure. All those aspects are important to consider before implementing miscanthus for energy and it requires an integrated and transdisciplinary assessment. Yet this methodology allows for a first estimate and discussion on the potential role of miscanthus for national energy transition before digging into more specific cases.

5 | CONCLUSION

Energy crops are an important option for increasing biomass contribution to the energy supply. However, there is controversy about land-use competition for those crops. Therefore, the concept of marginal lands has gained attention. Yet, the exact definition of marginal is subjective and needs to be carefully determined and discussed. The authors call for further interdisciplinary research to ensure positive societal impacts of energy crops on those marginal lands and ethical issues it may raise. In this work, we developed methodology to estimate the national potential of miscanthus (grown on marginal lands for industrial heating purposes), the cost range related to the whole supply chain and the general patterns for production, transportation and consumption at the district resolution level. An optimization model of supply chain was designed in order to characterize the exchanges between production and consumption points. France and Belgium were taken as case studies. It was shown that miscanthus on marginal lands could supply up to 38 TWh for France and 1.4 TWh for Belgium. It represents 27% and 2% of the forecasted industrial heat demand in 2030 for France and Belgium respectively. In general, chips are the most economical option as long as transportation distances are sufficiently small (less than ~150–200 km), with an average cost of 50 €/t. Pellets were shown only of marginal interest for specific conditions, representing 1.4% of the total miscanthus supply in France and 0% in Belgium (due to smaller transportation distances and higher internal consumption). The GSA showed that the yield variation has the strongest influence on final costs together with the distances and the miscanthus production costs. It was shown that the general pattern of the system is robust: miscanthus cultivation for local consumption in the form of chips with limited transportation distances. Furthermore, the pellet production is sensitive to transportation distances as well as to the availability of sufficient feedstock to ensure low pellet plant costs (scale effect). In any case, the pellet quantity remains marginal in the 1000 different simulations of the sensitivity analysis. Furthermore, considering the additional constraints of using marginal lands for energy crops (e.g. administrative, logistics or ecological), the relevance of pellets is even smaller. Therefore, the results suggest to avoid pellet production with miscanthus grown on marginal lands, and limit the cultivation of miscanthus on marginal lands using only the chips as the most economical option (i.e. promoting the local consumption). However, the option of using existing pellet plants to blend the woody feedstock with an alternative feedstock such as miscanthus can be an interesting option to study, depending on the local conditions and the technical features (Crawford et al., 2015; García et al., 2019).

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this article are openly available in Zenodo at https://doi.org/10.5281/zenodo.7520039.

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REFERENCES

Acaroğlu, M., & Aksoy, A. Ş. (2005). The cultivation and energy balance of miscanthus × giganteus production in Turkey. *Biomass and Bioenergy*, *29*, 42–48. https://doi.org/10.1016/j.biombioe.2005.01.002

Alakangas, E., Junginger, M., Van Dam, J., Hinge, J., Keränen, J., Olsson, O., Martikainen, A., Rathbauer, J., Sulzbacher, L., Vesterinen, P., & Vinterbäck, J. (2012). EUBIONET III—Solutions to biomass trade and market barriers. *Renewable and Sustainable Energy Reviews*, *16*, 4277–4290. https://doi.org/10.1016/j.rser.2012.03.051

Amaducci, S., Facciotto, G., Bergante, S., & Perego, A. (2017). Biomass production and energy balance of herbaceous and woody crops on marginal soils in the Po Valley. *GCB Bioenergy*, *9*, 31–45. https://doi.org/10.1111/gcbb.12341

Anderson, D. (2009). Productivism and ecologism: Changing dis/courses in TVET. *Work, Learning and Sustainable Development*, *8*, 35–57. https://doi.org/10.1007/978-1-4020-8194-1_3

Ayre, M. S. M. (2015). Community sustainability and agricultural landscape change: Insights into the durability and vulnerability of the productivist regime. *Sustainability Science*, *10*, 207–217. https://doi.org/10.1007/s11625-014-0268-2

Beringer, T., Lucht, W., & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, *3*, 299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x

Bioenergy Europe. (2019). *Statistical report—Biomass supply*. http://www.drax.com/media/56583/biomass-supply-report-2014.pdf

Bombeck, P.-L., and Gossiaux, L. (2016). *Panorama des filières bois-énergie et agrocombustibles en Wallonie*. ValBiom, 44.

Campbell, G. S. (1985). *Soil physics with BASIC: Transport models for soil-plant systems* (p. 150). Elsevier.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., & Pingoud, K. (2011). *Chapter 2 – Bioenergy* (pp. 209–332). IPCC.

Clifton-Brown, J. C., Stampfl, P. F., & Jones, M. B. (2004). Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, *10*, 509–518. https://doi.org/10.1111/j.1529-8817.2003.00749.x

Colla, M., Blondeau, J., & Jeanmart, H. (2022). Optimal use of lignocellulosic biomass for the energy transition, including the non-energy demand: The case of the Belgian energy system. *Frontiers in Energy Research*, *10*, 1–11. https://doi.org/10.3389/fenrg.2022.802327

Coppitters, D., Tsirikoglou, P., De Paepe, W., Kyprianidis, K., & Kalfas, A. (2022). RHEIA: Robust design optimization of renewable hydrogen and dErIved energy cArrier systems Statement of need. *Journal of Open Source Software*, *7*, 2020–2023. https://doi.org/10.21105/joss.04370

Crawford, N. C., Ray, A. E., Yancey, N. A., & Nagle, N. (2015). Evaluating the pelletization of "pure" and blended lignocellulosic biomass feedstocks. *Fuel Processing Technology*, *140*, 46–56. https://doi.org/10.1016/j.fuproc.2015.08.023

Daioglou, V., Wicke, B., Faaij, A. P. C., & van Vuuren, D. P. (2015). Competing uses of biomass for energy and chemicals: Implications for long-term global CO_2 mitigation potential. *GCB Bioenergy*, *7*, 1321–1334. https://doi.org/10.1111/gcbb.12228

Daraban, A. E., Jurcoane, Ş., & Voicea, I. (2015). Miscanthus giganteus—An overview about sustainable energy resource for household and small farms heating systems. *Romanian Biotechnology Letters*, *20*, 10369–10380.

Dauber, J., Brown, C., Fernando, A. L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., van Groenigen, K. J., Weih, M., & Zah, R. (2012). Bioenergy from "surplus" land: Environmental and socio-economic implications. *BioRisk*, *50*, 5–50. https://doi.org/10.3897/biorisk.7.3036

de la Rúa, C., & Lechón, Y. (2016). An integrated multi-regional input-output (MRIO) analysis of miscanthus biomass production in France: Socio-economic and climate change consequences. *Biomass and Bioenergy*, *94*, 21–30. https://doi.org/10.1016/j.biombioe.2016.08.003

Dubis, B., Jankowski, K. J., Załuski, D., & Sokólski, M. (2020). The effect of sewage sludge fertilization on the biomass yield of giant miscanthus and the energy balance of the production process. *Energy*, *206*, 118189. https://doi.org/10.1016/j.energy.2020.118189

EEX AG. (2018). *Argus biomass prices: Liquidity and usage increases in volatile pricing environment*, 1–2.

Elbersen, B., Eupen, van, E., Mantel, S., Verzandvoory, S., Boogaard, H., Mucher, S., et al. (2020). *Deliverable 2. 1 Definition and classification of marginal lands suitable for industrial crops in Europe*. EU Horiz.

Elbersen, B., Van Eupen, M., & Mccallum, I. (2018). *MAGIC – D2.3 – MAP-DB* (version 2).

European Commission. (2018). *In-depth analysis in support of the commission communication com (2018) 773—A clean planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*.

Eurostat (2022). Natural gas price statistics—Statistics explained. European Commission, 1–12. Retrieved September 24, 2021 from http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics

Faaij, A. P. (2018). Securing sustainable resource availability of biomass for energy applications in Europe: Review of recent literature. In *The role of biomass for energy and materials for GHG mitigation from a global and European perspective* (pp. 1–26). Energy.nl. https://energy.nl/wp-content/uploads/bioenergy-europe-eu-biomass-resources-andre-faaij-final-3.pdf

Fan, J., Kalnes, T. N., Alward, M., Klinger, J., Sadehvandi, A., & Shonnard, D. R. (2011). Life cycle assessment of electricity generation using fast pyrolysis bio-oil. *Renewable Energy*, *36*, 632–641. https://doi.org/10.1016/j.renene.2010.06.045

Fischer, G., Nachtergaele, F. O., Prieler, S., Teixeira, E., Tóth, G., van Velthuizen, H., et al. (2008). *Global agro-ecological zone V3—Model documentation*. https://doi.org/10.4060/cb4744en

Fusi, A., Bacenetti, J., Proto, A. R., Tedesco, D. E. A., Pessina, D., & Facchinetti, D. (2021). Pellet production from miscanthus: Energy and environmental assessment. *Energies*, *14*, 1–14. https://doi.org/10.3390/en14010073

García, R., Gil, M. V., Rubiera, F., & Pevida, C. (2019). Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets. *Fuel*, *251*, 739–753. https://doi.org/10.1016/j.fuel.2019.03.141

Gauthier, G. (2013). *Etude économique de la production et de la densification du miscanthus*. 1–24.

Gauthier, G., & Somer, L. (2013). *Guide pratique de la culture de miscanthus*. Doc. ValBiom Dispon. Sur Internet *1*, 31.

Gerwin, W., Repmann, F., Galatsidas, S., Vlachaki, D., Gounaris, N., Baumgarten, W., Volkmann, C., Keramitzis, D., Kiourtsis, F., & Freese, D. (2018). Assessment and quantification of marginal lands for biomass production in Europe using soil-quality indicators. *The Soil*, *4*, 267–290. https://doi.org/10.5194/soil-4-267-2018

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*, 1–18. https://doi.org/10.1038/s41597-020-0453-3

Hastings, A., Clifton-Brown, J., Wattenbach, M., Mitchell, C. P., & Smith, P. (2009). The development of MISCANFOR, a new miscanthus crop growth model: Towards more robust yield predictions under different climatic and soil conditions. *GCB Bioenergy*, *1*, 154–170. https://doi.org/10.1111/j.1757-1707.2009.01007.x

Hastings, A., Mos, M., Yesufu, J. A., McCalmont, J., Schwarz, K., Shafei, R., Ashman, C., Nunn, C., Schuele, H., Cosentino, S., Scalici, G., Scordia, D., Wagner, M., & Clifton-Brown, J. (2017). Economic and environmental assessment of seed and rhizome propagated miscanthus in the UK. *Frontiers in Plant Science*, *8*, 1–16. https://doi.org/10.3389/fpls.2017.01058

Heikkurinen, P., Ruuska, T., Kuokkanen, A., & Russell, S. (2021). Leaving productivism behind: Towards a holistic and processual philosophy of ecological. *Management*, *20*, 21–36.

Hoque, M., Sokhansanj, S., Bi, T., Mani, S., Jafari, L., Lim, J., et al. (2013). *Economics of pellet production for export market*. St. Joseph, Michigan: American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/2013.22062.

Hotmaps Project. (2019). Retrieved July 20, 2021 from https://www.hotmaps.eu/map.

IEA. (2021). *Net Zero by 2050 a roadmap for the global energy sector 222*. www.iea.org/t&c/

Illich, I. (1983). *Silence is a commons*. The CoEvolution Quarterly.

Iqbal, Y., Kiesel, A., Wagner, M., Nunn, C., Kalinina, O., Hastings, A. F. S. J., Clifton-Brown, J. C., & Lewandowski, I. (2017). Harvest time optimization for combustion quality of different miscanthus genotypes across Europe. *Frontiers in Plant Science*, *8*, 1–10. https://doi.org/10.3389/fpls.2017.00727

Jacobson, M., Marrison, D., Helsel, Z., Rak, D., Heil, N., & Forgeng, B. (2013). *Miscanthus budget for biomass production* (pp. 10–13). Penn State Extension. http://pubs.cas.psu.edu/FreePubs/PDFs/ee0081.pdf

Jankowski, K. J., Dubis, B., Budzyński, W. S., Bórawski, P., & Bułkowska, K. (2016). Energy efficiency of crops grown for biogas production in a large-scale farm in Poland. *Energy*, *109*, 277–286. https://doi.org/10.1016/j.energy.2016.04.087

Kazic, D., & Dessendier, E. (2022). Sortir de la production et de l'économie. *EcoRev*, *52*, 80–91. https://doi.org/10.3917/ecorev.052.0080

Khanna, M., Chen, L., Basso, B., Cai, X., Field, J. L., Guan, K., et al. (2021). Redefining marginal land for bioenergy crop production. *GCB Bioenergy*, *13*, 1590–1609. https://doi.org/10.1111/gcbb.12877

Khanna, M., Dhungana, B., & Clifton-Brown, J. (2008). Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass and Bioenergy*, *32*, 482–493. https://doi.org/10.1016/j.biombioe.2007.11.003

Kiesel, A., Nunn, C., Iqbal, Y., van der Weijde, T., Wagner, M., Özgüven, M., Tarakanov, I., Kalinina, O., Trindade, L. M., Clifton-Brown, J., & Lewandowski, I. (2017). Site-specific management of miscanthus genotypes for combustion and anaerobic digestion: A comparison of energy yields. *Frontiers in Plant Science*, *8*, 1–15. https://doi.org/10.3389/fpls.2017.00347

Kiesel, A., Wagner, M., Lewandowski, I., & Petig, E. (2019). Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. *GCB Bioenergy*, *11*, 34–49. https://doi.org/10.1111/gcbb.12567

Leakey, A. D. B. (2009). Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and fuel. *Proceedings of the Royal Society B: Biological Sciences*, *276*, 2333–2343. https://doi.org/10.1098/rspb.2008.1517

Levidow, L., Birch, K., & Papaioannou, T. (2012). Divergent paradigms of European agro-food innovation: The bio-economy (KBBE) as an R&D agenda. *Science, Technology, & Human Values*, *38*, 94–125. https://doi.org/10.1177/0162243912438143

López-Bellido, L., Wery, J., & López-Bellido, R. J. (2014). Energy crops: Prospects in the context of sustainable agriculture. *European Journal of Agronomy*, *60*, 1–12. https://doi.org/10.1016/j.eja.2014.07.001

Mantineo, M., D'Agosta, G. M., Copani, V., Patanè, C., & Cosentino, S. L. (2009). Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. *Field Crops Research*, *114*, 204–213. https://doi.org/10.1016/j.fcr.2009.07.020

Manzone, M., & Balsari, P. (2015). The energy consumption and economic costs of different vehicles used in transporting woodchips. *Fuel*, *139*, 511–515. https://doi.org/10.1016/j.fuel.2014.09.003

Material Economics. (2021). *EU biomass use in a net-zero economy—A course correction for EU biomass*.

Mehmood, M. A., Ibrahim, M., Rashid, U., Nawaz, M., Ali, S., Hussain, A., & Gull, M. (2017). Biomass production for bioenergy using marginal lands. *Sustainable Production and Consumption*, *9*, 3–21. https://doi.org/10.1016/j.spc.2016.08.003

Mellor, P., Lord, R. A., João, E., Thomas, R., & Hursthouse, A. (2021). Identifying non-agricultural marginal lands as a route to sustainable bioenergy provision – A review and holistic definition. *Renewable and Sustainable Energy Reviews*, *135*, 110220. https://doi.org/10.1016/j.rser.2020.110220

Moret, S., Codina Gironès, V., Bierlaire, M., & Maréchal, F. (2017). Characterization of input uncertainties in strategic energy planning models. *Applied Energy*, *202*, 597–617. https://doi.org/10.1016/j.apenergy.2017.05.106

Mupondwa, E., Li, X., Tabil, L., Phani, A., Sokhansanj, S., Stumborg, M., Gruber, M., & Laberge, S. (2012). Technoeconomic analysis of wheat straw densification in the Canadian Prairie Province of Manitoba. *Bioresource Technology*, *110*, 355–363. https://doi.org/10.1016/j.biortech.2012.01.100

Murphy, F., Devlin, G., & McDonnell, K. (2013). Miscanthus production and processing in Ireland: An analysis of energy requirements and environmental impacts. *Renewable and Sustainable Energy Reviews*, *23*, 412–420. https://doi.org/10.1016/j.rser.2013.01.058

Oxford University Press. (2022). *Oxford advanced learner's dictionary at oxford learner's dictionaries | Find meanings and definitions of words*. Retrieved June 2, 2022 from https://www.oxfordlearnersdictionaries.com/definition/english/

Pari, L. (2019). *D5.1—Inventory on available harvesting technology for industrial crops on marginal lands*.

PricewaterhouseCoopers et al. (2017). *Sustainable and optimal use of biomass for energy in the EU beyond 2020*. VITO, Utrecht University, TU Vienna, INFRO, Rütter Soceco & PwC. 170. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/biosustain_annexes_final.pdf%0Ahttps://ec.europa.eu/energy/en/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020

Ragwitz, M., Herbst, A., Hirzel, S., Rehfeldt, M., Reuter, M., & Steinbach, J. (2016). *Scenarios for heating & cooling demand and supply until 2020 and 2030*. https://ec.europa.eu/energy/sites/ener/files/documents/mapping-hc-final_report-wp2.pdf

S2Biom. (2016). *Vision for 1 billion dry tonnes lignocellulosic biomass as a contribution to biobased economy by 2030 in Europe. 38*.

Semere, T., & Slater, F. M. (2007). Ground flora, small mammal and bird species diversity in miscanthus (miscanthus×giganteus) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, *31*, 20–29. https://doi.org/10.1016/j.biombioe.2006.07.001

Seutin, Y., & Stilmant, D. (2020). *La production de miscanthus, quelles gestions pour quelles performances en Centre Ardenne?*

Shortall, O. (2015). *Rethinking bioenergy from an agricultural perspective: Ethical issues raised by perennial energy crop and crop residue production for energy in the UK and Denmark* [PhD thesis]. University of Nottingham.

Shortall, O. K. (2013). "Marginal land" for energy crops: Exploring definitions and embedded assumptions. *Energy Policy*, *62*, 19–27. https://doi.org/10.1016/j.enpol.2013.07.048

Shortall, O. K., Tegner, H., Sandøe, P., & Gamborg, C. (2019). Biomass and bioenergy room at the margins for energy-crops? A qualitative analysis of stakeholder views on the use of marginal land for biomass production in Denmark. *Biomass and Bioenergy*, *123*, 51–58. https://doi.org/10.1016/j.biombioe.2019.01.042

Sikkema, R., Junginger, M., Pichler, W., Hayes, S., & Faaij, A. P. C. (2012). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and The Netherlands. *Biofuels, Bioproducts and Biorefining*, *6*, 246–256. https://doi.org/10.1002/bbb

Smeets, E., Faaij, A., and Lewandowski, I. (2004). *A quickscan of global bio-energy potentials to 2050: An analysis of the regional availability of biomass resources for export in relation to the underlying factors*. Technical report.

Soldatos, P. (2015). Economic aspects of bioenergy production from perennial grasses in marginal lands of South Europe. *Bioenergy Research*, *8*, 1562–1573. https://doi.org/10.1007/s12155-015-9678-y

Stoof, C. R., Richards, B. K., Woodbury, P. B., Fabio, E. S., Brumbach, A. R., Cherney, J., das, S., Geohring, L., Hansen, J., Hornesky, J., Mayton, H., Mason, C., Ruestow, G., Smart, L. B., Volk, T. A., & Steenhuis, T. S. (2015). Untapped potential: Opportunities and challenges for sustainable bioenergy production from marginal lands in the Northeast USA. *Bioenergy Research*, *8*, 482–501. https://doi.org/10.1007/s12155-014-9515-8

Styles, D., & Jones, M. B. (2007). Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. *Biomass and Bioenergy*, *31*, 759–772. https://doi.org/10.1016/j.biombioe.2007.05.003

Sultana, A., Kumar, A., & Harfield, D. (2010). Development of Agri-pellet production cost and optimum size. *Bioresource Technology*, *101*, 5609–5621. https://doi.org/10.1016/j.biortech.2010.02.011

Suurs, R. A. A. (2002). Long Distance Bioenergy Logistics: An assessment of costs and energy consumption for various biomass transport chains. *Report NWS*, 1–78.

Thek, G., & Obernberger, I. (2012). *The pellet handbook*. https://doi.org/10.4324/9781849775328

Vera, I., Hoefnagels, R., Junginger, M., & Hilst, F. (2021). Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—A spatially explicit assessment under the sustainability criteria of the renewable energy directive recast. *GCB Bioenergy*, *1–23*, 1425–1447. https://doi.org/10.1111/gcbb.12867

Wang, S., Wang, S., Hastings, A., Pogson, M., & Smith, P. (2012). Economic and greenhouse gas costs of miscanthus supply chains in the United Kingdom. *GCB Bioenergy*, *4*, 358–363. https://doi.org/10.1111/j.1757-1707.2011.01125.x

Wilson, G. A. (2001). From productivism to post-productivism … and back again? Exploring the (un)changed natural and mental landscapes of European agriculture. *Transactions of the Institute of British Geographers*, *26*(1), 77–102. https://doi.org/10.1111/1475-5661.00007

Winkler, B., Mangold, A., von Cossel, M., Clifton-Brown, J., Pogrzeba, M., Lewandowski, I., Iqbal, Y., & Kiesel, A. (2020). Implementing miscanthus into farming systems: A review of agronomic practices, capital and labour demand. *Renewable and Sustainable Energy Reviews*, *132*, 110053. https://doi.org/10.1016/j.rser.2020.110053

Witzel, C. P., & Finger, R. (2016). Economic evaluation of miscanthus production – A review. *Renewable and Sustainable Energy Reviews*, *53*, 681–696. https://doi.org/10.1016/j.rser.2015.08.063

WWF. (2011). *The energy report 100% renewable energy by 2050*. https://doi.org/10.1007/bfb0087305

Yoshida, M., & Takata, K. (2019). Uncertainty simulation of wood chipping operation for bioenergy based on queuing theory. *Forests*, *10*, 822–831. https://doi.org/10.3390/f10090822

SUPPORTING INFORMATION

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