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Research Paper

Towards circularity in the wind industry: Optimal reverse supply network design under various policy scenarios

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ABSTRACT

Wind energy is key to supply renewable energy. However, the increasing number of end-of-life wind turbines is still predominantly landfilled, while regulatory aspects such as waste shipment and landfilling rules hinder the development and scalable implementation of reverse supply networks.

This work aims to understand how EU directives impact the structure and viability of circularity-enabling networks by investigating the optimal reverse supply network design for end-of-life wind turbine blades under different policy scenarios. Three policy scenarios were explored through a Mixed-Integer-Linear-Programming model: (i) 'as-is'; (ii) 'EU Proposal 2021/0367′, removing transboundary restrictions on waste shipments; (iii) 'Landfilling Ban' enforcing an EU-wide ban on landfilling composites. The optimal reverse supply networks with minimum costs were identified for each scenario, contextually determining location and sizing of recycling facilities and calculating landfilling quota and GHG emissions. The costs and emissions were minimum for the EU Proposal scenario, at 15,706,041€ and 2,081 tCO2e respectively. A sensitivity analysis on landfilling gate fees highlighted that they should be significantly increased to incentivise higher recycling rates and close material loops.

This research is the first to evaluate the effects of policy initiatives on the shaping of optimised reverse supply chains through mathematical programming methods. The work contributes to the waste management literature by designing optimal circular supply chain networks for the management of waste from wind turbines decommissioning at the EU-level to improve sustainability of renewable energy installations.

1. Introduction

Transition to renewable energy sources is key to achieve European carbon neutrality by 2050 (Mello et al., 2022). Wind energy is increasingly supplying clean energy (Liu et al., 2022): in 2016, around 77,000 wind turbines operated in Europe, corresponding to 154 GW capacity (Jensen and Skelton, 2018) and 17GW of new wind energy installations were delivered in Europe in 2021 (WindEurope, 2022).

Following rapid increase of wind turbine installations, a question arises regarding the End-of-Life (EoL) management of wind turbine blades (WTB), which are made of non-biodegradable fibre reinforced composites, such as Glass Fibre Reinforced Polymers (GFRP), and constitute the largest fraction of the materials that is not recycled on a blade (Cousins et al., 2019).

Wind turbines have approximately 20 years of service life and are occasionally decommissioned earlier. The first generation of wind turbines in Europe reached their EoL (Andersen et al., 2016) and an increased accumulation of EoL WTB is expected in the future (Lund et al., 2023), determining a great amount of GFRP material reaching the waste streams. Forecasts show that the EoL WTB waste in Europe will triple in 2050 compared to the 2020 levels, reaching 325,000 t/year (Lichtenegger et al., 2020).

Various alternatives for the management of EoL WTB exist, which can be classified into six categories ranked according to the EU Waste Hierarchy: prevention, reuse, repurpose, recycling, recovery and

Abbreviations: BMC, Bulk Moulding Compound; CE, Circular Economy; EoL, End-of-Life; GHG, Greenhouse Gas; GFRP, Glass Fibre Reinforced Polymers; MILP, Mixed Integer Linear Programming; NUTS, Nomenclature d'Unités Territoriales Statistiques – EU Classification of Territorial Units for Statistics; OR, Operational Research; SMC, Sheet Moulding Compound; WSR, Waste Shipment Regulation; WTB, Wind Turbine Blades.

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Nomenclature

Symbol	Description
Sets:	
c	potential customers c = 1..C
f	aggregated waste material suppliers f = 1..F
l	potential recycling facility locations (NUTS2 regions centroids) l = 1..L
mp	material processor locations mp = 1..MP
ps	processing stages of recycling facility (cutting in situ, shredding in plant) ps = 1..PS
s	potential recycling facility sizes s = 1..S
st	storage stages (before processing in recycling facility, after processing in recycling facility) st = 1..ST
w	landfilling areas locations (NUTS2 regions centroids) w = 1..W
Parameters:	
an	annuity factor (−)
Cap_s	processing capacity of recycling facility size s (t of input waste yr^{-1})
cdf_l	cost of diesel per country or region (€ l^{-1})
ce_l	cost of electricity (per facility location) (€ kWh^{-1})
cfil	cost of filler (€ t^{-1})
Ci	total recycling facility investment cost (€)
$cins_s$	insurance cost for recycling facility size s (estimated for different capacities with a scale up factor of 0.65 to reflect the economies of scale) (€ yr^{-1})
ci_s	investment cost for recycling facility size s (estimated for different capacities from actual data with a scale up factor of 0.65 to reflect the economies of scale) (€)
Cland	total cost of landfilling waste material (€ yr^{-1})
$clan_w$	cost of disposing waste (per landfill location) (€ t^{-1} of waste material)
Cm	total recycling facility maintenance cost (€ yr^{-1})
Cmf	total fuel cost for forklift machinery (€ yr^{-1})
cmf	fuel consumption for forklift machinery (l yr^{-1} t^{-1} recycling facility capacity)
Cmi	total investment cost for forklift machinery (€ yr^{-1})
cmi	rental cost for forklift machinery (€ yr^{-1} t^{-1} recycling facility capacity)
cmins	insurance cost for forklift machinery (€ yr^{-1} t^{-1} plant capacity)
Cmp	total cost of disposing the waste material in cement kiln facilities (€ yr^{-1})
cmp	cost of disposing waste in cement kiln facilities (€ t^{-1} of waste material)
cm_s	maintenance yearly cost for recycling facility size s (% of original investment)
$co2ee_l$	electricity carbon emissions factor per country (g CO_{2e} kWh^{-1})
$CO2fu_t$	carbon emissions from transportation (t_{CO2e} yr^{-1})
$Cov^c_{0,LB}$	total variable operational cost from pre-processing of waste (cutting in situ) for LANDFILLING BAN scenario: labour, tool wear and energy consumption (€ yr^{-1})
Cov^c_0	total variable operational cost from pre-processing of waste (cutting in situ) for AS-IS and EU PROPOSAL 2021/0367 scenarios: labour, tool wear and energy consumption (€ yr^{-1})
Cov^c_1	total variable operational cost from processing of waste (cutting in facility): labour, tool wear and energy consumption (€ yr^{-1})
co2t	carbon emissions cost (€ t^{-1}_{CO2e})
coc	variable cutting operating cost (tool wear and electricity) for waste processing in situ (€ t^{-1} of material processed)
cocf	variable cutting operating cost (tool wear and electricity) for waste processing in the recycling facility (€ t^{-1} of material processed)
coe	variable electricity consumption for waste shredding (kWh t^{-1} material processed)
Cof	total recycling facility fixed operational cost: insurance and labour cost (€ yr^{-1})
colc	variable cutting labour cost (€ t^{-1} material processed)
$cols_s$	fixed operating personnel cost for recycling facility (estimated for different capacities from actual data with a scale up factor of 0.25) (€)
$conv_{ps}$	Material conversion efficiency of processing stage ps (1: cutting in situ, 2: cutting in plant, 3: shredding in plant) (%)
cos	variable shredding operating cost (tool wear) (€ t^{-1} material processed)
Cov^s_1	total processing variable operational cost in the recycling facility (shredding): energy consumption and tool wear (€ yr^{-1})
cpcf	personnel cost for cutting in the recycling facility (€ t^{-1} material processed)
Cst	total storage cost (€ yr^{-1})
cst_{st}	Storage cost at storage stage st (€ t^{-1} plant capacity)
Ctin	total waste transportation cost from all suppliers to the recycling facility (€ yr^{-1})
Ctinmp	total waste transportation cost from all suppliers to the material processors mp = 1..MP (€ yr^{-1})
Ctinw	total waste transportation cost from all suppliers to the landfilling areas w = 1..W (€ yr^{-1})
Ctout	total product transportation cost from recycling facility to the customers (€ yr^{-1})
CO2el	electricity carbon emissions for recycling facility (t_{CO2e} yr^{-1})
$CO2fu_{o2}$	carbon emissions from fuel combustion from recycling facility operation (t_{CO2e} yr^{-1})
$d1_f$	Average first stage distance between material availability location and aggregated material supplier location (for each NUTS2 region) (km)
dem_c	Material demand of customer c (t/yr)
dr	Discount rate (%)
$dfl_{f,l}$	Second stage distance between aggregated material supplier f and recycling facility l (km)
$dfmp_{f,mp}$	distance between waste aggregated material supplier f and material processor mp (km)
$dfw_{f,w}$	Second stage distance between aggregated material supplier f and landfilling location w (km)
$dlc_{l,c}$	distance between recycling facility l and customer c (km)
Efd	carbon emission factor for diesel (g_{CO2e} l^{-1})
F	total annual cost of the reverse supply network (€)
fct	fuel consumption of full load heavy duty truck (l t^{-1} km^{-1})
Rfil	revenues from the use of the recycling fibres as fillers (€ yr^{-1})
sup_f	waste available at supplier f (AS-IS, EU PROPOSAL 2021/0367 scenarios) (t/yr)
$sup_{f,LB}$	waste available at supplier f (LANDFILLING BAN scenario) (t/yr)
tcin	Unitary cost of waste inbound transportation from suppliers to recycling/material processor facilities or landfilling areas: labour, insurance, maintenance (€ t^{-1} km^{-1})
tcinf	Unitary cost of waste inbound transportation from suppliers to recycling/material processor facilities or landfilling areas: fuel (€ t^{-1} km^{-1})
tcout	Unitary cost of recycled product transportation from

	recycling facilities to customers: labour, insurance, maintenance (€ t^{-1} km^{-1})
tcoutf	Unitary cost of recycled product transportation from recycling facilities to customers: fuel (€ t^{-1} km^{-1})
Y	useful life of operation (yr)
Decision Variables:	
$p_{f,mp}$	waste material flow from waste supplier f to material processor mp, positive variable (t/yr)
$p_{f,w}$	waste material flow from waste supplier f to landfilling area w, positive variable (t/yr)
$x_{f,l}$	waste material flow from waste supplier f to recycling facility l, positive variable (t/yr)
$y_{l,s}$	Existence of recycling facility of size s at location l, binary –
$z_{l,c}$	recycled material flow from recycling facility l to customer c, positive variable (t/yr)

disposal (Beauson et al., 2022). Interested readers can refer to Beauson et al. (2022), Cooperman et al. (2021), Liu et al. (2022, 2019), Rani et al. (2021) for an extended overview of the available EoL strategies. Despite the plethora of circular options for WTB, the main path for EoL WTB in Europe remains landfilling (Cousins et al., 2019), although this "will not be cheap/legal in the future as environmental legislation becomes increasingly restrictive for solid waste" (Liu et al., 2022). Landfilling is still pursued as circular options for WTB are currently commercially immature, with an intermediate technology readiness level between 3 and 7 (Cooperman et al., 2021). The only mature strategies are lifetime extension, incineration, cement coprocessing and mechanical recycling (Cooperman et al., 2021). Among such strategies, lifetime extension does not close the material loop (Mendoza et al., 2022) and it is not a viable long-term strategy, due to the limited availability of new sites for wind farms (Ziegler et al., 2018), while incineration and cement coprocessing solutions seat at the bottom of the EU Waste Hierarchy, suffering environmental (Cooperman et al., 2021) and economic drawbacks (Job, 2013; Mendoza et al., 2022).

The composite material waste from EoL WTB creates challenges and management issues (Sultan et al., 2018). Beauson et al., (2022) highlighted that the regulatory framework has to be harmonised to manage composite waste across borders (at regional level). Similarly, Heng et al., (2021) identified mechanical recycling as a promising solution that significantly reduces the GHG emissions, but lacks an enabling legislative framework to become economically profitable. Therefore, this paper focuses on the GFRP mechanical recycling EoL strategy for the development of circular supply networks for EoL WTB.

While the literature on reverse and circular supply networks design is growing (Van Engeland et al., 2020), research on reverse supply chains for WTB waste is limited. Sultan et al. (2018) proposed UK recycling facilities locations following the centre-of gravity methodology. Ghosh et al. (2022) used simulation to investigate the environmental and circularity implications of different scenarios in two US states with different EoL alternatives, while Rentizelas et al. (2021) and Sommer and Walther (2021) developed optimisation models for European reverse supply networks under different scenarios.

However, none of the previous studies integrated reverse supply chain design with existing regulatory aspects, which can hinder the development and scalable implementation of reverse supply networks. An increased integration of legislative initiatives in the circular economy (CE) literature is required to investigate "the impact of policy initiatives onto the shaping of supply chains" (Genovese et al., 2023). The lack of integration of policy developments within mathematical programming methods was also highlighted in a systematic review on supply chain design for the CE by MahmoumGonbadi et al., (2021), who urged to develop "models and methods to assess the effects of policy developments, such as European directives". Therefore, this work aims to understand the impact of different EU-wide policies and legislative initiatives on the emergence of circularity-enabling reverse supply chain networks for the waste management of WTB. The novelty of this work lies on evaluating the potential effects of policy initiatives on the emergence of optimised reverse supply chains through mathematical programming methods.

This work contributes to policy making, by revealing the reverse supply chain costs and environmental impacts of adhering to each policy initiative under optimal conditions, hence providing a best-case scenario, ultimately allowing the understanding for the need of various support measures. It also contributes to supporting decisions of stakeholders involved in reverse supply chains by defining ideal network structure. The academic contribution of the work is multi-fold in-line with its multidisciplinary nature. The work contributes to the waste management literature by designing optimal circular supply chain networks for the management of waste from wind turbines decommissioning to improve sustainability of renewable energy installations under different policy scenarios. The work also contributes to the circular supply chain management literature by adding the policy dimension compared to existing circular supply chain design models, incorporating existing and future regulatory aspects to inform the decision-making for EoL WTB.

2. European Union waste legislation landscape

The pillar of European Union (EU) policies on waste is the Waste Framework Directive (2008/98/EC) (Abeshev and Koppenborg, 2023). The Directive defines the European waste hierarchy, which orders waste management solutions: waste prevention, reuse, repurpose, recycling, recovery and disposal (Delaney et al., 2021). Landfilling is the least desirable option, but is still allowed for non-hazardous waste, such as WTB (Abdalla and Diani, 2021). However, composite materials are already banned from landfilling in Austria, Germany, Finland and in the Netherlands (Majewski et al., 2022). Additional EU countries rely marginally on landfilling as a waste management option (Beauson et al., 2022), meaning that this solution is becoming progressively more prohibitive within the EU.

Further EU regulations govern specifically the shipments of waste. The cornerstone regulation is EU Waste Shipment Regulation (WSR) No. 1013/2006 (European Commission, 2021a), which establishes procedures and control regimes for the shipment of waste within EU countries (European Parliament and Council, 2006). The regulation was amended in 2020 through the EU regulations 2020/2174 and 2020/1056 (European Parliament and Council, 2020a, European Parliament and Council, 2020b).

The European Commission aims to further update the regulations on waste shipments as part of the European Green Deal and the Circular Economy Action Plan in order to ease the transport of waste for recycling and re-use within the EU and to support the shift towards the CE (European Commission, 2021a, 2021b), as only 12 % of raw materials used in EU industry come from recycling (European Commission, 2021b). The EU aims to simplify procedures for intra-EU waste shipments, including a digitalisation of the waste shipments documentation, and to establish stricter conditions for waste shipments directed to incineration and landfilling, to make CE paths more attractive (European Commission, 2021a, 2021b). The proposal stems from the limitations of the existing WSR as "different levels and ways of applying and enforcing the WSR, often combined with different interpretations of its provisions and various inspection regimes, have hampered its optimal implementation throughout the EU" (European Commission, 2021a). These shortcomings in the implementation of WSR currently "limit or discourage legal shipments of good quality waste materials to recycling facilities", ultimately hampering the transition towards the CE (European Commission, 2021a).

The proposal also aims to reverse the current fragmentation of the EU internal market, by setting common rules on the classification of waste and updating the European List of Waste (European Commission, 2021a). This is particularly important for end-of-life WTB. While they are treated as non-hazardous waste EU-wide, WTB lack a unique EU reference number, as multiple materials are found in the waste, resulting in different labelling even within the same country due to the presence of both organic and inorganic materials (Beauson et al., 2022). The combined actions on facilitating intra-EU waste shipments and updating waste classification are expected to open opportunities for an EU-wide approach to recycling WTB. Optimised reverse networks are essential to ensure economic competitiveness and avoid environmental rebound effects.

3. Materials and methods

The research design (Fig. 1) kicked-off with the definition of the research aim, outlined in Section 1. The definition of the reverse supply network and of the legislative scenarios fed into the reverse supply network optimisation under different legislative scenarios, which was achieved thanks to a mixed-integer linear programming (MILP) mathematical model. The main outputs of the work were obtained at this stage, namely the reverse supply network architecture and the economic, environmental and circularity performance of the network. These were further investigated through a sensitivity analysis on the landfilling gate fees, which is a significant leverage for policy makers to stimulate circularity.

3.1. Reverse supply network definition

The reverse supply network proposed in Rentizelas et al. (2021) is expanded to investigate the impact of different EU-wide policies and legislative actions on circularity-enabling reverse supply chain networks for WTB waste within the EU.

The proposed network structure is presented in Fig. 2. The first processing stage for the EoL WTB is cutting them in large pieces at the wind farm. This practice is currently adopted for transporting the WTB waste for landfilling and is assumed across all waste management streams considered.

The recycling stream introduces an independent third-party entity for the mechanical recycling of the EoL WTB to retrieve the recycled GFRP (Kocabasoglu et al., 2007). The recycling process steps are extensively discussed in Rentizelas et al. (2021). The recycled fibres are supplied to customers in an open-loop supply chain, since material properties of mechanically recycled fibres do not allow a closed-loop supply chain within the wind industry. Potential customers were identified in Rentizelas et al. (2021) as the Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) manufacturers, where the recycled fibres are used as fillers in new thermoset polymer composites. The recycled fibres replace the $CaCO_3$ material, providing several benefits as illustrated in Derosa et al. (2005) and Mamanpush et al. (2018).

A material processor entity is the second option, which is an existing[1] facility that mechanically processes GFRP to supply it to cement kilns for a gate fee (Diez-Cañamero and Mendoza, 2023). The third waste stream option is landfilling.

3.2. Scenarios definition

The reverse supply networks defined in Section 3.1 were optimised under different legislative conditions. Two key regulations were adopted to define the scenarios, namely the existence or not of a) landfilling restrictions and b) transboundary restrictions on waste shipments. Based on the EU legislative framework evolution outlined in Section 2 and on the progressive tightening of landfilling legislation in Europe (Liu et al., 2022), the following three scenarios were defined:

1. **AS-IS:** represents the current scenario, with transboundary restrictions on waste shipments and without landfilling restrictions of waste at the EU-level, with the exception of few countries where a landfilling ban already exists, as detailed in Section 2.
2. **EU PROPOSAL 2021/0367**: removes the transboundary restrictions on waste shipments in line with the EU Proposal 2021/0367. No landfilling restrictions are in place, with the exception of the few countries where a landfilling ban already exists.
3. **LANDFILLING BAN**: goes beyond the EU Proposal 2021/0367, by exploring reverse supply networks with no transboundary restrictions on waste shipments and with EU-wide landfilling restrictions for GFRP. In this forward-looking scenario, it is assumed that whatever is not recycled, ends up in a material processing facility, where the waste is processed and utilised in cement kilns.

The fourth possible scenario, i.e. transboundary restrictions on shipments and landfilling restrictions of waste both being in place, was not considered as it is unlikely to arise in the future in light of the EU proposal 2021/3067 facilitation of waste shipments within the EU-27 and the European Green Deal.

3.3. Mathematical model

A MILP model was developed to investigate the optimal reverse supply network design for EoL WTB. The EoL WTB are transported from the waste suppliers ($f = 1 \ldots F$) either to the recycling facilities ($l = 1 \ldots L$), to the material processor entities $mp = 1..MP$ (*all scenarios*)[2] or to the landfilling areas ($w = 1..W$), whenever landfilling is allowed (scenarios *AS-IS* and *EU PROPOSAL 2021/0367*). The potential location ($l = 1 \ldots L$) and capacity ($s = 1 \ldots S$) of the recycling facilities are optimised by the model. The recycled material is delivered to the customers ($c = 1 \ldots C$). The objective function of the optimisation problem is to minimise the annual total cost of the reverse supply network, including all process stages ($ps = 1 \ldots PS$) up to the delivery of the recycled product to the end users or other waste stream options (landfilling or material processor). The reverse supply network CO2e emissions are also calculated to inform about the environmental impact. The decision variables of the optimisation model are:

- $x_{f,l}$ waste material flow from supplier f to recycling facility l, $f = 1 \ldots F$, $l = 1 \ldots L$
- $p_{f,w}$ waste material flow from supplier f to landfilling area w, $f = 1 \ldots F$, $w = 1 \ldots W$
- $p_{f,mp}$ waste material flow from supplier f to material processor mp, $f = 1..F$, $mp = 1..MP$
- $y_{l,s}$ binary variable that takes value 1 if recycling facility of capacity s is opened at a specific location l, and 0 otherwise, $l = 1 \ldots L$, $s = 1 \ldots S$
- $z_{l,c}$ recycled material flow from recycling facility l to customer c, $l = 1 \ldots L$, $c = 1 \ldots C$

The objective function of the model is described by Eq. (1) for scenarios 'AS-IS' and 'EU REGULATION 2021/0367′, where no new restrictions to landfilling are in place, and by Eq. (2) for the scenario 'LANDFILLING BAN'. Therefore, the decision variable ($p_{f,w}$) is only introduced in the 'AS-IS' and 'EU REGULATION 2021/0367′ scenarios to

[1] https://www.neocomp.eu/.

[2] Currently a single material processor facility exists in the EU: the cement co-processing plant is located in Bremen (Germany) with a capacity of 30,000 t/year (Diez-Cañamero and Mendoza, 2023).

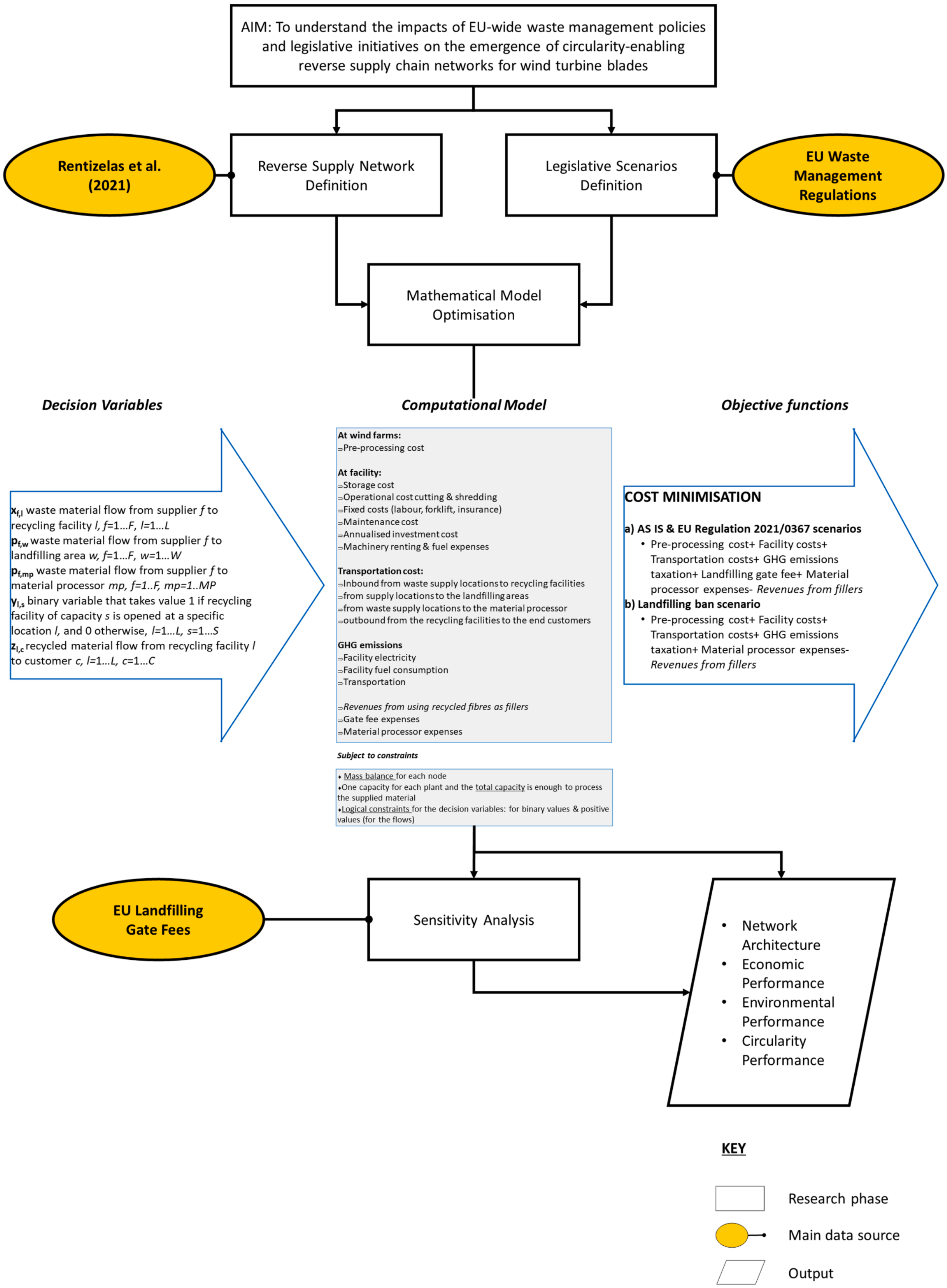

Fig. 1. Research Design.

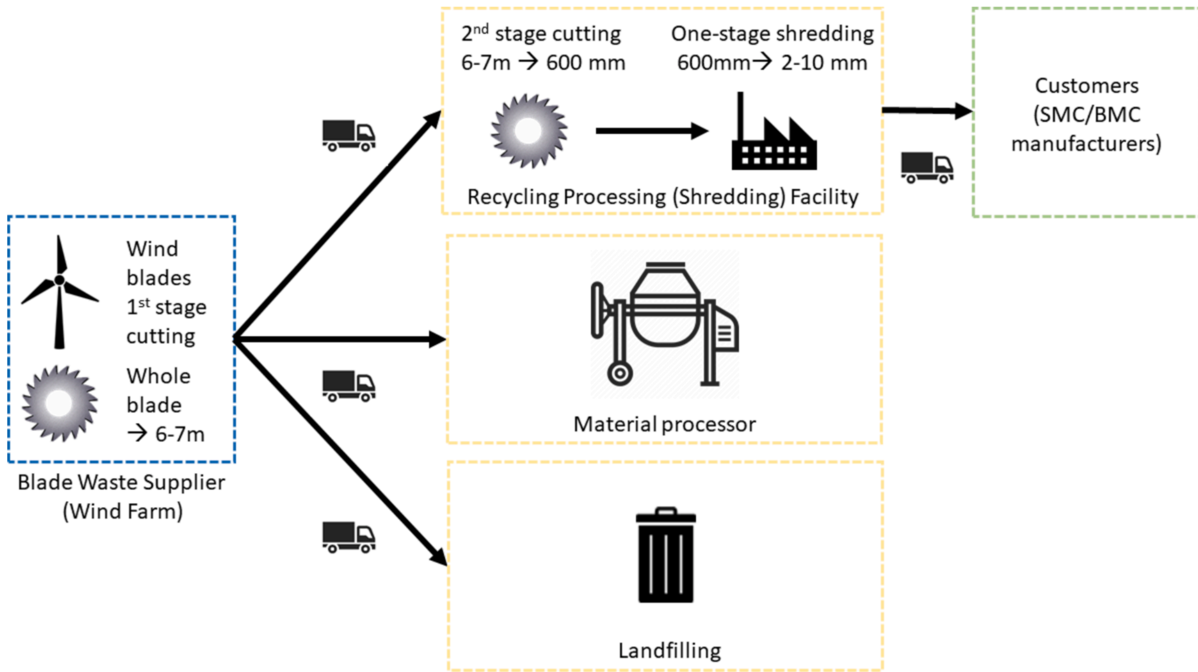

Fig. 2. Reverse Supply Network Structure.

account for the waste material flow from the wind farms to the landfilling locations. The same model and objective function are used for the 'AS-IS' and 'EU REGULATION 2021/0367′ scenarios, the only difference being the model being run and optimised at the country level in the 'AS-IS' scenario and at the EU-27 level in the latter scenario.

The decision variable $(p_{f,mp})$ is introduced in all scenarios to indicate the waste material from the wind farms to the material processor. In the 'AS-IS' scenario, the material processor option is only feasible for the countries that currently have this type of facilities, i.e., Germany, due to transboundary restrictions. In the other scenarios, this pathway can receive materials from all EU countries. In the 'LANDFILLING BAN' scenario, the material processor receives the entirety of the waste stream not sent to the recycling facilities.

Objective functions:

'AS-IS' and 'EU REGULATION 2021/0367′ scenarios:

$$\begin{aligned}\mathrm{MinF} = & \mathrm{Cov}_0^c + \mathrm{Cst} + \mathrm{Cov}_1^c + \mathrm{Cov}_1^s + \mathrm{Cm} + \mathrm{Cof} + \frac{\mathrm{Ci}}{\mathrm{an}} + \mathrm{Cmi} + \mathrm{Cmf} \\ & + \mathrm{Ctin} + \mathrm{Ctin}_w + \mathrm{Ctin}_{mp} + \mathrm{Ctout} + \mathrm{co2t}(\mathrm{CO2el} + \mathrm{CO2fu}_{o2} \\ & + \mathrm{CO2fu}_t) - \mathrm{Rfil} + \mathrm{Cland} + \mathrm{Cmp}\end{aligned} \tag{1}$$

'LANDFILLING BAN' scenario:

$$\begin{aligned}\mathrm{MinF} = & \mathrm{Cov}_{0,\,LB}^c + \mathrm{Cst} + \mathrm{Cov}_1^c + \mathrm{Cov}_1^s + \mathrm{Cm} + \mathrm{Cof} + \frac{\mathrm{Ci}}{\mathrm{an}} + \mathrm{Cmi} + \mathrm{Cmf} \\ & + \mathrm{Ctin} + \mathrm{Ctin}_{mp} + \mathrm{Ctout} + \mathrm{co2t}\left(\mathrm{CO2el} + \mathrm{CO2fu}_{o2} + \mathrm{CO2fu}_{t,\,LB}\right) \\ & - \mathrm{Rfil} + \mathrm{Cmp}\end{aligned} \tag{2}$$

The annual reverse supply network cost expressed with Eqs. (1) and (2) captures several cost items. The costs of each processing stage *ps* in the recycling facility are expressed as a function of the quantity of EoL WTB material (Eqs. (3)–(23)). The total amount of EoL WTB is pre-processed at the wind farms (Eqs. (3) and (4)). The annual reverse network cost considers also the storage cost of the input and output material at the recycling facility (Eq. (5)); the operational costs of cutting and shredding in the facility (Eqs. (6) and (7)); the fixed costs of the recycling facility (Eq. (8)), which includes personnel, forklifts and insurance costs; the maintenance cost (Eq. (9)); the annualised investment cost of the recycling facility (Eq. (10)), with the annuity estimated by Eq. (11); the forklift machinery renting and fuel cost (Eqs. (12)–(13)). The transportation costs between the supply network nodes are calculated as a function of the amount of material transported: Eq. (14) for the transport from the waste supply locations to the recycling facilities, Eq. (15) for the transport from the waste supply locations to the landfilling areas, Eq. (16) for the transport from the waste supply locations to the material processor and Eq. (17) for the outbound transport from the recycling facilities to the customers. The inbound transportation to recycling facilities consists of two distance elements, the first from the wind farms to theoretical material aggregation nodes (NUTS2 centroids), and the second from these nodes to the recycling facilities, in line with Rentizelas et al. (2021). The GHG emissions consider facility operation electricity and fuel consumption (Eqs. (18)–(19)) and transportation (Eqs. (20) and (21)). For the electricity consumption, the electricity carbon emission factors at the country level are used, whereas a standardised emissions factor is used for emissions due to diesel fuel use. Eq. (22) estimates the revenues from using the recycled fibres as fillers. Finally, Eqs. (23) and (24) account for the gate fee expenses at landfills (varying by country, see Supplementary Material S.2) or at the material processor.

$$\mathrm{Cov}_0^c = (\mathrm{coc} + \mathrm{colc}) \sum_{l=1}^{L} \sum_{f=1}^{F} \sum_{w=1}^{W} \sum_{mp=1}^{MP} (x_{f,l} + p_{f,w} + p_{f,mp}) \tag{3}$$

$$\mathrm{Cov}_{0,\,LB}^c = (\mathrm{coc} + \mathrm{colc}) \sum_{l=1}^{L} \sum_{f=1}^{F} \sum_{mp=1}^{MP} (x_{f,l} + p_{f,mp}) \tag{4}$$

$$\mathrm{Cst} = \sum_{st=1}^{ST} \sum_{l=1}^{L} \sum_{s=1}^{S} \mathrm{cst}_{st} \mathrm{Cap}_s y_{l,s} \tag{5}$$

$$\mathrm{Cov}_1^c = (\mathrm{cocf} + \mathrm{cpcf}) \sum_{l=1}^{L} \sum_{f=1}^{F} x_{f,l} \mathrm{conv}_1 \tag{6}$$

$$\mathrm{Cov}_1^s = \sum_{l=1}^{L} \left[(\mathrm{cos} + \mathrm{coe\,ce}_l) \sum_{f=1}^{F} x_{f,l} \mathrm{conv}_1 \mathrm{conv}_2 \right] \tag{7}$$

$$Cof = \sum_{s=1}^{S}\left(cols_s\sum_{l=1}^{L}y_{l,s}\right) + cmins\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L}y_{l,s}\right) + \sum_{s=1}^{S}\left(cins_s\sum_{l=1}^{L}y_{l,s}\right) \quad (8)$$

$$Cm = \sum_{s=1}^{S}(cm_s ci_s\sum_{l=1}^{L}y_{l,s}) \quad (9)$$

$$Ci = \sum_{s=1}^{S}(ci_s\sum_{l=1}^{L}y_{l,s}) \quad (10)$$

$$an = \frac{1-\frac{1}{(1+dr)^Y}}{dr} \quad (11)$$

$$Cmi = cmi\sum_{s=1}^{S}\left(Cap_s\sum_{l=1}^{L}y_{l,s}\right) \quad (12)$$

$$Cmf = cmf\sum_{l=1}^{L}(cdf_l\sum_{s=1}^{S}Cap_s y_{l,s}) \quad (13)$$

$$Ctin = \sum_{f=1}^{F}\sum_{l=1}^{L}(tcin + tcinf)conv_1(d1_f + dfl_{f,l})\,x_{f,l} \quad (14)$$

$$Ctin_W = \sum_{f=1}^{F}\sum_{w=1}^{W}(tcin + tcinf)conv_1(d1_f + dfw_{f,w})\,p_{f,w} \quad (15)$$

$$Ctin_{mp} = \sum_{f=1}^{F}\sum_{mp=1}^{MP}(tcin + tcinf)conv_1(d1_f + dfmp_{f,mp})p_{f,mp} \quad (16)$$

$$Ctout = (tcout + tcoutf)\sum_{l=1}^{L}\sum_{c=1}^{C}dlc_{l,c}z_{l,c} \quad (17)$$

$$CO2el = coe\sum_{l=1}^{L}(co2ee_l\sum_{s=1}^{S}Cap_s y_{l,s}/10^6) \quad (18)$$

$$CO2fu_{o2} = cmf\,efd\sum_{s=1}^{S}(Cap_s\sum_{l=1}^{L}y_{l,s}/10^6) \quad (19)$$

$$Cmp = cmp\sum_{f=1}^{F}\sum_{mp=1}^{MP}p_{f,mp} \quad (24)$$

The model is constrained by the following equations: mass balances are imposed on each node (Eq. (25)). The relationship between the mass of the waste available from each of the waste material supplier and the waste provided to all the facilities is modelled in Eq. (26) ('AS-IS' and 'EU PROPOSAL 2021/0367) and in Eq. (27) ('LANDFILLING BAN'). Finally, Eq. (28) ensures that the mass of the material demanded from each customer is satisfied from the recycled material flow from all facilities. A single capacity is allowed for each recycling facility location (Eq. (29)) and the capacity at each location must be sufficient to process all the waste allocated to it (Eq. (30)). Finally, logical constraints (Eqs. (31)–(35)) ensure positive and binary values of decision variables.

$$\sum_{c=1}^{C}z_{l,c} = \sum_{f=1}^{F}x_{f,l}\prod_{ps=1}^{PS}conv_{ps},\ l = 1\cdots L \quad (25)$$

$$sup_f = \sum_{l=1}^{L}x_{f,l} + \sum_{w=1}^{W}p_{f,w} + \sum_{mp=1}^{MP}p_{f,mp},\ f = 1\cdots F \quad (26)$$

$$sup_{f,LB} = \sum_{l=1}^{L}x_{f,l} + \sum_{mp=1}^{MP}p_{f,mp},\ f = 1\cdots F \quad (27)$$

$$dem_c \geq \sum_{l=1}^{L}z_{l,c},\ \ c = 1..C \quad (28)$$

$$\sum_{s=1}^{S}y_{l,s} \leq 1, l = 1..L \quad (29)$$

$$conv_1\sum_{f=1}^{F}x_{f,l} \leq \sum_{s=1}^{S}Cap_s y_{l,s}, l = 1..L \quad (30)$$

$$z_{l,c} \geq 0, l = 1..L,\ c = 1..C \quad (31)$$

$$x_{f,l} \geq 0,\ l = 1..L, f = 1..F \quad (32)$$

$$p_{f,w} \geq 0, w = 1..W, f = 1..F \quad (33)$$

$$p_{f,mp} \geq 0, mp = 1..MP, f = 1..F \quad (34)$$

$$CO2fu_t = fct\,efd\frac{\left[\begin{array}{c}\sum_{l=1}^{L}\sum_{f=1}^{F}(dfl_{f,l} + d1_f)conv_1x_{f,l} + \sum_{f=1}^{F}\sum_{w=1}^{W}conv_1(d1_f + dfw_{f,w})\,p_{f,w} + \\ \sum_{f=1}^{F}\sum_{mp=1}^{MP}conv_1(d1_f + dfmp_{f,mp})p_{f,mp} + \sum_{l=1}^{L}\sum_{c=1}^{C}dlc_{l,c}z_{l,c}\end{array}\right]}{10^6} \quad (20)$$

$$CO2fu_{t,\,LB} = fct\,efd\frac{\left[\sum_{l=1}^{L}\sum_{f=1}^{F}(dfl_{f,l} + d1_f)conv_1x_{f,l} + \sum_{f=1}^{F}\sum_{mp=1}^{MP}conv_1(d1_f + dfmp_{f,mp})p_{f,mp} + \sum_{l=1}^{L}\sum_{c=1}^{C}dlc_{l,c}z_{l,c}\right]}{10^6} \quad (21)$$

$$Rfil = cfil\sum_{f=1}^{F}\sum_{l=1}^{L}conv_1conv_2conv_3x_{f,l} \quad (22)$$

$$Clan = \sum_{f=1}^{F}\sum_{w=1}^{W}p_{f,w}clan_w \quad (23)$$

$$y_{l,s} = 0\text{ or }1,\ l = 1..L,\ s = 1..S \quad (35)$$

3.4. Assumptions

The geographical scope of the model is the EU-27, while the reference year is 2025. The amount of waste from wind turbines is estimated according to Lichtenegger et al. (2020) (Supplementary Material S.3).

Only WTB waste from EoL wind turbines is considered, while waste from manufacturing and servicing is outside the scope of this work. The complex cutting and sectioning of decommissioned WTB is assumed to take place on-site at wind farms for all scenarios prior to transportation (Lund et al., 2023), as it is not economically viable to transport the entire WTB.

Landfilling is available at the centroid of each of the 240 EU NUTS-2 administrative divisions, consistently with the registered landfilling sites in the EU (Eurostat, 2022). The 240 EU NUTS-2 centroids are also the potential locations for recycling facilities. The transportation transboundary restrictions considered are assumed only for the waste, while the recycled material can be transported across borders, in-line with existing regulations.

The material processor pathway exploits a single co-processing facility located in Bremen (Germany), the only facility of such kind within the EU, which accepts EOL WTB and process GFRP to supply it to cement kilns, handling up to 30,000 t of composite waste per year (WindEurope, 2020).

BMC/SMC customers were identified as the main secondary market for recycled fibres (Fonte and Xydis, 2021). Ten major customers in Europe were considered (2x in Italy, 2x in Spain, 2x in France, 3x in Germany and 1x in Poland), as per Rentizelas et al. (2021).

3.5. Sensitivity analysis

A sensitivity analysis investigated the impact of varying landfill gate fees on the outputs for the 'AS-IS' and the 'EU PROPOSAL' scenarios. In the 'AS-IS' scenario landfilling gate fees were increased at +20 % intervals for each country, in line with Rentizelas et al. (2021). This implies a relative increase in each country based on the current baseline landfill costs, as these display a high variance across the EU, spanning from 5€/t in Romania to 155 €/t in Sweden. The sensitivity analysis for the EU PROPOSAL scenario was instead performed using absolute EU-wide landfill costs, in light of progressive harmonisation of EU policies, setting landfill costs increments at 50€/t intervals across the EU. The maximum landfill cost was set at 200€/t, in line with Liu et al. (2022).

4. Results

The scenarios are evaluated under several dimensions: network architecture (Section 4.1), economic performance (Section 4.2), environmental impact (Section 4.4). The economic dimension is further explored through a sensitivity analysis on the price of landfilling gate fee

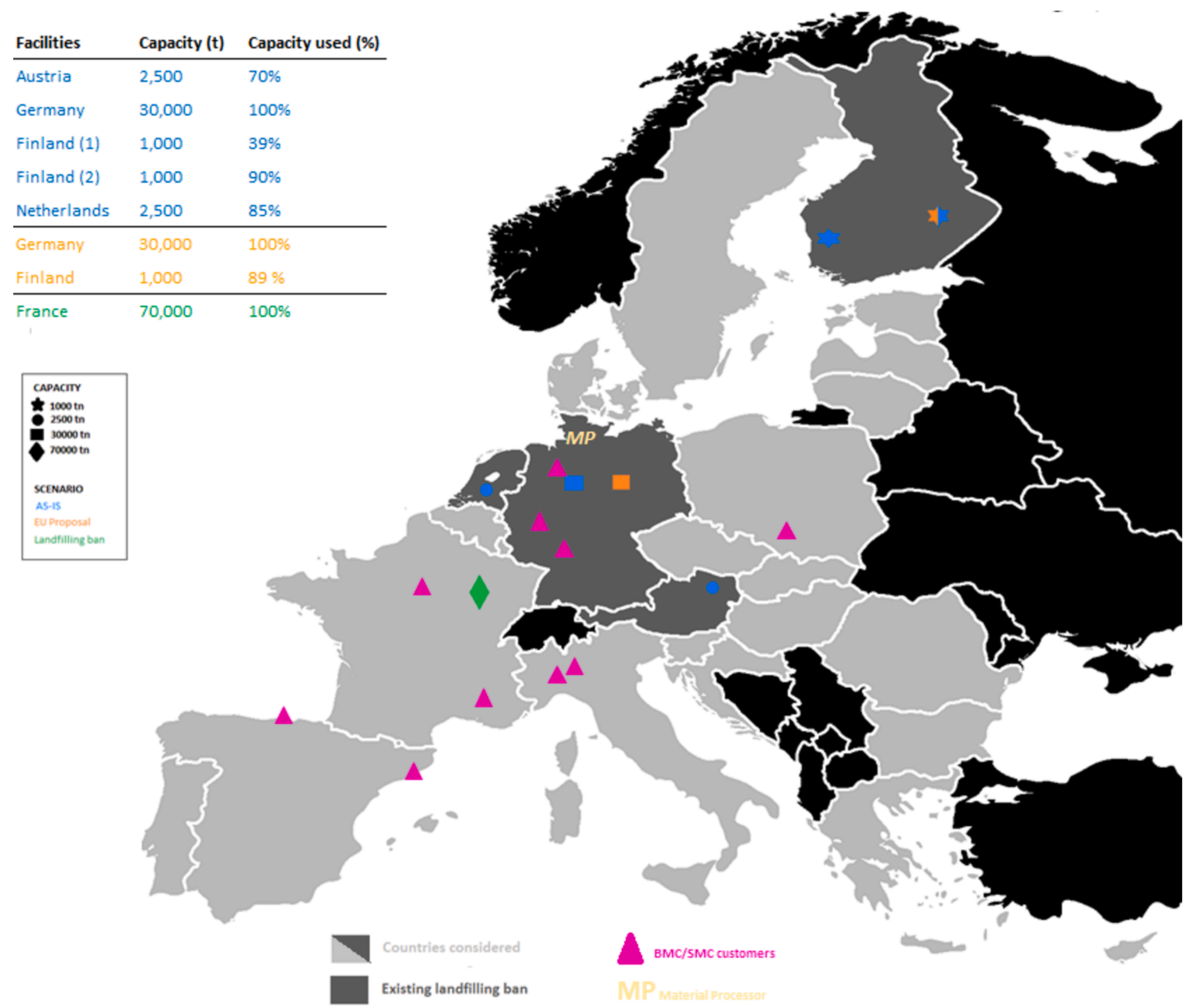

Fig. 3. Reverse Supply Network Architecture for the three scenarios.

to inform policy makers on the potential impact of policy developments on the economic attractiveness and viability of circular options (Section 4.3). The optimisation problem was implemented in GAMS and solved with LINDO in an Intel(R) Core(TM) i7-5500U CPU at 2.40 GHz, requiring 51.93 s to be solved. For the EU-27 application, 240 wind farms/waste supplying regions, 240 potential facility locations and 240 landfilling points were considered, along with, 10 potential capacity options for the facilities, ranging from 1,000 to 100,000 t/yr. A single material processor and 10 customer locations were considered in the model. Overall, 5 decision variables, 58,592 constraints and 177,622 variables were used to solve the mathematical model. The input parameters for the application of the model are available in the Supplementary Material S.1.

4.1. Network architecture

The network architecture (Fig. 3) differs significantly across the scenarios, in terms of number, location, size and capacity utilization of recycling facilities.

In the AS-IS scenario, the model only builds recycling facilities in countries which enforce a landfilling ban (Austria, Germany, Finland, Netherlands), tailoring the capacity of facilities to the expected EoL material flow originating within each country. The total installed capacity equals 37,000 t. A centralised facility is built in each of the countries, with the sole exception of Finland, where two 1,000 t facilities are built.

As transboundary waste shipments are allowed in the EU PROPOSAL scenario, the overall recycling installed capacity decreases to 31,000 t, with a 30,000 t facility in Germany, receiving material flow from Austria, Germany and the Netherlands and a 1,000 t facility in Finland receiving local waste. The waste generated in the four countries with a landfilling ban is still the only waste taking a circular path, however the intra-EU transportation is exploited to move more waste to cement co-processing.

Finally, the LANDFILLING BAN scenario displays a single 70,000 t recycling facility centrally located in eastern France, which absorbs the material flow from 24 EU countries. The only exceptions are Denmark, Sweden and Finland, whose material flow is directed to Germany for cement co-processing due to geographical proximity. The scenario favours a centralised network to exploit economies of scale and to minimise downstream transportation costs thanks to customer proximity, as the majority of BMC/SMC customers are located in central Europe.

The destination of waste (Fig. 4) shows the same quota of material taking the landfilling route in the AS-IS and EU PROPOSAL scenarios, as only waste material from Austria, Finland, Germany and the Netherlands is diverted from disposal due to the landfilling bans enforced in these countries. The 39 % of waste not being landfilled is predominantly recycled in both scenarios, although the recycling share shrinks from 37 % to 32 % due to economic reasons in the EU PROPOSAL, being compensated by an increase of the waste taking the cement co-processing route. All material enters a circular stream in the LANDFILLING BAN scenario, with 27 % of material almost saturating the cement co-processing capacity in Germany and 73 % of material recycled in the centralised facility in France.

4.2. Economic performance

The overall network operates at a loss for all scenarios (Table 1), as the revenues generated through recycling are insufficient to cover the reverse network costs. The total costs are minimum for the EU PROPOSAL scenario at 15,706,041€, 2.92 % less than the AS-IS scenario. Accordingly, the costs per waste material unit are minimum in the EU PROPOSAL scenario. On the other hand, costs per recycled material unit are maximum in the EU PROPOSAL scenario, due to a lower amount of recycled material, while they are minimum in the AS-IS scenario. Finally, the LANDFILLING BAN scenario displays almost double total costs compared to the other scenarios, largely due to the high inbound transportation costs of waste material from all EU regions to the recycling facility, which are over five times higher than the AS-IS and EU PROPOSAL scenarios (Fig. 5). These additional costs are not compensated by the filler revenues and the savings from avoided landfilling.

4.3. Sensitivity analysis/Landfilling Tax

4.3.1. AS-IS Scenario: Country level landfilling gate fee increases

The overall network architecture remains unchanged for increases of the landfilling gate fees up to 40 % over baseline values, as the share of recycled material at the EU-level remains stable at 37 % (Fig. 6a). The first change is observed for a landfilling gate fee increase of 60 %, as 71 % of Italian waste is recycled, thus reaching 44 % of material being recycled EU-wide. These values change incrementally for the 80 % landfilling gate fee increase, whereas at the 100 % increase threshold, all French waste material is recycled, along with 89 % of the Italian waste material, reaching 55 % of recycled material EU-wide. Finally,

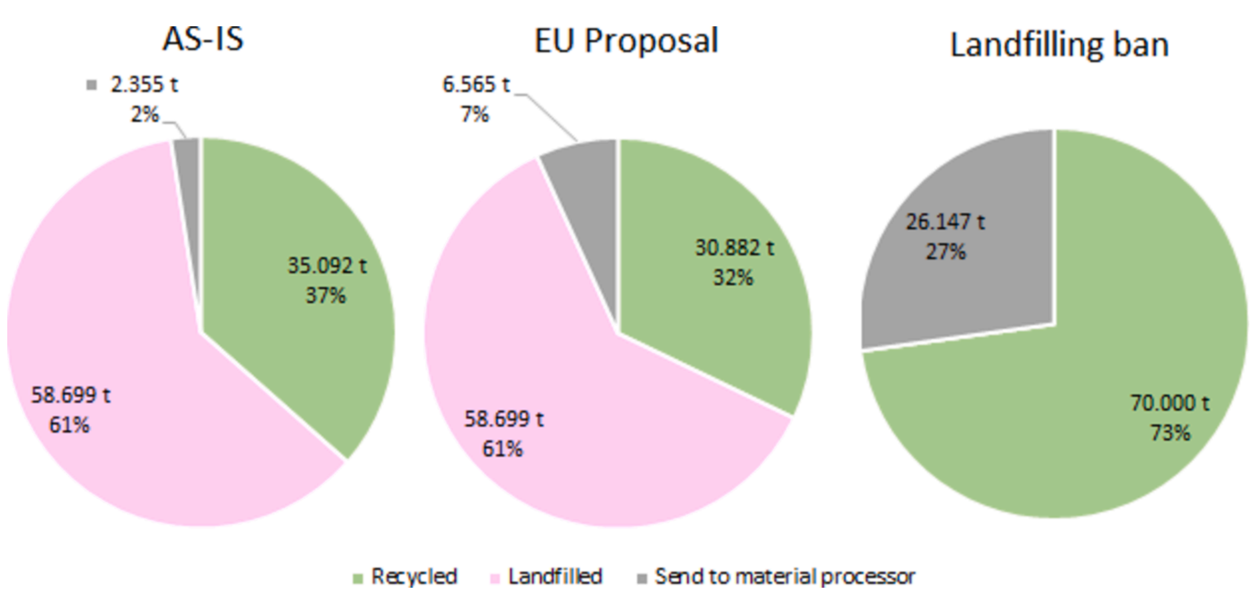

Fig. 4. Breakdown of material destinations by scenario.

Table 1
Economic performance breakdown for the three scenarios.

Scenarios	Filler revenues [€/annum]	Landfilling cost [€/annum]	Material processor cost [€/annum]	Recycling processing costs [€/annum]	Transport costs [€/annum]	Net revenues [€/annum]	Net revenues per unit of waste material [€/t]	Net revenues per unit of recycled material [€/t]
AS-IS	3,200,455	4,424,299	345,027	10,418,854	4,191,037	–16,178,764	–167	– 456
EU Proposal	2,816,468	4,424,299	961,700	8,780,037	4,356,472	–15,706,041	–162	– 503
Landfilling ban	6,384,000		3,829,750	11,495,932	23,763,805	–32,705,487	–337	– 463

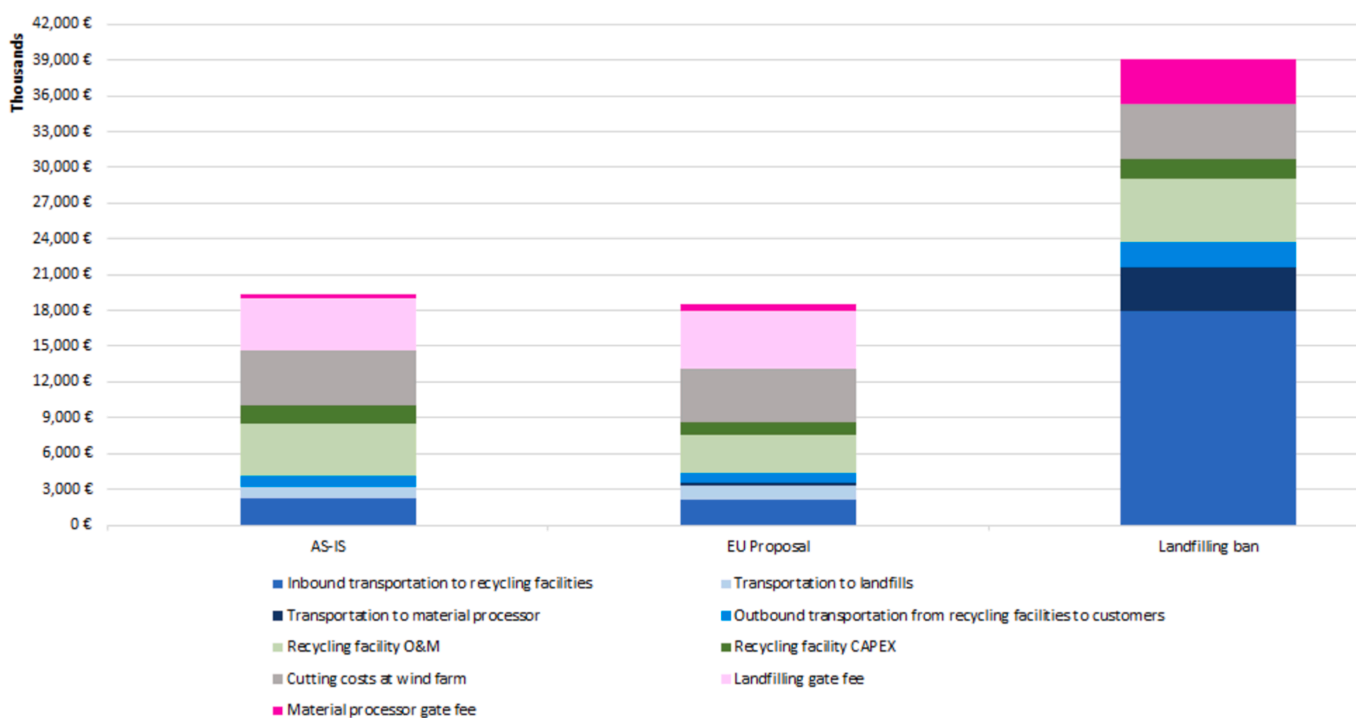

Fig. 5. Cost breakdown by scenario.

additional countries, such as Poland (100 % material recycled), Spain (52 %) and Sweden (60 %), divert waste towards recycling for increases of the landfilling gate fees of 200 %. For other countries, recycling does not occur irrespective of landfill gate fee increases. Under such circumstances, the amount of recycled material at the EU-level would equal 73 %. This value includes recycling in countries that have banned landfilling and have no other option than recycling irrespective of the landfill gate fee value, except Germany, which has a material processor domestically available as an alternative.

The sensitivity analysis of the AS-IS scenario demonstrates that incremental increases of the landfilling gate fees do not lead to increases in recycled materials, unless for gate fees increases larger than 100 % compared to current levels. Shifting from landfill to recycling is primarily driven by available waste material quantities, with a secondary effect of the level of landfilling gate fees. Large European countries, which can exploit economies of scale, shift towards recycling, with six out of the top-seven EU countries by waste WTB material displayed in Fig. 6a, the only exception being Portugal (6th by waste material), which currently has a very low landfilling gate fee. On the other hand, the initial value of the landfilling gate fee has a limited effect on the amount of material recycled under conditions introduced by the sensitivity analysis, as smaller countries with high landfilling gate fees, such as Slovenia (160 €/t), Luxembourg (150 €/t), Lithuania (140 €/t), do not generate enough waste material to establish economically viable dedicated recycling facilities even in the + 200 % landfilling gate fee case.

4.3.2. EU PROPOSAL Scenario: EU-wide landfilling gate fee

A single EU-wide landfilling gate fee would imply a harmonisation of rules across EU countries. Considering the variance of EU landfilling gate fees (Supplementary Material S.2), three levels were investigated: 100€/t, 150 €/t, 200€/t (Fig. 6b). Results demonstrate that the share of material recycled across the EU increases to 43 %, 56 % and 77 % respectively, compared to the initial value of 32 % (EU PROPOSAL scenario). Waste materials from multiple countries would enter the recycling route already for a 100€/t EU-wide landfilling gate fee. These would include countries currently having a higher national landfilling gate fee, i.e., Belgium and Luxembourg, which would benefit primarily from the removal of transboundary restrictions, as well as countries having a lower national landfilling gate fee, such as Czech Republic, France and Poland. In these cases, the increase of the landfilling gate fee makes the recycling route more economically attractive, benefitting also smaller countries, differently from the observations made in Section 4.3.1. As the landfill gate fee increases, further countries join the recycling route: 12 countries have part of their waste materials recycled, while 6 countries display a fully circular recycling network for their EoL WTB.

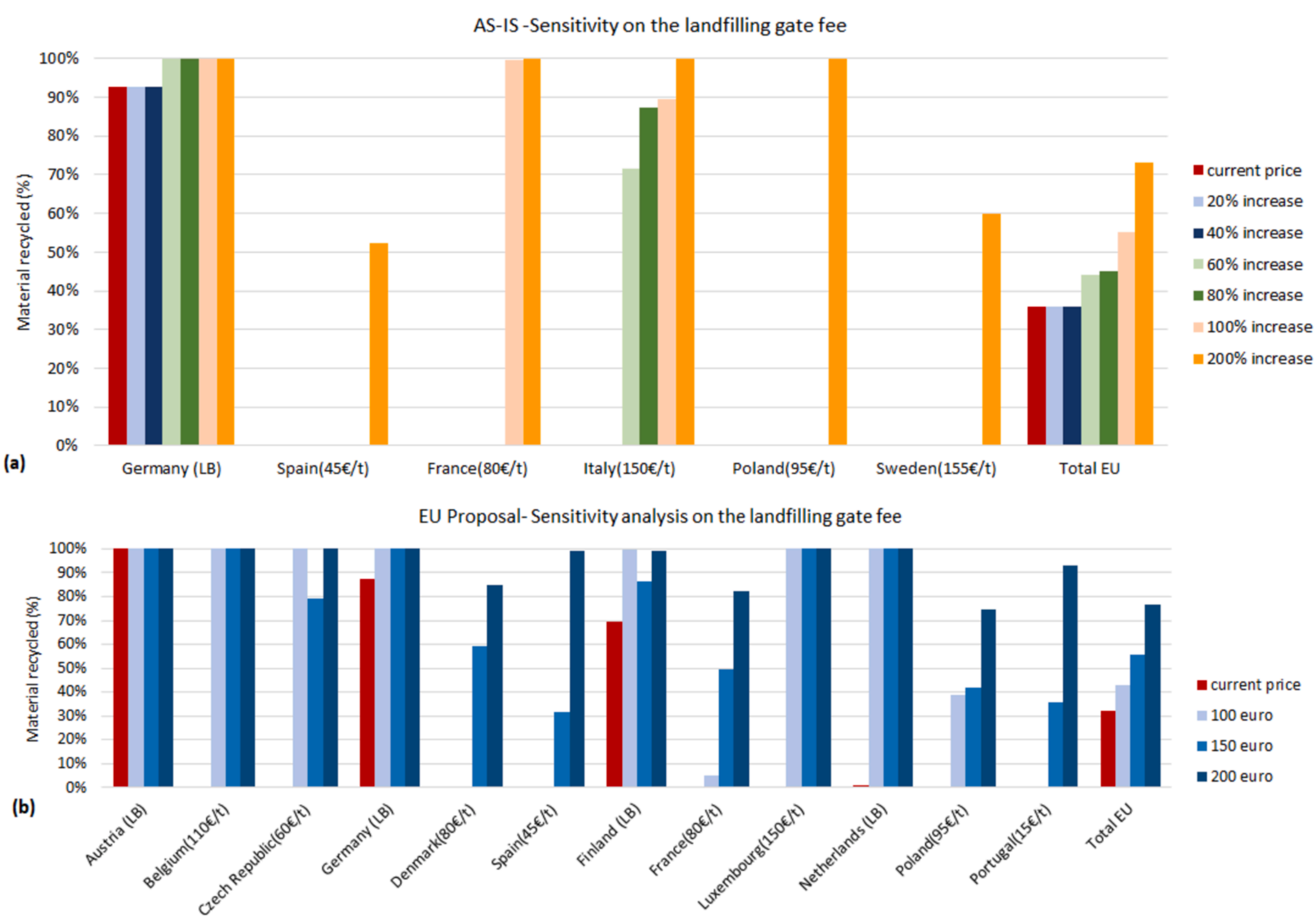

Fig. 6. (a) Country-by-country Landfilling Gate Fee increase impact on the amount of recycled material, (b) EU-wide Landfilling Gate Fee impact on the amount of recycled material.

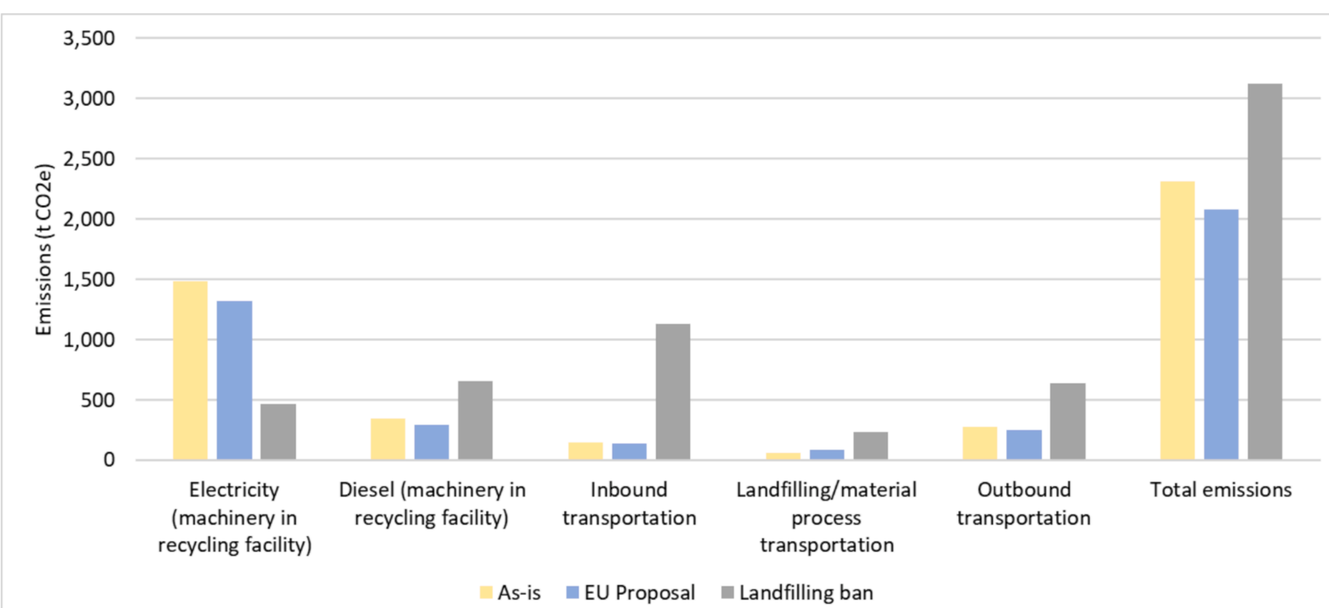

Fig. 7. GHG emissions breakdown by scenario.

4.4. Environmental impact

The environmental impact assessment complemented the analysis by reporting the CO2e emissions (Fig. 7). The EU PROPOSAL scenario displays the absolute lowest CO2e emissions, reducing emissions by over 10 % compared to the AS-IS scenario, thus achieving a win–win situation, as it combines best performing environmental and economic outcomes. On the other hand, the LANDFILLING BAN is ineffective in terms of environmental impacts as the increased inbound transportation requirements to the recycling facilities offset the reduction in CO2e emissions due to electricity – since the recycling facility is located in France, a country with low electricity emissions factor – and generate a + 34 % in total emissions compared to the AS-IS scenario. The WTB waste material is considered inert, and therefore is assumed to produce no emissions in the landfill.

5. Discussion and policy implications

The results, illustrated in Section 4, have implications for policy making, while the work overall has theoretical implications for the waste management, the CE, and the operational research literature.

5.1. Policy implications

Results confirmed that the EU PROPOSAL legislative action, which removes waste transportation barriers for recycling, effectively lowers costs and reduces emissions of optimised circular networks, albeit not drastically reducing them. However, the EU PROPOSAL does not change the share of materials diverted from landfilling, but leads to a more effective reverse supply network structure. Under the legislative proposal, an increased share of materials would take the cement co-processing route, which is more economically attractive compared to mechanical recycling, in line with the findings of Sommer and Walther (2021), albeit less favourable according to the EU Waste Hierarchy. These results highlight a trade-off between environmental and circularity objectives, confirming similar observations by Ghosh et al. (2022) in the US. This trade-off needs to be carefully evaluated by policy makers in future legislative actions to ensure policies are coherent with their intended sustainable development objectives.

On the other hand, a LANDFILLING BAN, while closing the material loop in line with EU policies aimed at increasing circularity, would increase both costs and environmental impacts (in terms of direct emissions from the recycling supply chain), highlighting an environment-circularity trade-off. The cost increase under this scenario is largely due to increased transportation requirements, differently from Ghosh et al. (2022), who found a minimal impact of transportation costs for different pathways of EoL material. This demonstrates that legislative action can trigger significant changes in the circular network structure and dynamics with direct consequences on the economic performance of the CE.

When framing CE policies, policy makers should balance stringent regulations, which define strict limits related to environmental practices (e.g., landfilling ban), with a market-based approach, which can facilitate the competitiveness and the uptake of CE practices, while stimulating CE-oriented innovations. As demonstrated in all scenarios, circular solutions for this particular material stream come at higher costs, ultimately leading to a circular system that is not economically viable unless external incentives are introduced. These could be based on a market-based approach, by progressively increasing the landfill gate fees and taxes. Alternatively, taxes or disincentives could target the use of virgin raw materials to favour recycled ones. As demonstrated in this work, focusing solely on landfill gate fees would require a substantial increase of +100 % to +200 % over current countries' baseline values, or at the levels of 150–200 €/t EU-wide, to lead to a significant shift towards recycling of WTB.

Policy makers could also focus on reducing the costs of the circularity-enabling reverse supply chains, by removing legislative barriers, such as the transboundary restrictions on waste shipments, a low-cost solution that yields easy-to-attain benefits, both economically and environmentally. Policy makers could further remove other existing barriers, such as the limited standardisation of the EU waste reference numbers, which hampers CE practices in multiple sectors, including the wind industry (Beauson et al., 2022). Additionally, based on the findings of this work, more end uses and users for the recycled materials could be identified to reduce the required transportation, which is the key cost element in the fully circular scenario. The end use considered in this work involve replacing a low-cost raw material; higher-value end uses should be identified to boost the revenues of the recycling value chain and improve its economic viability.

Finally, the work informs policy makers on the amount of materials that could be diverted from landfill under different policy scenarios. This information enables to estimate the resources that leave the EU economic system as waste and the resources that would be turned into secondary raw materials through recycling. Increasing the share of materials recycled is an EU policy-objective and can strategically diversify the supplies' sources for the EU industry, replacing imported virgin raw materials (European Commission, 2021a).

5.2. Theoretical implications

The interdisciplinary nature of the work, which exploits operational research-based methodologies to solve real problems at the intersection of waste management, CE, supply chain management and renewable energy, naturally leads to multiple contributions to theory.

The work contributes to the waste management literature by designing optimal circular supply chain networks for the management of waste from decommissioning of wind turbines, which is critical to improve sustainability of renewable energy installations, considering their whole lifecycle. This work expands the existing knowledge on circular supply chains by adding the policy dimension compared to available models, thus considering both waste transboundary regulations and landfilling directives, which can significantly impact the decision-making for EoL wind turbines management.

The work contributes also to the operational research literature by presenting an innovative application of established methods into a new domain, namely the evaluation of the effects of policy developments on the shaping of optimised reverse network architectures. This is achieved by assessing the effects of waste management policies on the economic, environmental and circularity performance of optimised circular networks in the specific case of GFRP originating from wind turbines within the EU.

6. Conclusions

This work aimed to understand the impact of different EU-wide policies and legislative actions on the emergence of circularity-enabling reverse supply chain networks for EoL WTB. Using a purpose-built MILP model, the EU-wide reverse network was optimised to minimise total costs under (i) the AS-IS scenario, (ii) an incumbent scenario enforcing the upcoming EU Proposal 2021/0367 and (iii) a future scenario where an EU-wide LANDFILLING BAN on composite materials is applied. A sensitivity analysis was carried out to investigate how policy instruments, such as increasing landfilling gate fee, could modify the optimal reverse network. Introducing a market-based approach with increasing landfilling gate fees boosts significantly the circularity of EoL WTB, thanks to an increased economic attractiveness of the recycling pathway. Furthermore, results highlight that the EU PROPOSAL scenario displays the lowest costs and emissions, achieving a win–win situation between environmental and economic objectives, albeit with a lower share of material being recycled compared to the AS-IS scenario. The maximum quota of recycled material (73 %) is instead achieved under the LANDFILLING BAN scenario, which displays the highest costs, as the increase of inbound transportation costs (46 % of total costs) outweigh the elimination of landfilling gate fee costs. A trade-off between environmental and circularity objectives was thus highlighted considering the EU PROPOSAL and the LANDFILLING BAN scenarios.

As every piece of research, this study is not immune from limitations. First, this research was conducted within the EU geographical domain and was informed by the EU legislative framework. Therefore, its generalisability to other geographical domains is limited to the mathematical model, which could be adapted to other contexts. Vice versa, the definition of the scenarios would require amendments to consider the local legislative framework to provide informative policy implications. Second, this work focused on intra-EU waste shipments and treats the EU-27 as a closed system. Nonetheless, EU exports 33 million tonnes of waste every year (European Commission, 2021b), however no information is available on the GFRP originated from exported WTB. This work could be extended by including this option to enhance the policy implications concerning extra-EU waste shipments. Third, this study limits the EoL options to mechanical recycling, cement co-processing and landfilling. A single cement co-processing currently operates in the EU (Deeney et al., 2021) and this is unlikely to change in the medium-term due to the investment costs and process modification required by cement factories to be able to accept GFRP (Beauson et al., 2022). Moreover, recycling remains a preferred option from a Waste Hierarchy perspective compared to cement co-processing (WindEurope, 2020). Future research may integrate the construction of further cement co-processing facilities to this study as well as other recycling technologies as they become mature. Fourth, this work estimates the emissions generated along the reverse supply chains, but did not adopt a lifecycle perspective, omitting potential material substitution benefits from replacing virgin with recycled material. Finally, this work only explored existing markets such as BMC and SMC for the recycled material obtained from recycling of WTB. As circular approaches become widespread (Berlin et al., 2022), it is likely that further commercial opportunities arise for recycled glass fibres, potentially leading to a less concentrated final market and a more distributed network structure due to the emergence of additional secondary markets. Similarly, the supplied EoL materials are also expected to increase (Lichtenegger et al., 2020), which could further determine a re-shaping of the circular network. Future research could therefore expand the current work by dynamically exploring the structure of circular networks, considering variations in EoL materials supply and recycled material demand over time, considering sequential capacity decisions over different planning horizons.

This work adopted an EU-wide system perspective to optimise the reverse supply network architecture for WTB and offer directions to policy makers, however the ultimate decision to build recycling facilities will remain within individual organisations, such as waste management and recycling companies, whose utility function will not necessarily be aligned with the overall system's one.

The EU indicated its commitment to move towards sustainability and the CE through policy initiatives. This work provided insights on circular pathways for the EoL WTB waste, while considering the impact of policy scenarios. Building on this information, policy makers may be better equipped to develop policy instruments able to achieve their intended objectives.

CRediT authorship contribution statement

N.L. Trivyza: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Tuni:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **A. Rentizelas:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.11.024.

Data availability

Data will be made available on request.

References

Abdalla, A., Diani, M., 2021. Legislation boundaries and recommendations for policy makers, Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites.

Abeshev, K., Koppenborg, F., 2023. More than just organics: Boosting separate collection of dry recyclables with door-to-door bio-waste collection in EU capitals. Waste Manag. 161, 156–165. https://doi.org/10.1016/j.wasman.2023.02.026.

Andersen, N., Eriksson, O., Hillman, K., Wallhagen, M., 2016. Wind turbines' end-of-life: quantification and characterisation of future waste materials on a national level. Energies 9. https://doi.org/10.3390/en9120999.

Beauson, J., Laurent, A., Rudolph, D.P., Pagh Jensen, J., 2022. The complex end-of-life of wind turbine blades: a review of the European context. Renew. Sustain. Energy Rev. 155. https://doi.org/10.1016/j.rser.2021.111847.

Berlin, D., Feldmann, A., Nuur, C., 2022. Supply network collaborations in a circular economy: A case study of Swedish steel recycling. Resour. Conserv. Recycl. 179, 106112. https://doi.org/10.1016/j.resconrec.2021.106112.

European Commission, 2021a. Proposal for a Regulation on shipments of waste and amending Regulations (EU) No 1257/2013 and (EU) No 2020/1056.

European Commission, 2021b. European Green Deal: New EU rules on waste shipments to support a clean and circular economy. doi: 10.2779/136716.

Cooperman, A., Eberle, A., Lantz, E., 2021. Wind turbine blade material in the United States: quantities, costs, and end-of-life options. Resour. Conserv. Recycl. 168. https://doi.org/10.1016/j.resconrec.2021.105439.

Cousins, D.S., Suzuki, Y., Murray, R.E., Samaniuk, J.R., Stebner, A.P., 2019. Recycling glass fiber thermoplastic composites from wind turbine blades. J. Clean. Prod. 209, 1252–1263. https://doi.org/10.1016/j.jclepro.2018.10.286.

Deeney, P., Nagle, A.J., Gough, F., Lemmertz, H., Delaney, E.L., McKinley, J.M., Graham, C., Leahy, P.G., Dunphy, N.P., Mullally, G., 2021. End-of-Life alternatives for wind turbine blades: sustainability Indices based on the UN sustainable development goals. Resour. Conserv. Recycl. 171. https://doi.org/10.1016/j.resconrec.2021.105642.

Delaney, E.L., McKinley, J.M., Megarry, W., Graham, C., Leahy, P.G., Bank, L.C., Gentry, R., 2021. An integrated geospatial approach for repurposing wind turbine blades. Resour. Conserv. Recycl. 170. https://doi.org/10.1016/j.resconrec.2021.105601.

Derosa, R., Telfeyan, E., Mayes, J.S., 2005. Current state of recycling sheet molding compounds and related materials. J. Thermoplast. Compos. Mater. 18, 219–240. https://doi.org/10.1177/0892705705045006.

Diez-Cañamero, B., Mendoza, J.M.F., 2023. Circular economy performance and carbon footprint of wind turbine blade waste management alternatives. Waste Manag. 164, 94–105. https://doi.org/10.1016/j.wasman.2023.03.041.

Eurostat, 2022. Number and capacity of recovery and disposal facilities by NUTS 2 regions [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/env_wasfac/default/table?lang=en (accessed 10.12.23).

Fonte, R., Xydis, G., 2021. Wind turbine blade recycling: An evaluation of the European market potential for recycled composite materials. J. Environ. Manage. 287. https://doi.org/10.1016/j.jenvman.2021.112269.

Genovese, A., Ponte, B., Cannella, S., Dominguez, R., 2023. Empowering the transition towards a circular economy through empirically-driven research: past, present, and future. Int. J. Prod. Econ. 258. https://doi.org/10.1016/j.ijpe.2022.108765.

Ghosh, T., Hanes, R., Key, A., Walzberg, J., Eberle, A., 2022. The circular economy life cycle assessment and visualization framework: a multistate case study of wind blade circularity in United States. Resour. Conserv. Recycl. 185. https://doi.org/10.1016/j.resconrec.2022.106531.

Heng, H., Meng, F., Mckechnie, J., 2021. Wind turbine blade wastes and the environmental impacts in Canada. Waste Manag. 133, 59–70. https://doi.org/10.1016/j.wasman.2021.07.032.

Jensen, J.P., Skelton, K., 2018. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. Renew. Sustain. Energy Rev. 97, 165–176. https://doi.org/10.1016/j.rser.2018.08.041.

Job, S., 2013. Recycling glass fibre reinforced composites – history and progress. Reinf. Plast. 57, 19–23. https://doi.org/10.1016/S0034-3617(13)70151-6.

Kocabasoglu, C., Prahinski, C., Klassen, R.D., 2007. Linking forward and reverse supply chain investments: The role of business uncertainty. J. Oper. Manag. 25, 1141–1160. https://doi.org/10.1016/j.jom.2007.01.015.

Lichtenegger, G., Rentizelas, A.A., Trivyza, N., Siegl, S., 2020. Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. Waste Manag. 106, 120–131. https://doi.org/10.1016/j.wasman.2020.03.018.

Liu, P., Meng, F., Barlow, C.Y., 2019. Wind turbine blade end-of-life options: An eco-audit comparison. J. Clean. Prod. 212, 1268–1281. https://doi.org/10.1016/j.jclepro.2018.12.043.

Liu, P., Meng, F., Barlow, C.Y., 2022. Wind turbine blade end-of-life options: An economic comparison. Resour. Conserv. Recycl. 180. https://doi.org/10.1016/j.resconrec.2022.106202.

Lund, K.W., Nielsen, M.L., Madsen, E.S., 2023. Sustainability assessment of new technologies using multi criteria decision making: a framework and application in sectioning end-of-life wind turbine blades. Renew. Sustain. Energy Rev. 184. https://doi.org/10.1016/j.rser.2023.113542.

MahmoumGonbadi, A., Genovese, A., Sgalambro, A., 2021. Closed-loop supply chain design for the transition towards a circular economy: A systematic literature review of methods, applications and current gaps. J. Clean. Prod. 323. https://doi.org/10.1016/j.jclepro.2021.129101.

Majewski, P., Florin, N., Jit, J., Stewart, R.A., 2022. End-of-life policy considerations for wind turbine blades. Renew. Sustain. Energy Rev. 164. https://doi.org/10.1016/j.rser.2022.112538.

Mamanpush, S.H., Tabatabaei, A.T., Li, H., Englund, K., 2018. Data on the mechanical properties of recycled wind turbine blade composites. Data Br. 19, 230–235. https://doi.org/10.1016/j.dib.2018.05.008.

Mello, G., Ferreira Dias, M., Robaina, M., 2022. Evaluation of the environmental impacts related to the wind farms end-of-life. Energy Reports 8, 35–40. https://doi.org/10.1016/j.egyr.2022.01.024.

Mendoza, J.M.F., Gallego-Schmid, A., Velenturf, A.P.M., Jensen, P.D., Ibarra, D., 2022. Circular economy business models and technology management strategies in the wind industry: sustainability potential, industrial challenges and opportunities. Renew. Sustain. Energy Rev. 163. https://doi.org/10.1016/j.rser.2022.112523.

European Parliament and Council, 2006. Regulation No 1013/2006 of 14 June 2006 on shipments of waste, Official Journal of the European Union.

European Parliament and Council, 2020a. Regulation (EU) 2020/1056 of the European Parliament and of the Council on electronic freight transport information.

European Parliament and Council, 2020b. Commission Delegated Regulation (EU) 2020/2174, Official Journal of the European Union.

Rani, M., Choudhary, P., Krishnan, V., Zafar, S., 2021. A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. Compos. Part B Eng. 215. https://doi.org/10.1016/j.compositesb.2021.108768.

Rentizelas, A., Trivyza, N., Oswald, S., Siegl, S., 2021. Reverse supply network design for circular economy pathways of wind turbine blades in Europe. Int. J. Prod. Res. 1–20. https://doi.org/10.1080/00207543.2020.1870016.

Sommer, V., Walther, G., 2021. Recycling and recovery infrastructures for glass and carbon fiber reinforced plastic waste from wind energy industry: A European case study. Waste Manag. 121, 265–275. https://doi.org/10.1016/j.wasman.2020.12.021.

Sultan, A.A.M., Mativenga, P.T., Lou, E., 2018. Managing Supply Chain Complexity: Foresight for Wind Turbine Composite Waste, in: Procedia CIRP. The Author(s), pp. 938–943. doi: 10.1016/j.procir.2017.11.027.

Van Engeland, J., Beliën, J., De Boeck, L., De Jaeger, S., 2020. Literature review: Strategic network optimization models in waste reverse supply chains. Omega (united Kingdom) 91. https://doi.org/10.1016/j.omega.2018.12.001.

WindEurope, 2020. Accelerating Wind Turbine Blade Circularity.

WindEurope, 2022. Wind Energy in Europe 2021 Statistics.

Ziegler, L., Gonzalez, E., Rubert, T., Smolka, U., Melero, J.J., 2018. Lifetime extension of onshore wind turbines: a review covering Germany, Spain, Denmark, and the UK. Renew. Sustain. Energy Rev. 82, 1261–1271. https://doi.org/10.1016/j.rser.2017.09.100.