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High-quality recycling through self-learning and resilient recycling networks using a combination of agent-based modelling and life cycle assessment

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Abstract. Especially in the case of long-lived products, the crucial questions about the proper implementation and assurance of high-quality recycling targets often only arise after decades. Furthermore, information about material composition is often not sufficiently known and communicated to the end user. With the presented extended socio-technical approach of a self-learning and resilient recycling network, which should include manufacturers and operators of wind farms, dismantlers, waste processors and recyclers, as well as authorities and players from research and development, such problems can be adequately addressed. On the one hand, this requires knowledge tools to ensure a high-quality material cycle, such as databases in which installed products and their characteristic values for the masses and materials used are documented. In addition, material flow modeling to track material flows generated for the end-of-life (EoL) of products including life cycle assessments of recycling and disposal routes, as well as forecasting tools for expected waste volumes are needed. On the other hand, a simulation tool such as agent-based modeling (ABM) is also needed to map courses of action and their impacts, taking into account stakeholders' interests in terms of target formulation of the recycling network. The example of wind turbine rotor blades is used to show how such an approach can be used for a meaningful recycling network, which supports the operator responsibility of wind farms as well as the extended producer responsibility of wind turbines with regard to sustainable recycling of long-lived products. The developed tools and especially their active combination are presented. In addition, the example of rotor blades is used to present the concrete possibilities for resource-saving control of the material flows.

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1 Model description

Our approach to a self-learning and resilient recycling network includes four key areas:

- Identification of relevant actors in the process chains and their roles, influence, responsibilities and interactions.
- Inventory of the recycling system with quantitative data, material qualities and recycling technologies.
- Definition of indicators for recyclability, circularity and recovery rates.
- Design of the recycling network with focus on self-learning and resilience.

As a first step, we developed knowledge tools to ensure a high-quality material cycle, such as databases in which installed products and their characteristic values for the masses and materials used are documented, material flow modeling to track material flows generated for the end-of-life (EoL) of products including life cycle assessments (LCAs) of recycling and disposal routes, as well as forecasting tools for expected waste volumes [1].

Figure 1 shows the tools developed and how they interact with each other.

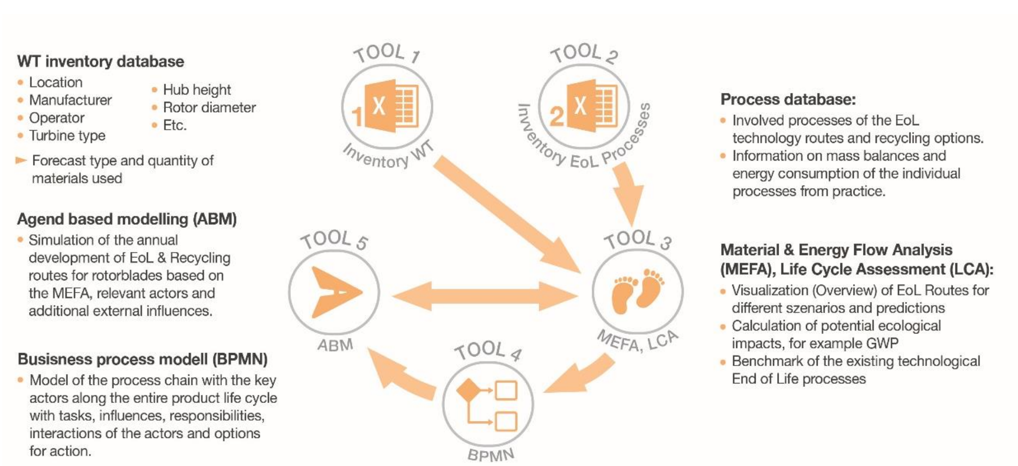

Figure 1: Toolkit and interactions for a resilient recycling network, (WT = Wind turbine)

Inventory and process data from Tools 1 and 2 form the basis for the calculation of environmental impacts and the material flow analyses in Tool 3. The LCA data and the business process information from Tool 4 form the basis for the agent-based model (Tool 5) to perform simulations considering other relevant sociotechnical aspects of a recycling network.

Agent-based modeling broadens the spectrum for simulating natural and sociotechnical systems, especially in the early stages of developing new systems or technical innovations [2]. The agent-based modeling software NetLogo [3] was used to model complex systems that evolve over time. Modelers can give instructions to many "agents" that operate

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independently. This allows exploration of the relationships and interactions between micro-level behavior and macro-level patterns that result from their interaction [4]. Possible evolutions of individual system components and also of the overall system can be calculated under defined conditions. The results should ultimately show how a system adapts to new conditions and how it responds to change (resistance).

2 Results of recycling paths

Figure 2 shows the projected quantities of EoL rotor blade masses for the onshore sector in Germany for the year 2036 with the expected recycling paths based on the state of the art and the market in 2020. The carbon reinforced plastic (CRP) portion is treated via pyrolysis to extract the carbon fibers. The glass fiber reinforced plastic (GRP) portion is energetically and partly material recycled in a cement plant. Complete material recycling is another potential route, such as using GRP in mineral plastic composite (MPC)-planks, paving stones or as furniture.

For the individual recycling paths, the processes were mapped using the information from Tool 2. Based on process data, screening LCAs were conducted to determine the global warming potential (GWP) and to compare the potential impacts of the respective recycling options. The screening LCAs are referring to ISO 14040/44 and DIN EN 15804 and were carried out with the GaBi-software [5-8]. The EC-JRC [9] characterisation factors for global warming potential mentioned in the DIN EN 15804 [7], based on the IPCC, were used.

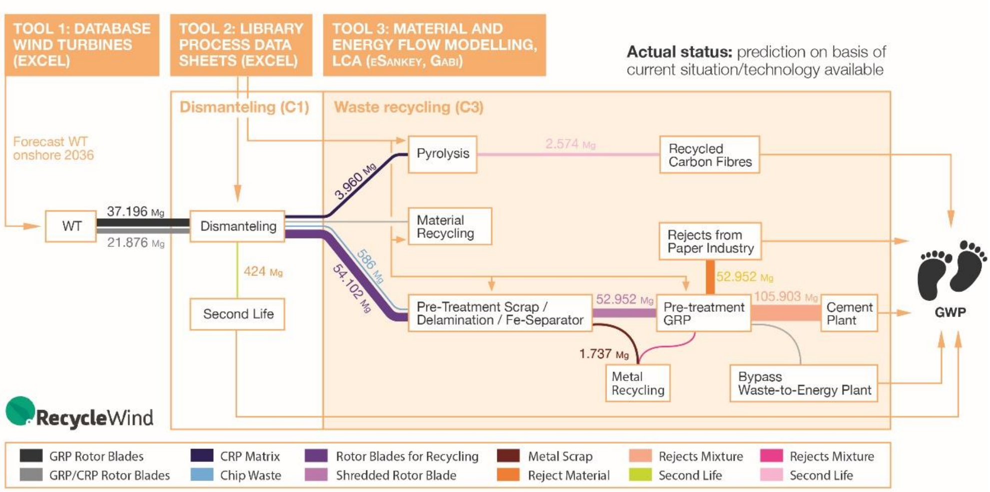

Figure 2: Sankey diagram of the deconstruction and recycling of a wind turbine (WT) in 2036 based on technology and market in 2020

The interaction of tools 1 to 3 already allows a good mapping and evaluation of current EoL-recycling routes for rotor blades. Recycling routes according to the state of the art were identified and industry data for these routes collected. For example, in the current revision of the LCAs for wind turbines in Germany [10], based on literature data, only energy recovery in a waste incineration plant was considered as a recycling route for rotor blades at EoL. However, our own surveys have shown that this no longer reflects the market situation.

Figure 3 shows the LCA-result of the cement path using the example of 1-2 MW wind turbines. Basis for the consideration of the material flows and the associated substitutions through the use of rotor blade materials in the cement plant were our trend analyses on the composition of rotor blades of this power class. Currently, the use of secondary materials in cement plants is around 65% [11] in relation to the demand for energy carriers. The remaining 35% are still covered by fossil fuels. Therefore, to calculate the credits from substitution of fossil fuels in the co-combustion of rotor blades in the cement plant, the substitution of fossil primary fuels (74% lignite, 26% hard coal) [11] was assumed. In addition, disposal in a waste incineration plant was presented for comparison. Here, the thermal energy generated was credited with energy from natural gas and the electricity generated as a result was credited with the European electricity mix.

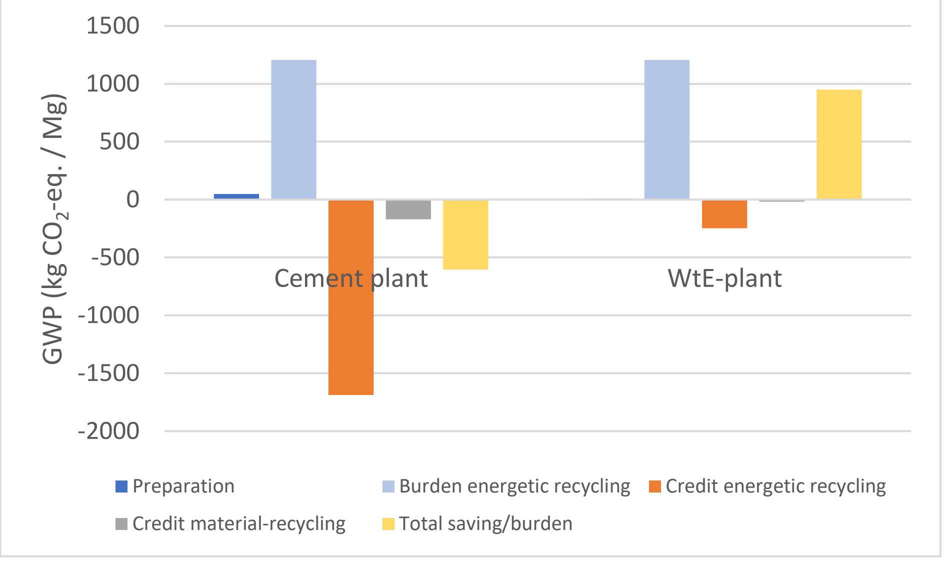

Figure 3: Global warming potential (GWP) of two different disposal routes of glass fiber reinforced plastic (GRP)-rotor blades from wind turbines.

The GWP for preparing the GRP-rotor blades for further treatment, i.e. shredding, is low in both cases. The credit for energy recycling in the cement plant is -1688 kg CO_2-eq./Mg GRP-rotor blade. In the waste incineration plant, on the other hand, there is only a credit of -248 kg CO_2-eq./Mg GRP-rotor blade. There are two reasons for this difference: In the waste-to-energy plant, electricity is usually generated in addition to heat and electricity generation has a lower efficiency than direct heat use. Secondly, the electricity mix also includes renewable energy sources that reduce the credit.

Another advantage of recycling in the cement plant is the material use of the glass fibers as a substitute for sand, limestone and kaolin. This is reflected in a credit of -170 kg CO_2-eq./Mg GRP-rotor blade. In the waste incineration plant, the glass fiber can partially hinder the combustion process. However, 60 % of the resulting slag, which also contains the glass fibers, can be used as a substitute for gravel in road construction [12]. This results in a credit of -17 kg CO_2-eq./Mg GRP-rotor blade. This is only 1/10 of the material credit in the cement plant.

In a cement plant, a total of 603 kg CO_2-eq./Mg GRP-rotor blade is avoided by using GRP-rotor blades compared to conventional fuel. However, incineration in a waste-to-energy plant results in a load of 948 kg CO_2-eq./Mg GRP-rotor blade. The recycling of GRP-rotor blades in a cement plant can thus be classified as ecologically more advantageous in terms of global warming compared to a waste incineration plant. However, this is only a snapshot, as processing and recycling routes can also change. Therefore, it is important to consider possible changes in business processes (Tool 4). For this purpose, the tasks, influences, responsibilities and interactions of the various actors were acquired and presented in process chains (shown in more detail in [1]).

3 Interim status of agent-based model

Based on the analyses of business processes (Tool 4) all relevant actors such as wind turbine manufactures, operators and recyclers are included in the agent-based model. Specific characteristics were assigned to the actors and divided into groups. The manufacturers are divided into groups which have different characteristics in terms of openness and innovation capacity and thus have an impact on the notional market price. The operators are divided into four group types (small + conventional, small + ecological, large + conventional, large + ecological), which have different characteristics in terms of willingness to pay. However, a relatively higher willingness to pay is always associated with the possibility of high-quality recycling. The willingness to pay in the customer group is also different. Customers with a high demand for material recovery (high-quality recycling) can be assigned a higher willingness to pay than conventional customers. The influence of the government as a research promoter of (new) technologies is integrated into the model through a price reduction potential of the respective technology.

On the recycler level, the different analyzed technology types (on the market or in development) for recycling rotor blades (GRP, CRP) as well as their technical properties, possible business models for the respective markets and recycling capacities are integrated as objects into the model. The technology development is considered by a cost degression through learning curve effects. In addition, the influence of a fictitious CO_2 price calculated from the LCA data as well as the CO_2 price development on the system can be investigated.

We have multiple agents at each of the different levels of the value chain interacting through the corresponding arrows. In the simulation, the evolution of the prices, recycling market, recycling quantity, recycling production and recycling quality can be calculated using annual steps for different scenarios. The allocation of recycling quantities is based on the willingness to pay of each customer group calculated in the program. The customer with the highest willingness to pay is determined and orders the technology whose recycling products are offered at this price. Then the next lowest willingness to pay is allocated until all available quantities have been distributed.

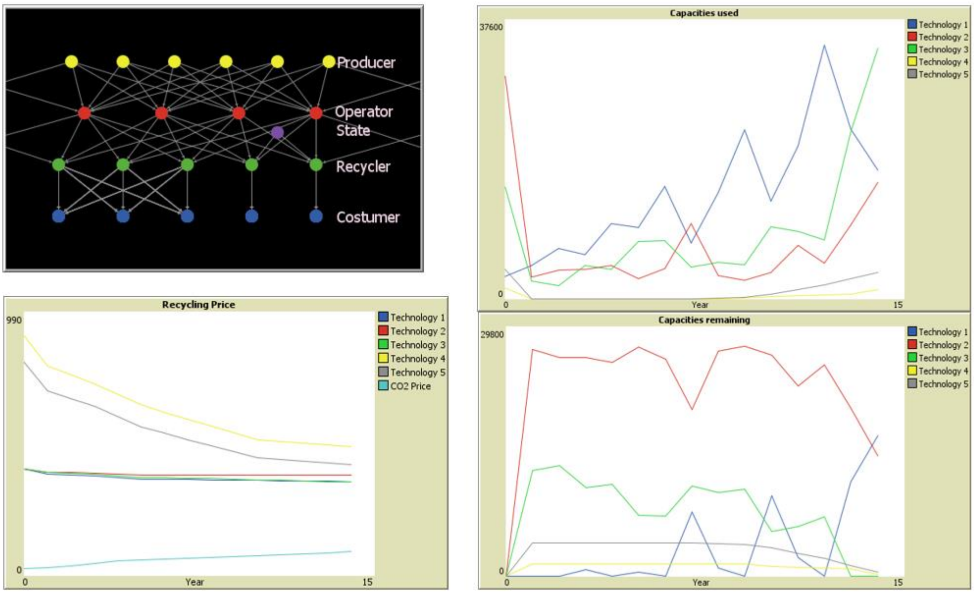

Figure 4: Scenario: Slightly differentiated price development over time (illustrations from the dashboard in NetLogo [3])

A current short work example is the scenario shown in Fig. 4. On the left can be seen the network structure and that the recycling prices of the two initially more expensive technologies (pyrolysis, solvolysis) converge over time with others due to learning curve effects and government support. In contrast, the prices of the other three technology paths differ only slightly. The right-hand side shows the capacity utilization and the volume distribution across the individual technology paths, with the total market volume expected to increase sharply in the next 15 years. The technologies have different capacities at the present time. The slight price differentiation leads to technology 1 in particular building up further capacities (the blue line touches the x-axis) and thus gaining further market shares. From the ninth year onwards, the price development of technologies 4 and 5 has progressed to such an extent that they are also taken into account when allocating the market volume for their rather higher-priced niche markets.

Currently, this connection between price development, willingness to pay and recycling capacities is being investigated in more detail in further scenarios.

4 Conclusions

Through the interaction of these different tools, we see the following benefits for the self-learning and resilient recycling network. The different technical, ecological and socio-economic tools and their interaction increase the overall understanding of network actors about interrelationships in recycling and promote the acceptance of the goal of high-quality recycling of wind turbines (e.g. rotor blades). All of the important influencing parameters (eco-performance, demand fluctuations, willingness to pay, innovation capacity, technological developments) can be dynamically analyzed and simulated in the network model when the framework conditions change (e.g. circular economy). Mapping the options for action and their effects, taking into account the interests of all relevant actors in relation to the target formulation of the recycling network, is facilitated.

Impulses for further development of the network, e.g. through new recycling technologies, can be easily integrated. New solution spaces and ideas for innovations are enabled, providing impulses for further optimization of the self-learning and resilient recycling network.

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