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PROOF OF CONCEPT – USING PROSPECTIVE HYBRID MFA-LCA TO EVALUATE THE ENVIRONMENTAL IMPLICATIONS OF CIRCULAR ECONOMY USING A CASE STUDY OF WOOD

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Abstract. Consistent evaluations of impacts induced by implementation of Circular Economy (CE) design processes and solutions within the built environment, necessitates decision-support tool development/advancement, as CE does not allow for business-as-usual assessments only. A preliminary test of concept that seeks to quantify the environmental implications of CE on a case study of wood, is presented here.

The core methodology is based on coupling of the Shared Socioeconomic Pathways (SSPs) with Material Flow Analysis (MFA) and consequential Life Cycle Assessment (cLCA). Applying this novel approach, a prospective consequential hybrid MFA-LCA analysis was initiated, to evaluate the mitigation challenges of CE design processes, through different formalized and generally accepted (i.e. consensus) scenarios.

The case study is based on Danish reference buildings, meeting the current building regulations, designed to replace conventional building materials with wood. This “wood-approach” for test of concept case study, is chosen due to the increasing interest in wood construction.

The development and calibration of a prospective model for different building material consumptions will further illuminate the connection between the to-be generated emissions and the marginal productions of the materials in question, under specific sets of societal development scenarios.

Keywords: Hybrid MFA-LCA, Consequential LCA, Circular Economy, Shared Socioeconomic Pathways (SSPs).

1. Introduction

Realistic future scenarios are needed to create robust policies for the future, and when investigating CE benefits and implications. CE research is mainly focused on obtainable benefits for the biosphere and technosphere, neglecting equally important societal aspects. New methods are required, to address different possible future socioeconomic trajectories. The process of addressing the operating space for humanity needs to be based on concrete assumptions on how different future scenarios are developed, corresponding to different mitigation and adaptation challenges. To forecast different pathway variations under certain socioeconomic paradigms and include these assumptions in the evaluation of the environmental impacts of CE solutions, a methodology is proposed, coupling various existing methods.

The scenario/assessment framework is based on the most recent development within climate modelling, the Shared Socioeconomic Pathways (SSPs) framework, extended with dynamic Material Flow Analysis (MFA) and dynamic consequential Life Cycle Assessment (cLCA). This combination, allows for prospective consequential hybrid MFA-LCA, addressing societal challenges and changes along different future pathways, by quantifying material stocks and evaluating the consequences of such changes, by calculating the environmental implications of CE implementation processes. See a schematic overview in Figure 1.

While the individual methods used in this paper are well known and applied in their respective established line of research, the coupling of them, is only found in isolated parts of the literature, e.g. [1], but mostly only as partial couplings.

The SSPs are gaining traction, considering prospective aspects of scenario development, possibly as they have also been used in the IPCC 6th Assessment Report [2]. They have, however, also been used in the literature to assess e.g. the CO_2 emissions of global cement production [3], Tokyo’s building sector emissions [4] and investigating the impact of material efficiency on climate mitigation [5], all under a socio-economic perspective.

In this study, we investigate how the SSP framework can be used to express different future pathways, presented through a case study on woody biomass, and thus contribute to the increasing pool of evidence and perspectives, for further prospective environmental implications quantification, when subjected to competing supply demands. The increasing focus on wood for energy and construction purposes allows to create

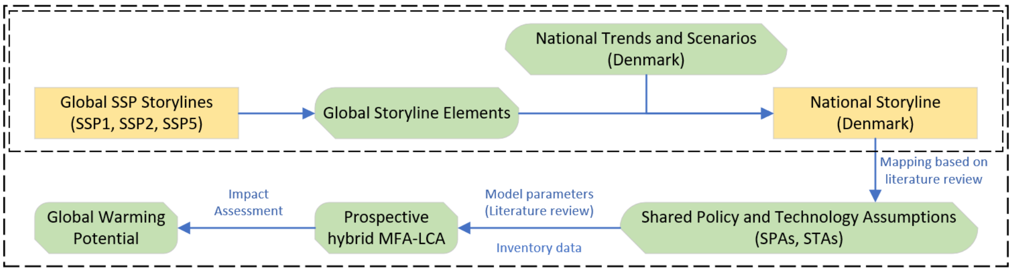

Figure 1. Schematic overview of applied methods. 1) Global SSP narratives are downscaled to national storyline elements, using national trends and scenarios, 2) Shared Policy and Technology Assumptions (SPAs, STAs) are created based on literature. Together with model assumptions, the inventory data for the hybrid MFA-LCA is created, 3) Calculations of the model estimates possible future impacts of different environmental indicators.

a case study with multiple potential pathways. The case study applied is thus used to illustrate a way to construct future scenarios for decision making, rather than to showcase a result for decision support.

1.1. Case study

Denmark has set a target of lowering GHG national emissions by 70 % compared to 1990 levels [6], and aims to phase out coal by 2030 [7], leaving biomass as the largest renewable energy source [8]. Additionally, there is a strong focus on shifting from conventional to wooden structures in Denmark. These competing wood applications are based on different political agendas, as well as future societal developments, e.g., the fact that wood has the ability to be reused/recycled more under different cascading options, implying that wood can potentially contribute to resource efficiency for both the energy and construction industry, using it according to the waste hierarchy.

2. Theory and proceeding methods

2.1. Theory

Scientists use climate models to understand how Greenhouse Gases (GHGs) and aerosols interact with Earth's climate system, and forecast possible changes [9]. By implementing socio-economic, technological, energy and land-use changes as input variables, climate models can be used to create socio-economic dependent emission scenarios and allow for further examination of future climate impacts and mitigation strategies under various societal paradigms [10].

In the need for a common and consistent set of updated and more detailed future scenarios, investigating the impact of different climate policies, that take into account basic elements of demographic and economic drivers, as well as developments in energy demand, land-use and air pollutants, based on different narratives for the future [11], the so-called SSP framework was created.

The SSP framework consists of five different narratives, one for each SSP, and every narrative expresses a different pathway based on future socioeconomic trends. The five narratives are expressed as: a world of sustainability (SSP1), business-as-usual (SSP2), a nationalist oriented world (SSP3), a world where societies suffer from increasing inequality (SSP4) and a future of increased economic growth and intensive energy use (SSP5) [12].

All scenarios include assumptions regarding climate policies and future technological developments, so-called Shared Policy Assumptions (SPAs) and Shared Technology Assumptions (STAs). SPAs are designed by considering mitigation challenges and expected impact of the mitigation policy of each narrative, along with flexibility given to the modelers to implement their own policy interventions [12].

2.2. Scenario Modelling

This section presents the general methodology and logic behind each step, and then exemplifies application, onto the case study. The exemplification addresses the SSP2 (business-as-usual) narrative, the SSP1 pathway (as a more sustainable future), and SSP5 (taking the highway) as an energy intensive future. This should illustrate the effect of increased wood consumption under different futures.

2.2.1. National SSP Narratives and scenario set-up

The global SSP narratives, as found in Riahi et al. [12], are adapted into national narratives. Quantitative documentation of the SSP elements such as population, urbanization and energy projections, is available in the International Institute for Applied Systems Analysis (IIASA) SSP Database [13], at global and national scale. The qualitative assumptions for all SSP scenarios can be seen in Table 1.

The population projections in SSP2 and SSP1 are in line with the global narratives, however SSP5 population projections diverge, due to high-tech and high-living standards, resulting in a higher growth rate. This deviation is based on the expectation on rich Organization for Economic Co-operation and Development (OECD) countries [14]. Education is a key element that can influence people's environmental awareness, leading to a change of consumption patterns and lifestyle [14], e.g., live in smaller houses in order to decrease material and energy consumption. Environmental awareness in SSP1 and SSP5 is

	Population growth	Environmental awareness	Energy demand	Fossil fuel development	Renewable's development	Recycling rates
SSP1	Moderate	Very high	Low	Low	High	High
SSP2	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
SSP5	High	High	High	High	Moderate	High

TABLE 1. Qualitative assumptions for national storylines, based on global narratives and national policies.

SPAs/STAS	SSP1	SSP2	SSP5
Biomass Energy	Phased out	Phased out	Moderate
Timber construction skills	Very high	Moderate	High
Building components' service life	Moderate	No progress	Moderate
Wood cascading	High	No progress	Moderate-high
Waste Treatment of building materials (EoL)	High	Moderate	High

TABLE 2. Shared Policy Assumptions (SPAs) and Shared Technology Assumptions (STAs) included in the model based on national policies.

considered high, however the SSP2 storyline follows historical patterns.

Denmark's future energy system is in line with the global political narratives. Thus, the SSP1 pathway is characterized by a relatively low energy demand, and very restrictive national environmental policies with high taxes on fossil fuels, to keep the mitigation challenges low. These policies create constrains on fossil fuel use, which leads to a rapid improvement of conversion technologies on biomass and other renewable sources. Oppositely, SSP5 represents an energy intensive and fossil fuel dependent future, with low fossil fuel prices and energy taxes. SSP2 represents an intermediate world.

Lastly, in line with core paradigms of the individual pathways, we assume that both SSP1 and SSP5 scenarios will have higher recycling rates and more sustainable material use of construction materials, than SSP2 scenarios.

2.2.2. National Shared Policy Assumptions and Shared Technology Assumptions

The SSP framework allows modelers to implement their own assumptions regarding climate change policies, as well as future sectoral trends and technological developments, while the SPAs consider e.g., national legislation, the STAs are considering future trends. The SPAs and STAs included in the case study model can be seen in Table 2.

The case study is focused on the increased wood consumption in two main sectors: construction and energy, thus the SPAs and STAs concerns questions regarding timber construction skills, cascading etc.

To ensure that woody biomass is used in sustainable manner for the production of electricity and heat, Danish political parties came to an agreement to set legal requirements on biomass applications [15]. This political decision was used for the SPAs in the case study. In SSP1 and SSP2, wood used as biomass for energy is phased out by the end of the century. In a sustainable scenario (i.e., SSP1) this policy is assumed to become very strict, leading to rapid change on how woody biomass is used. For SSP2 scenarios, we assume this policy agreement leads to a decrease of wood for energy at a slower rate than for SSP1, until wood is finally phased out. For SSP5, we assumed that the policy agreement is not strict enough, hence biomass follows the trend of the projected global SSP narrative. There are no current policies in Denmark to specify how wood should / or shouldn't be used in construction.

STAs implemented in the case study are targeted future trends in the building sector; ways that wood could help decarbonize the built environment, alternative wood cascading options, as well as optimal End-of-Life (EoL) treatment options of construction materials. The assumptions are distinguished in civil engineering skills, increased expertise of wood construction and increased future service life (durability) of building components.

2.3. Coupling forecasting with MFA-LCA

The demanded wood stock for construction and energy is quantified by coupling the above forecasted storylines with time dependent MFA-determined inventory, from 2020 until 2100, and then with cLCA.

The case study can be examined for every different SSP scenario, to express different future mitigation and adaptation challenges of CE of wood. The inputs are construction materials like concrete, bricks, steel, and wood which enter the system (inputs), and based on the scenario specific narratives, and the SPAs and STAs, one can calculate the forecasted CO_2 emissions and waste streams (output). Every SSP runs a certain set of parameters, concluding on different results, that help understand the potential under the CE concept. The sections below are purely illustrated through the case study.

Variable	Assumption
Average persons per dwelling (av.per.dw.)	SSP1av.per.dw. > SSP5av.per.dw. > SSP2av.per.dw.
Share of wood structures (wood.str.)	SSP1wood.str. > SSP5wood.str. > SSP2wood.str.
Share of conventional structures (conv.str.)	SSP2conv.str. > SSP5conv.str. > SSP1conv.str.
Service life of building components	SSP1life (+20 %) > SSP5life (+10 %) > SSP2life
Recovered Wood, class A+	SSP1A+ (25 %) > SSP5A+ (15 %) > SSP2A+
Recovered Wood, class A	SSP1A (25 %) > SSP5A (15 %) > SSP2A
Recovered Wood, class B	SSP1B (25 %) > SSP5B (15 %) > SSP2B
Recovered Wood, class C	SSP1C (25 %) > SSP5C (15 %) > SSP2C
Recovered Wood, class D	SSP2D > SSP5D >SSP1D

Table 3. Variables included in the model and the associated assumptions of the MFA model.

2.3.1. Building Stock Modeling

To estimate future building stock, the quantity of materials needed for construction purposes in Denmark, until 2100, must be identified. The assumptions are shown, qualitatively, in Table 3.

The reference buildings used in our study are based on competitive conventional and timber structure design, to illustrate the difference in material consumption [16]. The Bill of Materials (BoM) used, provide material quantities of the different archetypes, which are aggregated into material groupings and then projected to national level. The included archetypes are distinguished in detached (single-family) houses, semi-detached houses and multi-dwelling houses. In Denmark, the proportion of constructed buildings from 2009 to 2019 was mainly one to five floors, representing about 82 % of the total gross area [17]. Assuming this trend will remain constant for the period 2020 to 2100, the archetypes account for 82 % of the future building stock.

By using national housing statistics, the future building stock is extrapolated. The variables include the projections on number of people as indicated in the SSP Database [13], and the country's "share of residents per dwelling" statistics [18], which is assumed to remain constant in the future. The number of "average persons per dwelling" is estimated for each SSP in order to calculate the "total amount of buildings". To calculate the total amount of wood used to construct the "total amount of buildings", the share of wood and conventional structures (concrete/steel/bricks) is estimated.

The wood needed to renovate all new constructions, is based on the amount of people under each SSP, extrapolated consistently until 2100. The second variable used to model renovation of the future building stock is "service life of building components". In SSP2 the building service life is assumed business-as-usual, in SSP1 to last longer and in SSP5 assumed longer than SSP2 but still less than SSP1. By assuming different service lives per building component, the total amount of wood needed to renovate the new construction can be estimated, by creating renovation steps based on the service life of each wood building component.

Wood needed for renovation, is based on the existing building stock, documented by national statistics [19]. The same way as used in renovating new construction, the building components and their current service life are modelled, and the demand for wood is calculated by creating renovation steps based on the service life of each building component made of wood, excluding structural components. The renovation of the existing building stock does not relate to any applied assumptions, and it is thus modelled the same way for all SSPs, since wood supply is assumed to satisfy the demand for renovation of existing building stock first.

EoL is modelled for both wood products and the other construction materials. To account for substitution potential of using wood instead of other building materials, the potential applications, and mass flows, of wood recovered from construction and demolition waste (C&DW) were examined. Wood is classified into different cascading classes (A+, A, B, C, D) based on the size and the condition of what is recovered from C&DW, as presented in a Finish study [20]. SSP1 and SSP5 take advantage of these potential flows, however SSP2 is modelled based on current share. Shares for reuse of concrete and bricks, and recycling of remaining building materials [21, 22] are assumed for each SSP.

2.3.2. Energy consumption projections

Energy consumption is projected by extrapolating current energy sector until 2030, when coal is predicted to be phased out. In 2030, it is expected that biomass energy still plays an important part in the Danish energy system [23]. Three different scenarios were created to model biomass energy. For SSP1 it is assumed that biomass will follow the same decreasing trend as coal, after 2030, and eventually be phased out. In SSP2, biomass energy after 2030 follows coal's current annual decrease rate. SSP5 scenarios are modelled by implementing the annual energy demand growth as

Exemplary key findings, across projected future development pathways	**SSP1, Baseline**	**SSP2, Baseline**	**SSP5, Baseline**
Total Energy related emissions (million metric tons CO_2eq)	2.574	3.393	8.448
Tot. Construc. related emissions (million metric tons CO_2eq)	4.665	6.755	15.748
Per capita annual construction related emissions in period 2020–2100, for DK (kg CO_2eq/capita/yr)	6.05	9.32	11.1
Wood biomass for energy and construc. (million metric tons)	86.43	126.09	291.02
Potential avoided emissions from increased wood in construction (decrease in CO_2eq emissions)	-17.50 %	-10.78 %	-15.88 %

TABLE 4. Exemplary findings from applying the different future narratives, to the case study. The case study is executed on country level.

addressed in the SSP Database, resulting in biomass energy still existing. All remaining energy sources (oil, wind, solar, natural gas, hydro, geothermal, biogas, heat) have a reference year 2030, and follow the annual growth rates, as obtained from the SSP Database.

Biomass energy production includes many different sources, but we focus only on woody biomass, thus the sources included in our model are wood chips, wood pellets and firewood. Waste wood is excluded from the model because it is assumed that this fraction includes the waste wood in C&DW, which will be calculated in the EoL, while wood waste from other sources, such as households is assumed very low, thus excluded. It is assumed that the share of each stream used to produce biomass energy is the same in the future as it is in 2019. Parameters relating to production and imports of biomass energy, and the respective calorific values are obtained from national energy statistics [24]. Since emissions from trading wood occur to the country of origin [25], import quantities are excluded from the model, to account only for the fraction of woody biomass produced in Denmark.

2.3.3. LIFE CYCLE ASSESSMENT

The MFA is based on a variety of parameters and assumptions that investigate the consequences of a change in demand of wood for energy and construction purposes, under different futures. Thus, by choosing the cLCA approach, the model inherently has the ability to account for when marginal suppliers change their production capacity in response to an increased wood demand.

The functional unit is defined as: "The accumulative amount of kilos of building materials per square meter of floor area (kg/m^2) for Denmark in 2100". The model excludes the operational phase, but considers "Benefits and loads beyond system boundary", calculating credits and drawbacks from CE implementations. The model is dependent on the future scenarios for Denmark, under the SSP framework.

The modelling was made by using openLCA 1.10.3 [26], the database used is Ecoinvent 3.7 [27] and the impact assessment used is ReCiPe Midpoint (H) V1.13 [28].

2.3.4. SUBSTITUTION POTENTIAL

The quantified wood stock assumes a trend in the future for more wooden structures. By running a baseline scenario, assuming that there will be no increase on wooden structures for all SSP scenarios, and by comparing the results with those obtained from the scenarios derived though the above MFA calculation, we can identify differences in material quantities used. Class D quantities from C&DW, are used for energy recovery. The energy from wood combustion of a given year, will substitute the marginal fossil fuel energy source (oil or gas) in the same year, for all SSP scenarios.

3. RESULTS AND DISCUSSION

Coupling the SSP framework with MFA and LCA, provides the opportunity to model prospective wood chain in Denmark. Selected scenarios represent different narratives of extreme changes towards sustainability (SSP1), intensive energy dependency (SSP5), and development based in historical developments (SSP2). In the absence of strong policies, SSP2 is the future that society will most likely move towards. To enhance the comparison between the different narratives, we demonstrate some findings of the case study pathways in Table 4, which highlight how the presented approach can evaluate the complex interconnected systems that CE concept touches upon.

The outcome of cases assessed with the method can provide insight for political decisions associated. In context of the case study, it could further help establish an overview for the future framework and development of forest-sector based industries and wood trade for Denmark. Exploring ways to meet modelled demands, underlines that wood is a limited resource. Hence, forest plantation strategies could include measures for forest management, to optimize balance between afforestation/deforestation and wood harvesting, and set regulatory agendas, e.g., restricting the amount of primary wood used for fuel.

4. Conclusion

In this study, we investigate how the SSP framework can be used to express different future pathways, and thus set the foundation for further prospective sustainability performance quantification, when subjected to e.g. competing supply demands. The case study applied is used to illustrate a way to construct future scenarios for decision making at policy level, rather than to showcase a result for decision support. The suggested coupling methodology is an investigative approach to assess sustainability potential under different future pathways, for the applied case study it is wood used in Denmark, achieved by coupling climate modelling with environmental engineering methodologies. By applying this concept, upstream supply chain activities and hotspots with considerable environmental implications are identified (by forecasting the substitution potential of the building materials), but also crucial societal parameters that will contribute to set future policies to keep the world temperature from rising.

The proof of concept and method presented, carries limitations and implications. It requires careful parameterization and supporting peer-reviewed literature to limit uncertainties and excess opinionated model parameterization, when downscaling to national storylines. Also, by adding more socioeconomic elements in the model, e.g., GDP or urbanization, the results may diverge. Future development should be on establishing more robust scenario projections.

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Supplementary materials

Information on applied LCA model and LCI can be obtained by contacting the corresponding author.

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