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The CO_2NSTRUCT European project: Modelling the role of Circular Economy in construction value chains for a carbon-neutral Europe

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Abstract. Linear climate mitigation models look into aggregated economic sectors and model greenhouse gas (GHG) emissions disregarding downstream value chains, making particular sectors accountable for downstream (or upstream) GHG emissions. Hence, the present climate mitigation models inconsistently account for indirect GHG emissions; underrepresent upstream and downstream value chains; do not address Circular Economy (CE) practices; do not cover resource consumption, thus not considering materials' circularity. To provide curated policy support for decision-making for carbon neutrality and other Sustainable Development Goals (SDGs), models need to shift from linear to circular. To achieve this, a link between energy-climate mitigation modelling and cradle-to-cradle assessment CE analytical tools must be established. This is the core issue covered in the CO_2NSTRUCT Horizon project (2022-2026). CO_2NSTRUCT proposes a framework to supplement the well-established JRC-EU-TIMES model, using a highly comprehensive technological representation with CE measures. The framework will apply CE measures to the value chain of six carbon-intensive construction materials (i.e., cement, steel, brick, glass, wood, and insulation materials) and will provide new components to the JRC-EU-TIMES model, including citizen behaviour; societal impacts; rebound effects; supply and value chains. The results will be used for policy approaches integrating CE into climate change mitigation actions.

1. Introduction

Climate mitigation models are most suitable for representing linear patterns of economic activity. Greenhouse gas (GHG) emissions are modelled per economic sector (resource extraction, industry, energy production, final energy use, etc.) without considering downstream value chains. This means that, for example, for the cement sector, GHG emissions associated with cement production are seen by climate mitigation models as the sole responsibility of the cement industry. Upstream and downstream value chains are poorly represented, indirect GHG emissions are seldom included, and extending product lifetime, sharing models, and feedback loops - common to circular economy (CE) measures - are not considered. Increased resource use for climate mitigation, whether from the EU or the rest of the world, is not addressed. Thus, current climate mitigation models cannot account for materials' circularity. To achieve carbon neutrality with minimal impact on other Sustainable Development Goals (SDGs) – like industry, innovation, and infrastructure (SDG9), responsible consumption and production (SDG12), and good health and well-being (SDG3) – it is needed to transform linear models used for policy support into circular models. To do so, the gap between energy-climate mitigation modelling and CE analytical tools used for cradle-to-cradle assessments (e.g., LCA-Life Cycle Assessment, MFA-Material Flow Analysis, or value-chain analysis) should be bridged. Climate mitigation models, in turn, require a high level of technical detail to represent CE measures and integrate feedback loops characteristic of CE practices. Existing climate mitigation models need a major technological leap to address these CE technical aspects. This is the main challenge addressed in the CO_2NSTRUCT European project.

CO_2NSTRUCT: "Modelling the role of circular economy structure value chains for a carbon-neutral Europe" is a European Horizon, Research and Innovation Action (RIA) project involving seven organizations from seven countries (Denmark, Greece, Italy, Spain, Portugal, Germany, and the United Kingdom). The project, which started in June 2022 with a duration of four years, is coordinated by the Technical University of Denmark (DTU).

The project aims to develop a framework that will augment a well-known open climate mitigation energy systems model, with highly detailed technology representation - JRC-EU-TIMES (hereafter referred to as TIMES) - with CE measures. The framework will focus on implementing CE measures for the value chain of six carbon-intensive construction materials (cement, steel, brick, glass, wood, and insulation materials), and it will combine the following components with the TIMES linear energy-climate mitigation model: (i) high-resolution value chain representation; (ii) embodied energy, materials and GHG emissions (and other externalities); (iii) comprehensive menu of CE measures including feedback loops; (iv) citizen behaviour towards CE and climate mitigation; (v) CE analytical tools, and (vi) rebound effects of CE measures from higher resource consumption (within and outside EU+ [1]) and social impacts as employment or inequalities. These will lead to a richer set of circular climate mitigation options to be modelled in TIMES. The framework will apply several CE scenarios to understand the short-term (2030) and future (2050 and 2070) and ensure carbon neutrality by at least 2050. This will be used to understand current and future potential CE contributions in Europe to GHG emissions reductions and will be translated into sound and effective policy support information for climate mitigation. Although the CO_2NSTRUCT framework is applied to the whole EU+ energy production and consumption system (disaggregated per country), the consortium will emphasize on two highly relevant economic case studies, henceforth named clusters: (1) offshore Renewable Energy Sources (RES) energy production and (2) buildings.

CO_2NSTRUCT has set the following stand-alone objectives in line with the development of the project climate mitigation modelling framework:

- To define the baseline of material flows, carbon, water, and embodied energy of materials across six carbon-intensive construction materials value chains and to create a dataset for construction materials, including CE measures. Means of verification: Creation of an open-access database verified by key stakeholders.
- To develop a strategy to quantify citizen behaviour and key stakeholder opinion on CE measures of six construction materials and incorporate its results in the TIMES energy-climate mitigation model. Means of verification: Performing of a survey in the 7 participating countries, involving at least 1400 citizens and conduction of at least 25 key stakeholders' interviews.

- To map the CE value chain for each of the six carbon-intensive construction materials. Means of verification: Value chain conceptual model, validated by key stakeholders.
- To identify the social implications of the transition towards CE in the selected value chains. Means of verification: The created open-access database will include estimated social impacts, allowing for visualization of data on mitigation options, value chains and framework structure.
- To develop a new climate mitigation modelling framework for the construction materials value chain that includes an account for CE feedback loops and other CE tools, their rebound effects, expected citizen engagement, and an evaluation of externalities for different CE climate mitigation scenarios. Means of verification: An augmented open TIMES energy-climate mitigation model including CE options.
- To integrate CE into climate action, policies, and externalities. Means of verification: At least 10 policy-making recommendations and at least 19 meetings/workshops with policy makers and other key stakeholders.

The methodology that will be undertaken to accomplish the aforementioned objectives is illustrated in Figure 1. This includes how Data, Models & Tools, Scenarios & Pathways are interconnected with each other and how they relate to the project's objectives.

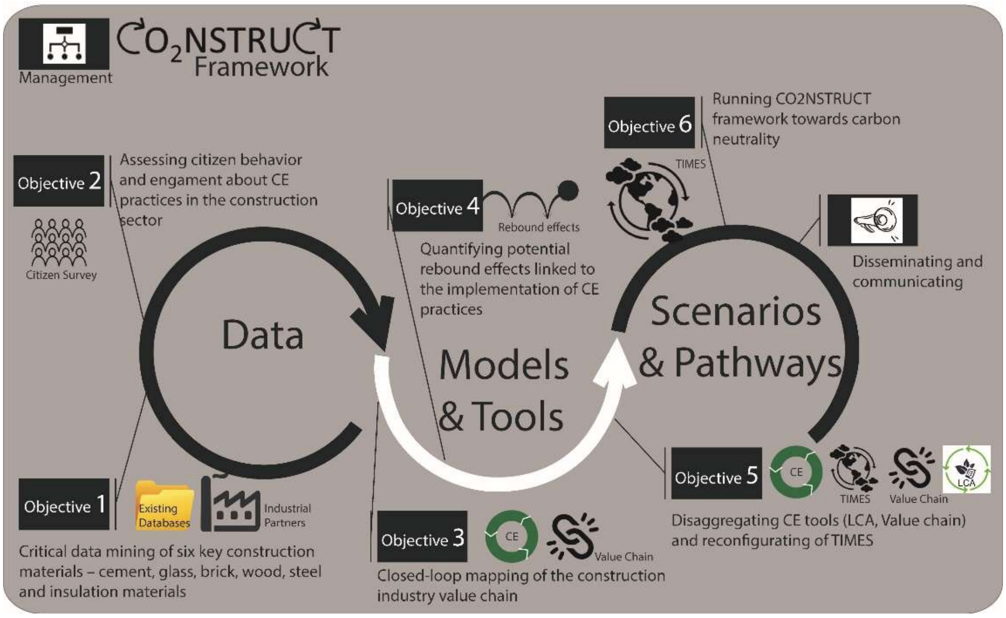

Figure 1. Interconnectivity and workflow of the CO_2NSTRUCT project

The main novelty of CO_2NSTRUCT will be the development of new modelling abilities to connect existing and well-established CE tools with climate mitigation models. The consortium anticipates that the expanded circular climate mitigation framework will broaden its current use by having a better representation of carbon-intensive industrial value chains (cement, steel, brick, glass, wood and insulation materials), considering varied environmental indicator data (embodied GHG emissions, air pollutants, water, energy), and closed-loop value chains (containing CE impacts and feedback loops). This expanded "Circular TIMES" model will deliver knowledge for concrete solutions for industry and policymakers. Additionally, it is envisaged that the modelling outcomes will be designed to support exploring new business concepts focused on CE and carbon-neutral construction products/services.

This study presents the main objectives of CO_2NSTRUCT project regarding existing knowledge gaps and related state-of-the-art in the specific field. It also identifies the novelties and the foreseen actions to accomplish the project's goals throughout the project duration.

2. Creation of a dataset for construction materials, including CE measures

Accurately accounting for CO_2 emissions (from construction materials, buildings, and offshore RES energy production) is limited because of omitted methodological assumptions of LCA studies. There is an increasing amount of available data (big data) [2], but at the same time, there is a lack of attention paid to embodied impacts in building-related energy research [3]. In other words, despite the increasing amount of data, there is still a lack of reliable and meaningful data to supply to the existing models. In addition, the existing data is siloed – it is represented in a range of different formats, preventing direct comparison and synergetic insights. This is only aggravated when it comes to CE options, with convoluted data flows and intricate connections and loops within the supply network. Academia and industry communities would benefit from an ontological approach to data management in this field. This is a clear gap; meaningful data is missing for reliable circular climate mitigation scenarios projection.

One of the main objectives of CO_2NSTRUCT project is to create a dataset for construction materials, including CE measures. During the project, data will be gathered and treated on environmental externalities and they will be translated it into indicators such as GHG and air pollutant emissions, embodied energy, water, materials costs, and mass balances about business-as-usual practices along their value chains. To achieve this, the following steps will be followed:

- Screen and retrieve data from the usage of cement, steel, wood, brick, glass, and insulation materials in existing databases.
- Gather emission/usage data (embodied energy, GHG, water) throughout the six construction materials' supply chain and other life cycle stages.
- Explore links between occupant behaviour modelling for energy consumption and circular economy strategies.
- Validate information with key stakeholders.

CO_2NSTRUCT goes beyond GHG emission alone and combines multiple environmental flows – water use embodied energy of materials, and air pollutant emissions – including economic data and occupant behaviour of buildings to provide a curated database. The knowledge of citizen/consumer behaviour on CE measures along the six materials' value chains for its use in offshore RES energy production and buildings will also be added to the database. The database will account for data source and format differences and (perhaps more importantly) for location-related variations in transportation and energy mix makeup.

In CO_2NSTRUCT a curated, open-access database will be created that will support integrating different environmental vectors (GHG emissions, water usage, air pollutant emissions, and embodied energy data) of six carbon-intensive construction materials into climate mitigation models.

3. Developing a strategy to quantify citizen behaviour and key stakeholder opinion toward CE and climate mitigation

The concept of CE in the construction sector represents an economic model that considers both the building construction and their infrastructures to maintain materials, products, and components at their maximum technical, economic and environmental values [4].

There is substantial literature debating the theoretical merits of reducing, reusing, recycling, and other CE practices [5]. There is evidence that recycled construction and demolition (C&D) waste products are technically feasible [6] and regulated in the construction sector [7]. However, there is strong resistance to the reuse and recycling of C&D waste in construction projects [8, 9], while poor information is available on who can influence the decision to use recycled or reused products in the sector [10]. There is currently insufficient information and little empirical evidence on the behavior and preferences of consumers and other stakeholders in the use of CE practices, both in buildings and in offshore RES energy production [11], and there is a need to assess their influence. Shooshtarian et al. [12] have identified six categories to have a representative sample of stakeholders: client, government, recycler, architect, civil/structural engineer, and builder, as these stakeholders exert a strong influence on the construction and energy sector [13,14].

CO_2NSTRUCT project aims to bridge the gap of missing empirical evidence related to consumer and other stakeholder behaviour and preferences on the use of CE practices by developing a strategy to quantify citizen behaviour and key stakeholder opinion toward CE and climate mitigation. The first step is to analyse citizen awareness and behaviour on CE and climate change aspects and their effect on the development of climate change mitigation models. The analysis will start with a bibliographic analysis of existing surveys on the project topics to identify gaps and potential research topics of citizen behaviour on CE for climate change mitigation. Then, a quantitative survey will be conducted, using questionnaires on the citizen behaviour (response and reactions) on circular construction materials and their contribution to the reduction of CO_2. The quantitative survey will be performed in the seven participating project counties (Denmark, Greece, Italy, Spain, Portugal, Germany, and the UK), involving at least 200 participants per different country. The survey will advance the understanding of the important criteria to citizens and collect their opinions on the six construction materials analysed by the project. Moreover, the study will investigate their awareness and willingness to pay for materials produced, taking CE values into account.

Key stakeholders will be identified, and actions to engage them will take place. The stakeholder engagement strategy will include:

- Interviews with at least 25 EU and national associations and key policy and construction sector stakeholders, including citizen unions and building owners. Stakeholders will be interviewed on their perception of construction materials CE about financial, environmental, social, and policy aspects.
- Qualitative analysis of the results of the interviews.
- Synthesis and comparison of the quantitative results from the survey and the qualitative analyses of interviews' results.
- Conduction of choice experiments focusing on specific stakeholder categories; quantitative analysis of collected data.
- Involvement and interaction of stakeholders throughout the process development of the project to gather feedback to develop and improve the climate mitigation scenarios for circular construction.

The results of the abovementioned analysis will be incorporated into the TIMES climate mitigation model.

In parallel, occupants'/stakeholders' materials and energy behavior will be examined through simulation tools in the following two clusters:

- *Buildings*. This sector strongly influences energy consumption, resources, waste, and emissions, which must be optimized to meet the climate change targets set by the European Union [15]. This research will explore how space-sharing models could affect energy consumption in commercial and residential buildings.
- *Offshore RES energy production*. An important point in energy consumption and carbon reduction is renewable generation and its connections to other parts of the energy system. This research will analyze how component sharing, reuse, and industrial symbiosis scenarios contribute to reducing energy and materials in offshore RES installations.

Several sensitivity analyses will be carried out using simulation tools to quantify the influence of occupant behavior on building energy consumption. For this purpose, a simulation environment will be developed by coupling dynamic simulation models with parametrization tools, allowing the assessment of the building energy performance under different configurations. A web tool for buildings will also be developed to analyze the environmental impact reduction potential of space sharing in various scenarios (office, multi-family housing, commercial building types, etc.). Finally, an interactive website for offshore RES energy production will highlight different scenarios based on the results obtained from energy reduction analysis of several component reuse, sharing, and industrial symbiosis solutions on offshore RES facilities (including ports).

Data obtained from the quantitative survey on citizens' behaviour on CE measures and sensitivity analyses will be assessed, and their results will be fed into TIMES, allowing the impacts of the CE to be quantified. Incorporating this data into TIMES will improve the understanding of society's response and behavioural changes. This knowledge will facilitate the design, assessment, and identification of optimal solutions adapted to climate change.

4. Mapping CE practices in the supply and value chains in the construction sector

EU policies support the production and consumption patterns change across the whole Value Chains towards a CE [16]. Construction materials Value Chains are in the limelight because of their economic and environmental impacts [17]. Since CE may reshape construction materials Value Chains, this field has attracted rising interest [18]. The development of detailed material-specific mapping of their CE-based Value Chains is still unaddressed, even though academics have devoted significant efforts to shed light on the CE-driven construction industry topic [19]. Such a mapping effort is both topical and urgent because the circular transition in the industry needs to involve all manifold portions of the Value Chain [20].

Current climate mitigation models are conceived for linear models of economic activity, i.e., linear production and consumption patterns. This means that they are not able to assess the impact that material circularity and the extended/intensified use of products have on polluting emissions and energy consumption across the Supply and Value Chains, from raw material extraction of the end-of-life phase of products or materials, and, eventually, on climate change. However, developing a framework to augment climate-energy models with CE options requires figuring out how a CE affects the material flows, their transformation processes, and the related energy needs from a life cycle perspective in the Construction sector. Gathering this information requires understanding the changes, such as material and energy flows, operations, and distribution channels, that the circular transition is entailing in the multi-layered Construction Supply Chain (SC) and singling out which actions, called CE practices, have been or will be deployed to pursue the circular transition in this context. This is of the utmost importance to define a list of requirements to embed the CE in the TIMES model and develop a generalizable framework that may allow other climate-energy models to account for circularity.

With this aim, data concerning basic and non-basic industries involved in the Construction sector in linear and closed-loop settings will be collected and analysed for the six carbon-intensive construction materials. To do so, the following activities are planned by CO_2NSTRUCT:

- *Mapping of the Construction materials SC*. This activity, which is currently ongoing, aims to map the SC of the six carbon-intensive construction materials by depicting the involved actors, supply channels, and main flows (information, material, value). These SCs may include players or distribution channels from other industries that typically feed the Construction sector (e.g., textiles). This activity is needed to create a snapshot of the current structure of the Construction sector in terms of, for instance, production and transportation volumes, energy needs, main supply relationships, and actors. Such a snapshot will provide a baseline in which a CE may be applied. The data will be collected from different EU countries. To reduce the lack of regulatory cohesiveness across borders, countries with relevant characteristics and different readiness levels related to legislation will be clustered.
- *Identification and analysis of CE practices along with the six carbon-intensive construction materials*. The growing attention to the circular transition has stimulated the conception of manifold practices to establish a CE and create circular SCs. Therefore, this activity will consist of identifying such practices by reviewing the grey literature and developing case studies in the Construction sector. The identified practices will be analysed and reviewed with the support of the End Users' Board (a board which will be established within the project including representatives from the scientific community, policymakers and the industrial sector) to single out the most meaningful ones in the Construction industry.
- *Mapping of the six carbon-intensive construction materials Closed-Loop SCs*. This activity aims to map the changes that the identified CE practices imply in the SCs of the six selected carbon-intensive materials. The resulting so-called Closed-Loop Supply Chains (CLSCs) may involve new stakeholders and material loops between different stages of single or multiple SCs related to the Construction sector. However, such loops may also occur between a Construction SC and a SC from another sector. For example, a construction material might be replaced by a bio-based equivalent coming from the agriculture sector. The CLSCs representation summarises the SC structural changes due to the circular transition. It highlights both the SC stages in which a CE is taking place and the spots that may show untapped circular potential.

- *Mapping of the six carbon-intensive construction materials Value Chain*. Once the CLSCs are identified, the related Value Chains will be mapped to understand how the circular transition may create environmental-friendly value starting from the material extraction in the basic industries. This will pinpoint the main activities through which the selected materials acquire or recover value across the supply channels and the extent of these value variations.

The four above-listed activities will provide the information needed to elicit the requirements needed to augment the TIMES model with CE options and translate the CE practices into modified materials, water, and energy consumption, and subsequent GHG emissions reductions (as well as for other externalities). This will be used as a reference to develop the framework to enrich other energy-climate models with circular production and consumption patterns.

5. Identification of potential rebound effects and social impacts of CE measures implementation

The CE has emerged as an essentially contested concept that is expected to transform economic activities in such a way as to reduce their reliance on non-renewable energy and carbon-intensive material flows [21]. A transition from a linear to a CE would entail a paradigmatic shift of both business models and design strategies to prolong use, reuse and close the loop between post-use waste and production, ultimately leading to the reduction of resources used in primary production [22]. While CE is anticipated to radically reconstruct the relationship between ecological systems and economic activities, its discourse is characterised by an apolitical and technocratic framing that ignores the transformational implications of such transition [23].

"Circular economy rebound" refers to a state where the increased efficiency linked to CE activities is offset by increased levels of production and consumption [24]. This phenomenon is directly associated with the reductionist view of CE as an engineering system preoccupied with closing material loops, completely overlooking market mechanisms [25]. The main objective of CE is for secondary production, which involves the sum of reuse and recycling activities, to displace primary production. Rebound effects occur when secondary production, which has a lower per-unit-production impact, results in increased levels of primary production. This can be generally attributed to three mechanisms: insufficient substitutability of secondary goods, price effects, and broader socio-economic transformational effects.

Insufficient substitutability is linked to the perception of secondary goods being of inferior quality that deems them undesirable to the end customer. Consequently, secondary goods are produced in addition to - rather than instead of - primary goods, thus nullifying the benefits of CE practices. On the other hand, price or income effects are associated with the impact of increased secondary production on prices. Increasing the supply of secondary goods in the market, they compete to substitute primary goods. However, perceived as goods of lower quality compared to their primary production counterparts, they will be offered at discounted prices. According to the law of supply and demand, the increase in the supply of secondary goods will also result in a decrease in the price of substitute (primary goods), since suppliers are competing to attract more buyers. As prices drop, the demand for both goods will increase since consumers perceive themselves to have a comparatively higher income than before (income effect). The increase in demand will then lead to an increase in prices, and the market will move toward a state of equilibrium of a lower price but higher quantity. At that equilibrium point, supply will match the demand, which means that suppliers produce just enough at the right price to satisfy consumer demand. However, the extent to which secondary production can replace primary production on a one-to-one basis is uncertain, as it will depend on buyers' and sellers' responses to prices and their willingness to substitute new with refurbished products. Last, broader socio-economic transformational effects concern the indirect consequences of the transition to a CE on employment, income, immigration, and overall consumption patterns. For instance, increased demand for recycled and refurbished products could result in the re-emergence of repair occupations, which have systematically disappeared over the last decades, with unknown implications for employment in other industrial sectors (such as extractive ones). Nonetheless, the most prominent implication concerns the link between CE and economic growth, closely related to a production increase, thus, a simultaneous decrease of associated environmental benefits.

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All these issues are extremely relevant to the construction sector, given its reliance on extractive industries; for this reason, the rebound potential of CE solutions will be at the forefront of the research activities conducted in the CO_2NSTRUCT project.

6. Developing CO_2NSTRUCT Circular Climate Mitigation Modelling Framework and Scenarios

Current climate mitigation models cannot sufficiently consider CE measures or interconnected resource needs despite improvements in this direction. Existing Integrated Assessment Models (IAM) for climate mitigation modelling, such as IMAGE, MESSAGE, WITCH-GLOBIOM, etc., have been powerful tools for improving our understanding of the climate change problem and the potential pathways to deal with it as included in Intergovernmental Panel on Climate Change - Fifth Assessment Report (IPCC AR5) [26]. However, IAM cannot perform integrated resource assessment and modelling [27] since they often focus on a single resource or are applied on an aggregated scale. On the other hand, existing technology energy-climate mitigation models (as TIMES) have been linked to other tools/methods to investigate connections between energy and other systems [28], but such efforts did not: (i) address trade-offs and benefits across the technologies' life cycle; (ii) consider materials value chains nor the possibility for closing loops, (iii) quantify effects on optimal decarbonization pathways regarding additional economic/social aspects (e.g., investment needs, energy prices). Thus, climate mitigation models are linear and/or do not have sufficient technical detail to adequately capture value chains, and feedback loops inherent to CE options. Embodied energy, water, and emissions are not considered while modelling climate mitigation pathways. Rebound effects and cradle-to-cradle analysis are not done, as well as changes to more circular consumption patterns (e.g. sharing). This limits our capability to shift towards a carbon-neutral economy since CE is not accounted for urgently.

CO_2NSTRUCT will develop and implement a novel circular climate mitigation framework integrating CE options, complex value chains, citizen behaviour, externalities, and rebound effects with a well-known TIMES energy-climate mitigation model for the whole of EU+.

Within CO_2NSTRUCT circular framework for climate mitigation, the outcomes of the work steps already developed by the project will be incorporated. The six construction materials will be identified and described and the CE measures applied to the supply and value chains. The framework will include functionalities from existing CE analytic tools adding the functionalities necessary for climate mitigation models. Specifically, the overlaps and gaps within the CE tools will be identified starting with the analysis of existing and established CE analytical tools. A characterization of CE tools will follow this according to defined criteria. The review will pay special attention to how climate mitigation issues are currently dealt with in CE tools (e.g. MFA, Substance Flow Analysis-SFA, input-output analysis-IOA, LCA, social LCA- sLCA, embodied carbon footprint analysis, among other). Recent and innovative CE tools will also be considered. Secondary data will be complemented with a survey targeting experts in the field. Concrete recommendations for integrating GHG mitigation on CE tools will be made.

Based on the assessed CE tools, an ontology for "circular mitigation" will be developed. Gaps and missing links between TIMES and CE analytical tools will be identified. A step-by-step "conceptual breakdown" of the TIMES model components will be realised, contrasting them with the accomplished so far outputs of the project. It will be identified where and how to include in TIMES:

- CE feedback loops, detailed sub-division of processes and sectors, as well as more detailed modelling of more materials with mass balances;
- CE measures mainly related to consumption changes (i.e. sharing, extending lifetime) that may not necessarily require modelling of loops, but instead changes in TIMES exogenous energy services and materials demand;
- GHG & air pollutants emission data embodied energy, and water use/water scarcity footprint;
- consumer/citizen behaviour towards the adoption of CE measures;
- environmental and social rebound effects.

The beta version of the framework will contain essential features to convert the TIMES model into a full "circular climate mitigation model". Subsequently, the TIMES model will be assessed to determine which elements can be included from the beta version of the framework, considering computational and data limitations for all countries in the model. Another important decision factor will be the need to ensure the replication and usage of the framework with other non-TIMES climate mitigation models. Decisions will be made on the extent of integration of TIMES with CE analytical tools, i.e. from full integration (for example bringing LCA into TIMES by using "externality factors" as shadow costs) to soft linking TIMES with e.g. sLCA. As a final result, the structure for all needed TIMES files including CE measures will be prepared. To support framework replicability, the data obtained from the previous tasks will be compiled in a user-friendly database for climate mitigation modelers.

The developed CO_2NSTRUCT framework will be then implemented to quantify CE's potential contribution to climate goals. The synergies and antagonisms between CE and climate mitigation pathways toward carbon neutrality will be quantified for this. Results will be obtained for the entire EU energy production and consumption system. Still, the studied CE role focus on the six high-carbon and pervasive construction materials, with special emphasis on the clusters (1) offshore RES energy production and (2) buildings, two major areas where urgent (and sustainable) climate action is required.

CO_2NSTRUCT framework will drive the TIMES model from linear to circular climate mitigation. The augmented model will be used to simulate different pathways to meet the carbon neutrality goals of the EU for the short/long term. At least the following CE measures will be considered: (i) Reduce: reflects reduction strategies a reduction of materials/products needs and production; (ii) Share: reflects a sharing economy and society, supported by new business models and a rethinking of equipment/services, that may not need to be purchased as they can be shared (i.e. sharing building space or offshore infrastructure); (iii) Repair: considers a lifetime extension of buildings and of infrastructure for offshore energy production; (iv) Recycle: waste materials used as raw through reprocessing (ex. recycling of C&D waste by cement industry) and (vi) a combination of the above. Different scenarios will be co-developed with industry and policymakers considering different degrees of CE adoption across the six-construction materials value chains. The scenarios will be built on the two clusters: offshore RES energy production (cluster 1) and buildings (cluster 2). After running TIMES with these scenarios, the following quantitative outputs will be obtained from the model: GHG (and other) emissions gains, impacts on both GHG abatement and energy costs, impacts on materials and water consumption, value chain hotspots for most effective CE measures that impact GHG mitigation, and a ranking of CE measures according to their capability to mitigate GHG emissions. This model output will be transformed into an innovative CE measures labeling scheme with GHG mitigation indicators. The TIMES model results will be translated into policy recommendations to integrate CE into climate, energy, environmental, and economic policies toward carbon neutrality.

7. Conclusion

Climate Mitigation models are used to evaluate economic activity patterns. However, the existing models are mainly linear, and they do not account for the materials' circularity. CO_2NSTRUCT project aims to develop a framework that will augment the well-known open climate mitigation energy systems model "TIMES model" with CE measures. The framework will focus on implementing CE measures for the value chain of six carbon-intensive construction materials (cement, steel, brick, glass, wood, and insulation materials) with emphasis on two clusters (1) offshore RES energy production and (2) buildings, two major areas where urgent (and sustainable) climate action is required. CO_2NSTRUCT framework is expected to integrate CE options, complex value chains, citizen behaviour, externalities, and rebound effects into the TIMES model. The augmented model will be used to simulate different pathways to meet the carbon neutrality goals of the EU for the short/long term. The TIMES model results will be translated into policy recommendations to integrate CE into climate, energy, environmental, and economic policies toward carbon neutrality.

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References

[1] European Open Science Cloud (EOSC) Portal - [www Document] EU+ Countries: EU Member States and Associated Countries: https://eosc-portal.eu/policy/EU-Countries

[2] Wu X, Zhu X, Wu G Q and Ding W 2013 Data mining with big data *IEEE transactions on knowledge and data engineering* **26**(1) pp 97-107

[3] Röck M, Saade M R M, Balouktsi M, Rasmussen F N, Birgisdottir H, Frischknecht R, … and Passer A 2020 Embodied GHG emissions of buildings–The hidden challenge for effective climate change mitigation *Applied Energy* **258** 114107

[4] González A, Sendra C, Herena A, Rosquillas M and Vaz D 2021 Methodology to assess the circularity in building construction and refurbishment activities *Resources, Conservation & Recycling Advances* **12** 200051

[5] Oluleye B I, Chan D W, Saka A B and Olawumi T O 2022 Circular economy research on building construction and demolition waste: A global review of current trends and future research directions *Journal of Cleaner Production* 131927

[6] Ekins P, Domenech T, Drummond P, Bleischwitz R, Hughes N and Lotti L 2019 The Circular Economy: What, Why, How and Where Background paper for an OECD/EC Workshop on 5 July 2019 within the workshop series "Managing environmental and energy transitions for regions and cities", Paris

[7] Wu H, Zuo J, Zillante G, Wang J and Yuan H 2019 Status quo and future directions of construction and demolition waste research: A critical review *Journal of Cleaner Production* **240** 118163

[8] Opoku A, Deng J, Elmualim A, Ekung S, Hussien A A and Abdalla S B 2022 Sustainable procurement in construction and the realisation of the sustainable development goal (SDG) 12 *Journal of Cleaner Production* **376** 134294

[9] Oyedele L O, Ajayi S O and Kadiri K O 2014 Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement *Resources, Conservation and Recycling* **93** pp 23-31

[10] Charef R 2022 Supporting construction stakeholders with the circular economy: A trans-scaler framework to understand the holistic approach *Cleaner Engineering and Technology* **8** 100454

[11] Xu X, Xiao B and Li C Z 2021 Stakeholders' power over the impact issues of building energy performance gap: A two-mode social network analysis *Journal of Cleaner Production* **289** 125623

[12] Shooshtarian S, Caldera S, Maqsood T and Ryley T 2020 Using recycled construction and demolition waste products: A review of stakeholders' perceptions, decisions, and motivations *Recycling* **5**(4) 31

[13] Giorgi S, Lavagna M, Wang K, Osmani M, Liu G and Campioli A 2022 Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five European countries policies and practices *Journal of Cleaner Production* **336** 130395

[14] Guerra B C and Leite F 2021 Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers *Resources, Conservation and Recycling* **170** 105617

[15] European Union Energy Efficient Buildings - [www Document] Energy Performance of Buildings Directive: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

[16] Camilleri M A 2020 European environment policy for the circular economy: Implications for business and industry stakeholders *Sustainable Development* **28**(6) pp 1804-1812

[17] Norouzi M, Chàfer M, Cabeza L F, Jiménez L and Boer D 2021 Circular economy in the building and construction sector: A scientific evolution analysis *Journal of Building Engineering* **44** 102704

[18] Eberhardt L C M, Birkved M and Birgisdottir H 2022 Building design and construction strategies for a circular economy *Architectural Engineering and Design Management* **18**(2) pp 93-113

[19] Benachio G L F, Freitas M D C D and Tavares S F 2020 Circular economy in the construction industry: A systematic literature review *Journal of Cleaner Production* **260** 121046
[20] Munaro M R, Tavares S F and Bragança L 2020 Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment *Journal of Cleaner Production* **260** 121134
[21] Korhonen J, Nuur C, Feldmann A and Birkie S E 2018 Circular economy as an essentially contested concept *Journal of Cleaner Production* **175** pp 544-552
[22] Bocken N M, De Pauw I, Bakker C and Van Der Grinten B 2016 Product design and business model strategies for a circular economy *Journal of Industrial and Production Engineering* **33**(5) pp 308-320
[23] Genovese A and Pansera M 2021 The circular economy at a crossroads: technocratic eco-modernism or convivial technology for social revolution? *Capitalism Nature Socialism* **32**(2) pp 95-113
[24] Maier J, Geyer R and Zink T 2020 Circular economy rebound *In Handbook of the Circular Economy* Edward Elgar Publishing
[25] Zink T and Geyer R 2017 Circular economy rebound *Journal of Industrial Ecology* **21**(3) pp 593-602
[26] Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, ... and Van Vuuren D P 2014 Assessing transformation pathways Assessing Transformation Pathways In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
[27] Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, ... and Yumkella K K 2011 Considering the energy, water and food nexus: Towards an integrated modelling approach *Energy Policy* **39**(12) pp 7896-7906
[28] Luderer G, Pehl M, Arvesen A, Gibon T, Bodirsky B L, de Boer H S, ... and Hertwich E G 2019 Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies *Nature Communications* **10**(1) pp 1-13