Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

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Summary

Material circularity and energy efficiency are highly relevant and intertwined issues for the transition towards a carbon-neutral and circular built environment. In the Netherlands, the building sector has been rendered a priority towards a circular and low-carbon society. Regarding material circularity, the Netherlands has the best practice of construction and demolition waste (CDW) management over the world, achieving an almost 100% recovery rate. However, most CDW is downcycled for road base backfilling, which is considered as a low value-added treatment. Moreover, the Netherlands is already facing the problem of saturation of road construction. It is urgent to explore an outlet for the vast surplus of waste concrete to make the construction supply chain more circular. To improve the material efficiency within the construction sector, the Netherlands launched the "A circular economy in the Netherlands by 2050", aiming to achieve an interim target of 50% less use of primary raw materials by 2030 and a long-term goal of a fully circular economy by 2050. On the other hand, the housing stock in the Netherlands is poorly insulated and obsolete; about half of the building stock was constructed between the 1950s and 1970s before minimum energy performance requirements were introduced in 1995. The government of the Netherlands has set up ambitious energy renovation goals that aim to achieve the decarbonization goal by 2030 and 2050. The upcoming extensive renovation wave in the Netherlands not only in return increases the burden of resources but also raises new problems surrounding their disposal. This thesis explored potential solutions for these twin issues in light of a novel technological system. This system presents an energy–material efficiency solution for energy renovation of building stocks with prefabricated concrete elements (PCEs) with recycled CDW as feedstock. Life cycle assessment (LCA) and life cycle costing (LCC) were combined with dynamic material flow analysis (MFA) to estimate the economic and environmental implications at both a product level and a national level. Therefore, this thesis puts forward the following overarching research question: "*what are the potential impacts of the application of selected novel technological systems to enhance circular use of materials, energy efficiency and carbon neutrality in the residential sector of the Netherlands?*". Based on the main research question, five sub-questions were investigated in the thesis:

RQ1. Assessment of concrete recycling at the product (material) level

Is it possible to achieve environmental-economic win-win situation in high-grade concrete recycling? Would the innovations trigger any potential problem-shifts between different impact categories? **(Chapter 2)**

RQ2. Assessment of the PCE-new system for new building construction at a product (element) level

What are the environmental and economic implications of using the prefabricated element system (PCE-new) for cladding walls to improve building energy efficiency in new constructions in the Netherlands? **(Chapter 3)**

RQ3. Assessment of the PCE-refurb system for existing building renovation at a product (element) level

What are the environmental and economic implications of using the prefabricated element system (PCE-refurb) to over-clad existing buildings for energy refurbishment in the Netherlands? How is the applicability of the PCE-refurb under different climatic conditions? **(Chapter 4)**

RQ4. Assessment of turnover of the housing stock at the country level

How much CDW from the construction, demolition, and renovation of the Dutch housing stock will arise from 2015 to 2050? To which extent the CDW can be recycled as a feedstock in building energy renovation in the Netherlands? **(Chapter 5)**

RQ5. Assessment of implementing the recycling and prefabrication systems at the country level

What are the up-scaled environmental benefits and economic consequences of implementing the recycling and prefabrication systems in the Netherlands? To which extent can the proposed recycling and prefabrication system achieve the prospective circularity goal and decarbonization goal of the Netherlands? **(Chapter 6)**

To answer the first sub-question, Chapter 2 proposed a framework for LCA/LCC-type eco-efficiency assessment to investigate multiple technological systems for high-value-added recycling concrete and to identify key factors for cost-effective concrete recycling. This case study concluded that the most eco-efficient technological routes for recycling waste concrete are technologies that recycle the waste concrete on-site and produce high-value secondary products. We found the most environmentally sound and cost-saving way for concrete recycling is the integrated mobile Advanced dry recovery (ADR) and Heating air classification system (HAS), which had the highest eco-efficiency score. Regarding individual impact categories, 10 out of 15 environmental impact indicators show that the integrated ADR and HAS is superior to the other technological systems. At the same time, it has the highest environmental impact in photochemical ozone formation, particulate matter, acidification, terrestrial eutrophication, and marine eutrophication. These drawbacks are due to the fact that the pilot-scale HAS the pilot-scale HAS is still uses fossil fuel diesel to thermally decompose the concrete waste. An industrial-scale HAS will use cleaner energy such as renewable electricity.

Regarding the second sub-question, Chapter 3 used a monetary method to combine LCA and LCC to assess the life cycle performance of the green PCE-new as façade for a new building over 120 years in comparison to those of manufacturing and using a baseline PCE-new. The main difference is that the green PCE-new uses an aerogel that isolates better as expanded polystyrene (EPS) used in the baseline PCE-new. Moreover, the green PCE-new comprises recycled materials made from CDW while the baseline PCE only uses virgin materials. The production of the aerogel is much more energy-intensive as EPS, the difference over the life cycle is however limited. If we look only at direct costs, green PCE-new is slightly cheaper. If on top of this the external costs of greenhouse gas (GHG) emissions are included, avoided emissions lead to an additional cost advantage. Considerable uncertainties exist however in such calculations.

As of the third sub-question, Chapter 4 conducted a payback-based LCC and LCA to assess the life cycle performance of energy conservation, carbon mitigation, and cost reduction of the green PCE-refurb for refurbishing existing buildings in the Netherlands. We analyzed how reuse and recovery of the PCE-refurb influence the carbon-energy-investment payback periods. The results of the Dutch case indicate an apparent environment-economic trade-off. There appeared indeed to be a positive energy and carbon payback (within approximately 17 years). There was however not a good economic payback (more than 100 years). This indicates that manufacturing and using a PCE-refurb for energy renovation will reduce energy use and GHG emissions but it is costly. The PCE refurb can however be designed in a way that it can be reused, by applying easy-to-disassemble joints. Such design allows them to be reused again after one service life, which helps to overcome this cost disadvantage. It was found that using secondary materials in the PCE-refurb can just slightly reduce the three types of payback periods, while the reuse of the PCE-refurb can considerably shorten the three types of payback periods in three cases. To comprehensively examine the applicability of the PCE-refurb system, two additional cases were analysed for the Swedish and Spanish situations. Results show that implementing the green PCE-refurb in a colder zone would result in shorter payback periods for energy conservation, carbon mitigation, and costs.

With respect to the fourth sub-question, Chapter 5 applied dynamic MFA to explore the supply-demand balance of secondary raw materials made from CDW (including normal-weight and lightweight concrete, glass, insulation mineral wool, steel) and the secondary raw materials demanded for manufacturing PCEs in building energy renovation from 2015 to 2050. The main results show that with the advanced recycling system ADR and HAS, the secondary raw materials recovered from normal-weight concrete waste, glass waste, and insulation mineral wool waste will be more than sufficient to support the manufacturing of PCE-new walls. However, for emerging materials – such as lightweight concrete – the related waste will not be sufficient in a near future to meet the raw material demand for large scale refurbishment with PCE-refurb walls. The

Netherlands will further stay dependent on imports for certain building materials. Use of recycled materials will reduce such imports. In short, ADR and HAS support upcycling of CDW for use in PCEs, but primary raw materials are still needed for emerging materials such as lightweight concrete. Additionally, this case study also demonstrates that the projected amount of renovation waste exceeds the amount of construction waste. Under the circumstance of extensive building energy renovation in the EU, it is important to take into account the management of renovation waste.

For the last sub-question, Chapter 6 proposed an integrated framework that combines the dynamic MFA with LCA and LCC to explore the product-level and up-scaled performance of the PCE solutions for constructing new building construction and renovating existing buildings in the Netherlands from 2015 to 2050. The product-level and up-scaled results were expressed via an annual value approach and an actual-time value approach. The selection of different estimation approaches led to different conclusions. The actual-time value reveals the trade-offs of energy renovation between GHG emissions and material extraction reduction/cost saving. However, the annual value approach proves the comprehensive benefits of the PCE-refurb system compared with the business-as-usual (BAU) scenario in which no renovation (REN-scenario) or (accelerated) rebuilding (REB-scenario) takes place to realise targets with regard to energy efficiency. This study also evaluated the extent to which the circularity and decarbonization goals can be realized by up-scaling the proposed PCE system to the residential building sector in a scenario of renovating existing buildings (REN) and accelerated demolition and rebuilding (REB). The results show the BAU and REN scenarios cannot reduce resource uses till 2050. Accelerated demolition and rebuilding (the REB scenario) scores even worse on material use. Advanced technological systems in the REN scenario can however realise a shift from the current dominant route of downcycling of CDW to 98% recycling. Overall it hence does not seem possible to realise the Dutch circularity goals for 2030 and 2050 for the built environment in the BAU and REN scenarios. Furthermore, operational GHG emissions of the residential building stock in 2030 and 2050 were quantified under the three scenarios. We found that if not any energy renovation strategy is applied as in the baseline BAU scenario, the decarbonization goal by 2030 or 2050 cannot be realised. In the REN scenario, implementing the PCE system for extensive energy renovation in the Netherlands can achieve the interim goal of 49% carbon mitigation by 2030, but still cannot realize carbon-neutrality by 2050. The REB scenario can achieve this since it only builds only near zero energy houses, and replaces traditional gas-based systems with electricity-based systems. It does so however at tremendous costs and with very high material requirements.

Overall, Chapters 2 to 6 evaluated the novel PCE technological system from both economic and environmental perspectives and at both product level and country level.

From the **material circularity** perspective, we examined the priority of building lifetime extension, element reuse, and material recovery in the three-layer framework. We found that (i) building lifetime extension is the most desirable option for material circularity, ii) element reuse is less preferable but still show noticeably environmental and economic benefits, and iii) the benefits of material recovery are almost negligible compared with the first two options. From the **energy efficiency** and carbon-neutrality perspective, this thesis illustrated that passively improving the insulation level of the housing façade is necessary, while electrification and the use of renewable electricity is another key factor that contributes to realising a carbon-neutral built environment. The results provide insights into the opportunities and challenges of realising a circular and carbon-neutral built environment. The thesis also illustrates how LCA, LCC and MFA can be integrated for an assessment that scales up analyses at the product level to a national level. Further research could focus on exploring a broader scope of innovations for circularity and carbon-neutrality in the built environment in different regions, and further work on overcoming some remaining inconsistencies between LCA, LCC and MFA.