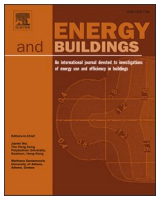
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Industrialized district-level renovation of similar buildings in proximity: Environmental, economic, and renovation production implications

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ABSTRACT

District-level renovation is a promising strategy to decarbonize the European Union's building stock, yet the impact of using industrialized methods at scale remains underexplored. This research addresses this gap through analysis of a four-building district renovation in Estonia, using prefabricated facade elements. The study evaluates 16 renovation packages and three construction management scenarios to quantify the trade-offs between cost, project duration, embodied carbon (product and construction stages, A1-A5), and operational carbon (use stage, B6).

The results reveal that the exterior finish material is the dominant driver of both cost and embodied carbon, with wooden cladding being the most economical and lowest-carbon option upfront. Moreover, the findings reveal a trade-off: the packages that deliver the best long-term operational performance do so at the cost of a higher embodied carbon footprint. Furthermore, the analysis of construction management demonstrates that accelerated schedules not only reduce prefabricated renovation duration by over 70% but also decrease overhead costs by up to 3.4% with a negligible impact on on-site emissions. Additionally, district-level procurement can reduce costs by up to 10% in materials and labor.

This study provides an integrated analysis for assessing industrialized approach for district-level renovations. It offers actionable insights for stakeholders by demonstrating that the lowest-carbon material choices can also be the most cost-effective and that the optimal renovation strategy is not a single technical solution but a decision of balancing cost, carbon and time.

1. Introduction

In Europe, the building stock accounts for approximately 40 % of total energy consumption and 36 % of greenhouse gas (GHG) emissions [1]. To address this, the European Commission suggested the Renovation Wave strategy [2], which aims to reduce the climate impact of the built environment and construction sector. This strategy has two main objectives: (1) to decrease energy consumption by applying the "energy efficiency first" principle and transitioning from non-renewable to renewable resources, and (2) to stimulate economic growth.

While there are many studies on operational carbon (B6) and product stage (A1-A3) embodied carbon, the standalone assessments of construction operations (A4-A5) are less common [3,4]). Even within LCA reviews, A4 and A5 stages are omitted in about a third of the B6-reporting cases [5]; where included, A4-A5 stages are frequently handled with simplified assumptions (transport-only or proxy averages), indicating little and inconsistent coverage of the construction stage. Furthermore, the economic and environmental factors and advantages of renovating multiple buildings together, especially during the construction operations stage, remain underexplored. While economies of scale are often assumed to offer advantages in such cases, the specifics and trade-offs require further investigation. Recent studies have also highlighted that renovation projects are prone to cost overruns due to increased complexity [6]. While the economic challenges of renovation are well-documented, the implications of district-level renovations using industrialized methods remain insufficiently studied. In particular, there are gaps in understanding how construction operations and industrialized renovation processes affect the economic and sustainability outcomes at scale.

This study implements a case study approach to evaluate the impact of industrialized renovation methods on district-level construction operations and their environmental, economic, and production

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implications [7]. A scenario-based analysis compares sequential, two-at-a-time, and four-at-a-time renovation strategies to assess energy savings, carbon emissions, and cost and time efficiency, while meeting energy performance classes A, B, and C. The analysis follows the EN15978:2011 standard for building life-cycle assessment (*EN 15978*, [8], covering mainly both product (A1–A3) and construction stages (A4–A5). The focus is on multiple similar apartment buildings located in close proximity, characterized by comparable architecture, building configuration, and feasible renovation measures. As part of the scope, prefabricated ventilated timber façade systems across common exterior finishes are compared to capture how material choices affect the impact on embodied carbon and cost.

This analysis is applicable in other locations by adapting context-specific inputs. In practice, this means (1) mapping local building typologies and baseline systems, (2) reflecting climate and energy context (national primary energy factors and carrier mixes for electricity and district heating), and (3) using local emission factors and costs. As these inputs vary, absolute energy, carbon, cost, and time values will change, but the comparative logic across renovation packages and management strategies remains consistent.

2. Research background

The built environment and construction sector contribute significantly to climate change (European [1]. The EU's response to the urgency of climate change is grounded in the "energy efficiency first" principle and the decarbonization of the built environment and construction sector [9]. The Renovation Wave strategy [10] positions sustainable renovation as a key instrument to reduce emissions, transition to renewable resources, and address the climate–energy–poverty trilemma (European [2].

Due to the low building replacement rate [11,12], around 75 % of the EU's building stock is energy inefficient, and 80–90 % of these buildings are expected to be still in use by 2050 [13]. That is, renovation, and not only new construction, is critical to achieving climate neutrality [14]. Effectively delivered deep renovation can reduce CO_2 emissions up to 70 %, depending on local energy mixes and renovation depth [15,16]. Moreover, the application of circular construction principles in renovation can further reduce emissions from construction and demolition activities [17,18,19].

Renovation also delivers economic benefits (European [2]. Renovation is often more cost-effective than demolition and the construction of a new building [19,20], supports job generation, and stimulates economic growth [21]. For example, 1 million euro investment to building renovation created 17 jobs in Estonia [22], leading to tax revenues for governments and decreased costs of social assistance [14]. Grants are important to stimulate renovation activity, and renovation grants up to 30 % of the project initial investment cost are economically neutral [22].

Despite clear environmental and economic benefits, the EU's average annual renovation rates remain at around 1 %, far below the 3 % necessary to meet Green Deal 2050 targets [13]. Low renovation reasons can be divided into two categories:

- **Demand-side barriers**, including lack of motivation, financing [23]), awareness, and trust in the process [24],
- **Supply-side barriers**, including insufficient organizational capacity, lack of skilled labor and poor-quality services [25].

Most studies have tended to focus on individual buildings, addressing indoor climate [26], energy performance [27], or life-cycle and cost-benefit analysis [28,22,29]. Yet, many renovation projects fail due to the prebound (overestimating the expected savings) and rebound (failure to deliver expected savings) effects [30,31], caused by (1) environmental variability (e.g., climate change and uncertainties in weather files), (2) design and construction quality issues, and (3) human behavior (e.g., heating controls, excessive energy consumption) [32].

Recent studies argue that single-building renovations are insufficient to achieve climate goals [33,25,34,12]. Consequently, much research has shifted from individual renovations to large-scale interventions [14,35,36], including clusters, neighborhoods, and districts, potentially offering economies of scale and enabling the development of integrated solutions. For example, the Positive Energy Districts (PEDs) have been proposed [37].

Research on district-level renovation has focused on technical, methodological, and demand-side aspects. While studies highlight potential benefits in terms of energy and emissions reduction [38], evidence of actual cost-effectiveness and performance remains limited. Evaluations of methodologies like IEA EBC Annex 75 [12] and LCA-based assessments [39] show mixed results. Husiev et al. [25] reported minimal benefits over single-building renovations and noted challenges such as fragmented ownership, weak regulation, and limited technical capacity. These gaps highlight the need for further research on the environmental, economic and operational impacts of large-scale, industrialized renovation.

District-level interventions may support reducing costs and timelines, but they also introduce complexity due to more intense logistics, stakeholder engagement, and financing. To address this, this study seeks to answer the following research question: How does the industrialized renovation of multiple similar buildings in proximity simultaneously impact project cost, time efficiency, energy savings and carbon emissions, while meeting energy performance classes A, B, and C?

Aligned to the EN15978:2011 standard, the study is structured in two parts:

Assessment of the cost, embodied carbon and energy of alternative prefabricated renovation solutions (product stages, A1 to A3) placed into the long-term context of operational energy and carbon (operational stage, B6).
Analysis of construction processes, focusing on resource use and its implications on project cost, duration and emissions (construction stages, A4 to A5).

2.1. Research methods and materials

This study adopts a case study approach [7], which enables an in-depth analysis of the complexities of industrialized district-level renovation of similar buildings in close proximity. The analysis follows the EN15978:2011 standard for assessing the environmental performance of buildings throughout their lifecycle, with main focus in this study is on the product (A1-A3) and construction (A4-A5) stages. Fig. 1 depicts the scope of the study. As such, the presentation and analysis of results is divided into two parts:

- Product and operational stage (A1-A3, B6): This part evaluates the typical constructions, costs and carbon emissions of alternative renovation measures and packages, with a focus on prefabricated external wall solutions from used in Estonian renovation projects. That is, only actually considered and implemented solutions were analyzed. Data on typical constructions and costs were sources sourced from already delivered renovation projects, construction material and product retailers and manufacturers. All costs presented in this study are exclusive of VAT. Embodied carbon data were derived from Environmental Product Declarations (EPDs) and the Estonian building carbon footprint calculator (Ministry of Climate, 2024). To place these upfront impacts in a long-term context, the analysis then assesses the operational performance (B6) of each package. The post-renovation operational carbon footprint was calculated using the Estonian methodology for calculating building energy performance [40].
- Construction stage (A4-A5): This examines the operations involved in renovating multiple similar buildings with prefabricated methods,

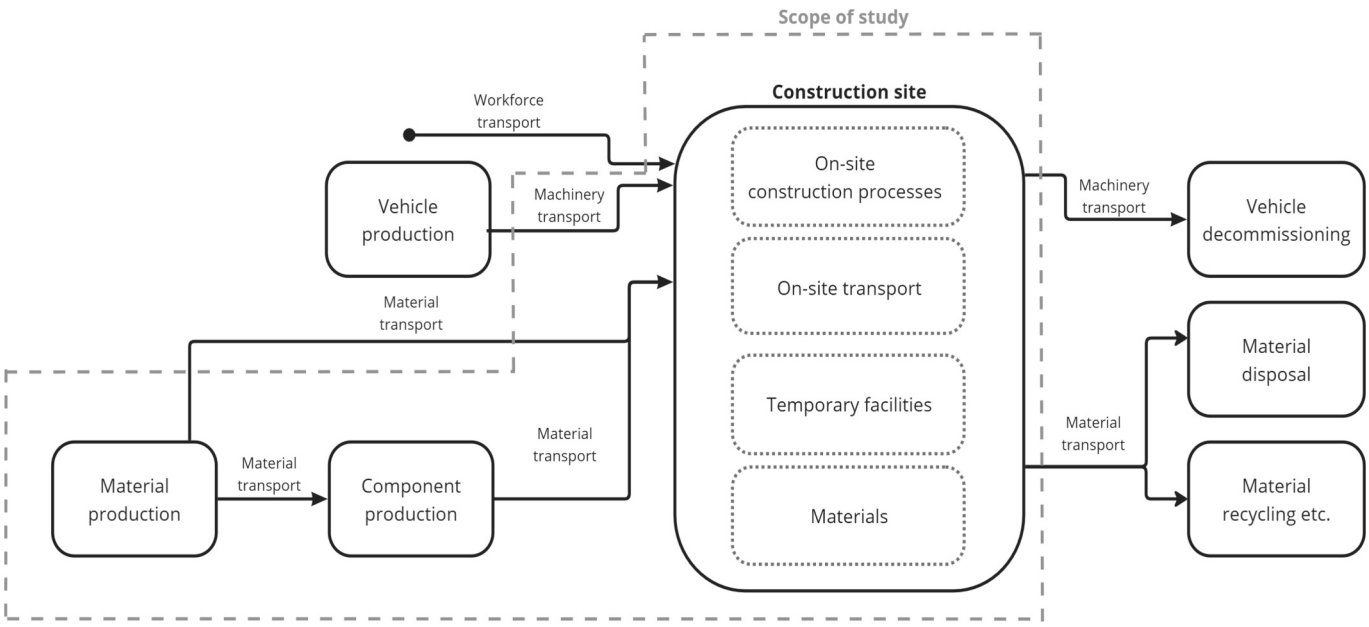


Fig. 1. Scope of study regarding carbon emissions in construction processes, Weigert et al. [4]

including transport and on-site construction. Data on construction machinery energy consumption was collected to assess carbon impacts. The analysis is informed by best practices, previous case studies [41,42], and input from practitioners experienced in prefabricated renovation projects.

2.2. Pilot site and buildings

This study's pilot site is located in the Mustamäe residential district of Tallinn, where four nearly identical apartment buildings, constructed in the 1960 s using prefabricated concrete sandwich panels, require energy renovation due to significant heat losses and thermal discomfort. These buildings are part of pilot initiatives aimed at accelerating the renovation of typical Soviet-era multi-story apartment buildings in Estonia. Fig. 2 presents the pilot site and a close-up view of the four typical apartment buildings.

The baseline scenario assumes unrenovated external walls and roofs with poor thermal performance (U-value of 0.90 and 0.87 W/(m^{2}K) respectively) [43]. Buildings are equipped with natural ventilation and connected to district heating for both space heating and domestic hot water (DHW), with a single-pipe radiator system, which is representative of the local building stock. Although partial renovations have been carried out (e.g., such as window replacements and end-wall insulation), full-scale renovation has not yet been implemented. Project documentation has been prepared for selected references buildings, including wall and roof insulation as well as ventilation and heating system upgrades, with cost estimates based on current market prices. The environmental impact is assessed based on a typical building lifespan of 50 years. Table 1 presents the main characteristics of the four residential buildings included in the study.

2.3. Product stage: Renovation design measures and packages

One main goal of renovation activity is to improve building energy performance by upgrading the thermal envelope, upgrading and replacing heating and ventilation systems, and integrating renewable energy technologies. Potential energy savings in this study are driven by the remaining headroom to energy class thresholds, which in turn



Fig. 2. The pilot site in Tallinn (left) and one of four typical apartment buildings (right).

Table 1
Main characteristics of four selected pilot buildings.

Characteristic	Value
Construction year	1960 s
Building footprint, m^2	855–864
Net floor area, m^2	4,493–4,529
Heated building area, m^2	3,744–3,774
Net façade area, m^2	1,753
Area of windows and doors, m^2	596
Number of floors (above/underground)	5/1
Primary construction material	Concrete sandwich panels
Baseline primary energy consumption per heated building area, kWh/(m^2a)	154–178
Approximate distance to neighboring building, m	45

reflects each building's measured baseline and any prior partial renovations. Based on three years of monthly pre-renovation utility data by energy carrier (district heat, domestic hot water, electricity, and natural gas where applicable), normalized by heated area and heating degree days and converted from final to primary energy using national primary energy factors (PEFs), the baseline performance of the four buildings is 154–178 kWh/(m^2·a), shown in Table 1. Achieving a:

- **C-class rating** (≤150 kWh/(m^2a)) requires reducing energy consumption by 4–28 kWh/(m^2a), or 18,032–126,224 kWh annually depending on the building.
- **B-class rating** (≤125 kWh/m^2a) requires reducing energy consumption by 29–53 kWh/(m^2a) or 130,732–238,924 kWh annually depending on the building.
- **A-class rating** (≤105 kWh/(m^2a)) requires reducing energy consumption by 49–73 kWh/(m^2a) or 220,892–329,084 kWh annually depending on the building.

Table 2 summarizes individual renovation measures for the selected buildings. These are typical solutions that have been used in Estonian prefabricated renovation projects, including quantities, costs, and corresponding environmental impacts, measured as global warming potential (GWP). To reflect the building's lifecycle, the GWP for each measure is adjusted with a B4 stage replacement coefficient, which accounts for the future replacement of components with a shorter lifespan than the building itself. For example, while long-lasting elements like the wall and roof structures have a coefficient of 1.0, components like windows are assigned a coefficient of 1.3, and technical systems such as HVAC and PV panels have coefficients of 2.0 and 2.5, respectively [44]. In this study, only energy renovation measures are considered. Prefabricated external walls are described separately due to their elevated focus in this study.

Material choices play a key role in reducing the overall carbon

Table 2
Individual renovation measures and characteristics per renovation component measure.

Code	Building part	Description	Unit	Quantity	Cost (VAT excluded), €	Weight, kg/unit	Mass, kg	UnitGWP_{tot}, $kgCO_2e/kg$	GWP_{tot} (A1-A3), $kgCO_2e$
R1	Roof	Timber frame, EPS insulation, mineral wool rigid insulation	m^2	920	90,709	18.82	17,314	1.38	23,893
R2	Roof (raised)	Timber frame, prefabricated ventilated timber roof insulation panels	m^2	920	227,129	44.18	40,647	0.42	17,171
FW	Foundation wall	Bitumen waterproofing membrane, EPS insulation, cement fibre board (U <= 0,13 W/(m^2K))	m^2	146	11,051	17.80	2,598	1.47	3,833
W	Windows	Triple-glazed, typical frame (U < 0,9 W/(m^2K))	pc	276	133,400	39.00	22,640	3.47	78,564
D	External doors	Insulated (U < 0,9 W/(m^2K))	pc	8	20,800	59.00	924	1.51	1,397
HS1	Exhaust heat pump heating system	Radiators	pc	244	21,960	22.60	5,514	1.80	9,926
		Modular valves	pc	244	5,051	0.24	58	1.70	99
		Thermostat heads	pc	240	2,460	0.13	31	3.11	99
		Radiator pipework	pc	1,750	6,125	2.00	857	2.20	1,115
		Fresh air elements	pc	160	14,757	3.14	320	1.30	704
HS2	Mechanical ventilation heating system	Radiators	pc	244	21,960	22.60	5,514	1.80	9,926
		Modular valves	pc	244	5,051	0.24	58	1.70	99
		Thermostat heads	pc	240	2,460	0.13	31	3.11	99
		Radiator pipework	m	1,750	6,125	0.49	857	1.30	1,115
		Heating vent pipework	m	168	1,625	3.14	527	1.30	686
VS1	Exhaust heat pump ventilation system	HDPE facade pipework	m	618	5,321	0.47	290	3.11	903
		HDPE roof pipework	m	376	2,447	0.43	161	3.11	503
		Sheet metal pipework in thermal insulation	m	325	9,744	2.30	747	4.29	3,205
		Sheet metal pipework outside	m	6	640	11.00	70	4.29	302
		Pipework inside apartment	m	184	975	1.60	294	4.29	1,263
		Exhaust ceiling vent	pc	164	1,479	0.40	65	1.80	118
		Fire dampers	pc	80	3,600	0.40	32	1.70	54
		Access panels	pc	80	505	0.80	64	1.30	83
		Fresh air dampers	pc	24	912	0.56	13	2.20	30
VS2	Mechanical ventilation system	HDPE facade pipework	m	2,600	22,386	0.47	1,222	3.11	3,800
		HDPE roof pipework	m	770	5,005	0.43	331	3.11	1,030
		Sheet metal pipework in thermal insulation	m	348	10,440	2.30	800	4.29	3,434
		Sheet metal pipework outside	m	18	1,760	11.00	193	4.29	831
		Pipework inside apartment	m	232	1,230	1.60	371	4.29	1,592
		Exhaust ceiling vent	pc	164	1,479	0.40	65	1.80	118
		Supply ceiling vents	pc	160	2,454	0.40	64	1.80	115
		Fire dampers	pc	240	10,800	0.40	96	1.70	163
		Access panels	pc	80	505	0.80	64	1.30	83
		Fresh air dampers	pc	24	912	0.56	13	2.20	30
PV	PV panels	Power output 226 W/m^2	kW	50	50,000	12.19	2,696	23.00	62,016

footprint by enhancing thermal performance and energy efficiency. This study evaluates four prefabricated ventilated timber façade systems with three different finishing materials (Table 3), previously implemented in completed Estonian renovation projects. Altogether 12 different prefabricated wall systems are compared. These systems have a varied insulation thickness and construction details, affecting energy performance and carbon impact. Their comparison provides a basis for selecting facade solutions that align with overall renovation goals of the pilot site.

In past projects, Class C renovations typically used 150 mm insulation (EW4), while B- and A-class used 200 mm (EW3 and EW2), and 270 mm (EW1), respectively. It is important to note, while external walls are important, a building's energy performance class as a whole depends on a combination of renovation measures. The main difference between class B and A is that a class A requires installing renewable energy source, often achieved with the integration of photovoltaic (PV) panels in Estonia. This is the reason for the minimal difference between EW2 and EW3, achieving A and B energy class of buildings, respectively.

In addition to material manufacturing impact, the study addresses the energy used in assembling prefabricated elements at the factory, covering both electricity and wood pellet consumption That particular factory uses on average 22 tons of wood pellets annually for heating. This is converted using the energy content of wood pellets (4.85 kWh/kg [45]. Electricity consumption is subject to seasonal variation, lower consumption in July reflects a two-week collective holiday, while higher consumption during winter months is attributed to the use of electric heaters in wardrobes and increased lighting demand. The factory's yearly energy usage from electricity totals 91,291 kWh.

2.4. Construction stage: Renovation production process model and initial data

This section describes the industrialized renovation process model for renovating multiple similar buildings in proximity using prefabricated wall and roof elements. It is developed based on lessons learned from past pilot projects and feedback from renovation team members, emphasizing project duration, cost, and carbon emissions associated with construction machinery (e.g., cranes, lifts). Three renovation process scenarios for renovating building walls and roofs with prefabricated elements are compared:

Sequential (Scenario 1): Each building is renovated independently. This approach typically results in the longest total duration but requires the least initial resource investment and minimal coordination.

Two-at-the-time (Scenario 2): Two buildings are renovated in parallel, reducing overall duration and there is partially overlapping resource use. Moderate coordination is needed between teams.

All-at-once (Scenario 3): All four buildings are renovated more or less simultaneously. This approach has the shortest timeline but needs high initial resource input and extensive coordination and logistics management.

All three renovation scenarios begin with surveying (e.g., laser scanning and photogrammetry) to capture existing conditions, followed by a three-month design stage per building, including preliminary design to detailed design stages. Although similarities among four buildings allow for parallel design and reuse of solutions, local differences (such as window or door placements, different façade conditions and building entrance solutions) may require small design adjustments per building. However, the exact analysis of pre-installation steps is outside the scope of this study.

The renovation packages are different combinations of individual renovation measures in Table 2, and the impact of these packages are reflected in A1-A3 (product stage) and B6 (use stage) results. For the renovation production process model, the focus is on prefabricated envelope works (external wall, roof, windows), i.e., the tasks that determine heavy machinery use and site logistics. Management scenarios vary the degree of how much work is conducted in parallel between buildings (sequential, two-at-a-time, four-at-a-time) for selected envelope tasks. Other measures either require minimal heavy machinery and/or occur in parallel and thus are held constant and not shown in the sequence but remain included in the package-level cost and embodied and operational carbon totals. Extending the sequence to additional measures (e.g., PV installation, HVAC works) would expand the number of possible scenario combinations and increase absolute duration and overhead costs, but this is beyond the present scope.

Table 4 breaks prefabrication-related envelope renovation measures into specific tasks, productivity metrics (i.e., unit, quantity, and man-hour/unit), and resource needs for renovating walls and roofs per building (Scenario 1). General builders (4 workers split into 2 crews)

Table 3
Descriptions of the external wall design details and characteristics per facade area produced.

Code	External wall description	Exterior finish	Weight, kg/m^2	GWP$_{tot}$ (A1-A3), kgCO$_2$e/m^2	GWP$_{tot}$ (A1-A3), kgCO$_2$e/kg	Cost (VAT excluded), €/m^2
EW1	Ventilated timber facade with 200 + 70 mm mineral wool insulation; 30 mm rigid mineral wool wind barrier	Fibre cement board	32.1	20.9	0.65	67.5
		Wooden cladding	28.9	10	0.35	37.1
		Steel and aluminum panel	31.6	44.6	1.41	55.8
		Average:	30.8	25.2	0.80	53.5
EW2	Ventilated timber facade with 200 mm mineral wool insulation; 10 mm gypsum (plaster) wind barrier	Fiber cement board	31.2	18.1	0.57	59.3
		Wooden cladding	28.8	7.2	0.25	28.9
		Steel and aluminum panel	31.7	41.8	1.33	47.7
		Average:	30.7	22.4	0.72	45.3
EW3	Ventilated timber facade with 200 mm mineral wool insulation; 13 mm rigid mineral wool wind barrier	fibre cement board	26.9	18.2	0.68	61.3
		wooden cladding	23.4	7.3	0.31	30.9
		steel and aluminum panel	26.7	41.9	1.59	49.6
		Average:	25.7	22.5	0.86	47.3
EW4	Ventilated timber facade with 150 mm mineral wool insulation; 13 mm rigid mineral wool wind barrier	fibre cement board	26	17.4	0.67	56.9
		wooden cladding	22.8	6.5	0.28	26.6
		steel and aluminum panel	25.5	41.1	1.61	45.3
		Average:	24.8	21.7	0.86	42.9

Table 4
Renovation tasks, productivity metrics, construction labor and machinery need per building.

No	Renovation tasks	Unit	Quantity	Consumption rate, man-hour/unit	Duration, days	Crew count	Workers per crew	Worker count	Crane count	Crane rental, days	Lift count	Lift rental, days
1	Facade preparation, demolition of existing balconies	pc	144	1.33	6	2	2	4	0	0	4	6
2	Anchor installation	pc	282	0.11	1	2	2	4	0	0	4	1
3	Load-bearing beam installation	m	170	0.38	4	1	2	2	0	0	0	0
4	Roof elements support frame	m^2	900	1.42	20	1	8	8	1	1	0	0
5	Removal of existing windows	pc	276	3.33	10	2	3	6	2	10	4	10
	Prefabricated facade element installation	pc	144									
6	Vapor and air tightening of joints	m	900	0.16	6	3	1	3	0	0	3	6
7	Prefabricated roof element installation	pc	63	1.14	3	1	3	3	1	3	0	0
8	Horizontal joint flashing installation	m	872	0.06	2	3	1	3	0	0	3	2
9	Roof finish installation	m^2	900	0.04	2	1	2	2	0	0	0	0

complete façade preparation and roof frame construction over 6 and 20 days, respectively. Specialized trades handle tasks such as anchor installation (4 installers for 1 day), load-bearing beam installation (2 installers for 4 days), and installation of prefabricated façade elements (6 installers for 10 days, with crane support). Additional activities include vapor and air sealing (3 installers for 6 days) and roof finishing (2 installers for 2 days).

The environmental and economic impacts of renovation activities are evaluated based on machinery data. Information regarding machinery needs and costs was received from renovation experts and cross-checked against current supplier quotes. For each task the machine type (crane, lift), count and duration were recorded. The greenhouse gas emissions information was taken from Tang et al. [46]. The following cost rates and greenhouse gas emissions for diesel machinery are assumed: (1) **crane** – 26.6 $kgCO_2e/h$ at €60/hour, and (2) **lift** – 4.3 $kgCO_2e/h$ at €19/hour. The number of cranes and lifts per work are presented in Table 4. In Scenarios 2 and 3, these labor and machinery demands double and quadruple, respectively, to account for simultaneous renovation across buildings. Fig. 3 illustrates the data presented in Table 4, showcasing the typical sequence, overlap and dependencies of the prefabrication-related renovation works of the building envelope.

A representative construction-stage cost estimate is compiled from contractor bids for comparable Estonian renovation projects. To illustrate district-scale procurement, a 10 % reduction to unit rates for direct materials and labor, based on input from suppliers, is applied. Some categories, such as site overheads, client's reserve, and surveys are not adjusted.

To model the economies of scale in site overheads inherent in a district-level project, a distinction is made between direct and indirect resources in the construction management scenarios. Direct production resources, such as the construction crews and machinery required for physical work, are scaled linearly with the number of simultaneous

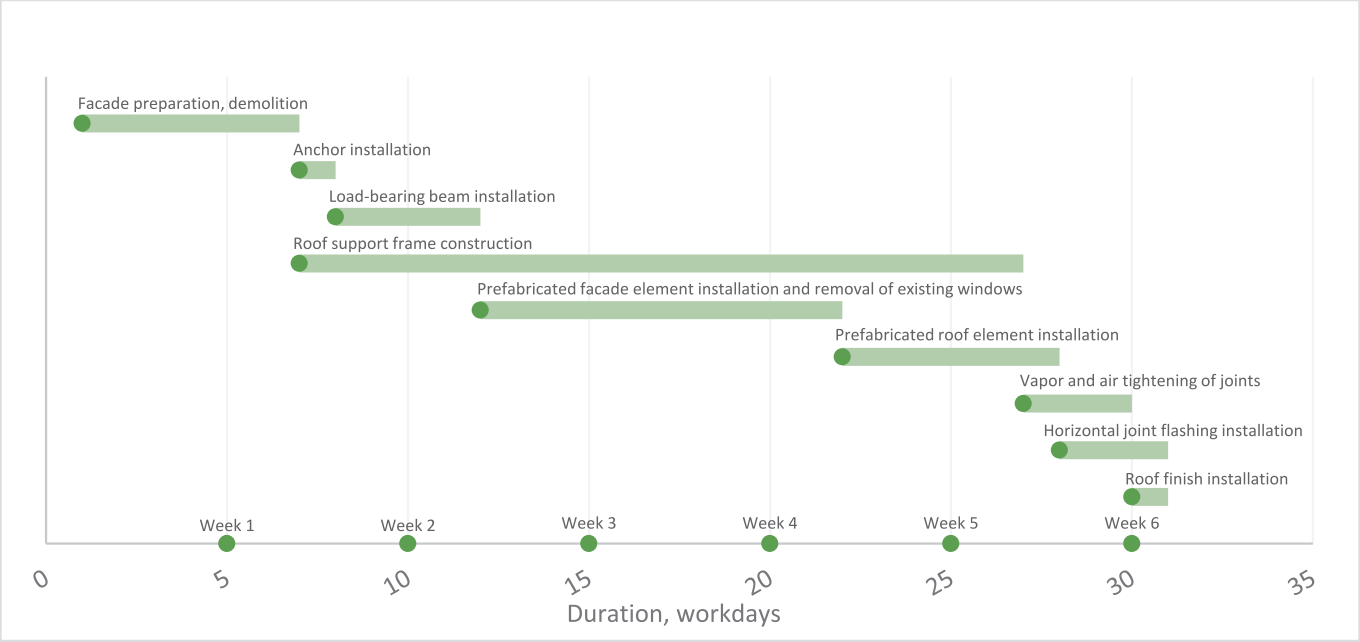


Fig. 3. Sequence of prefabrication-related renovation works.

building sites (i.e., doubled for Scenario 2 and quadrupled for Scenario 3). However, indirect, time-based overheads such as supervising staff and site facilities do not scale linearly. The cost of these resources is primarily a function of project duration and management complexity, not a direct multiplication of output. To account for the economies of scale in the accelerated scenarios, the non-linear scaling of overheads is modeled using the exponential rule from construction cost engineering [47]. Following the examples for complex projects, a cost exponent of m = 0.6 was selected. Using this principle, the calculated overhead coefficients are 1.52 for Scenario 2 and 2.30 for Scenario 3.

3. Results

In this section, the results of the analysis are presented, highlighting the impact of different scenarios on the overall economic and environmental aspects of the renovation project.

3.1. Product stage: External wall

From the prefabricated external wall data in Table 3, several observations can be made. Most importantly, the type of the exterior finish material dominates both the cost and embodied carbon of external wall systems (see Fig. 4). External walls with wooden cladding (W) have the lowest GWPtot (A1–A3) (ranging between 6.50 and 10.0 $kgCO_2e/m^2$) and the lowest cost (26.6 – 37.1 €/m^2) per m^2 of facade produced. Steel and aluminum panels (SA) have the highest carbon impact, ranging between 41.1 and 44.6 $kgCO_2e/m^2$, and is second in terms of cost, ranging between 45.3 and 55.8 €/m^2. Fiber cement board (FC) is the most expensive, cost ranging between 56.9 and 67.5 €/m^2, and it is in-between regarding embodied carbon, ranging from 17.4 to 20.9 $kgCO_2e/m^2$ per wall system.

Fig. 4 depicts wall types of different insulation thicknesses within 3 exterior finish groups. The analysis shows that within each exterior finish, embodied carbon rises with insulation thickness, varying up to 4 $kgCO_2e/m^2$. However, this is minor compared to the exterior finish material impact, which can alter the GWP by up to 35 $kgCO_2e/m^2$. Similarly, a detailed comparison of the two wall systems with different wind barrier materials (10 mm gypsum plasterboard (EW2) and 13 mm rigid mineral wool (EW3)) highlights that while their total GWP per m^2 is nearly identical, the GWP per kg and cost are slightly higher for the mineral wool option. This demonstrates that also small differences in material type can have a visible impact on the final cost and emissions when accumulated across large-scale projects. Overall, this analysis reveals that the EW4 with wooden cladding at 6.5 $kgCO_2e/m^2$ has the lowest embodied carbon and is also the cheapest at 26.6 €/m^2, reinforcing the finding that the lowest carbon choice can also be the most economical. However, these calculations reflect only the initial cost and A1–A3 stages. Over a 50-year design building lifespan differences in service life and maintenance cycles (e.g., repainting/oiling of wooden cladding) can alter the total cost, and a life-cycle cost (LCC) assessment could yield a different ranking.

Furthermore, the embodied carbon of prefabrication is assessed. In 2023, the total energy consumption for the preassembly factory (excluding July) amounted to 89,141 kWh of electricity and 97,812 kWh of wood pellets. On average, 2,500 m2 of prefabricated elements were produced per month, resulting in an average energy consumption of 6.80 kWh/m2. Based on Estonia's carbon intensity factor for electricity (0.693 $kgCO_2e/kWh$) [48] and wood pellets (0.024 $kgCO_2e/kWh$) (Graanul [49], the added embodied carbon from the assembly of prefabricated facade elements was calculated to be 2.33 $kgCO_2e/m^2$ of façade element, resulting in an average of 12.8 % increase in the total embodied carbon. Fig. 5 visualizes total A1-A3 embodied carbon for the external wall types by combining the material manufacturing impacts from Table 3 with the factory assembly impacts, with an average of 91.7 % stemming from initial product manufacturing and 8.3 % from the assembly process. The results are presented by exterior finish type.

3.2. Product stage: Renovation packages

The study assesses 16 renovation packages (Table 6), each combining one of four external wall systems (EW1-EW4), one of two roof types (R1-R2), and one of two HVAC solutions, exhaust heat pump heating (HS1 + VS1) or central mechanical heat recovery (HS2 + VS2). The same foundation wall insulation, windows and doors are used in every package. PV panels are only included in those targeting energy class A.

Post-renovation energy performance by end use of the renovation packages is presented in Table 5. Final energy is reported for electricity

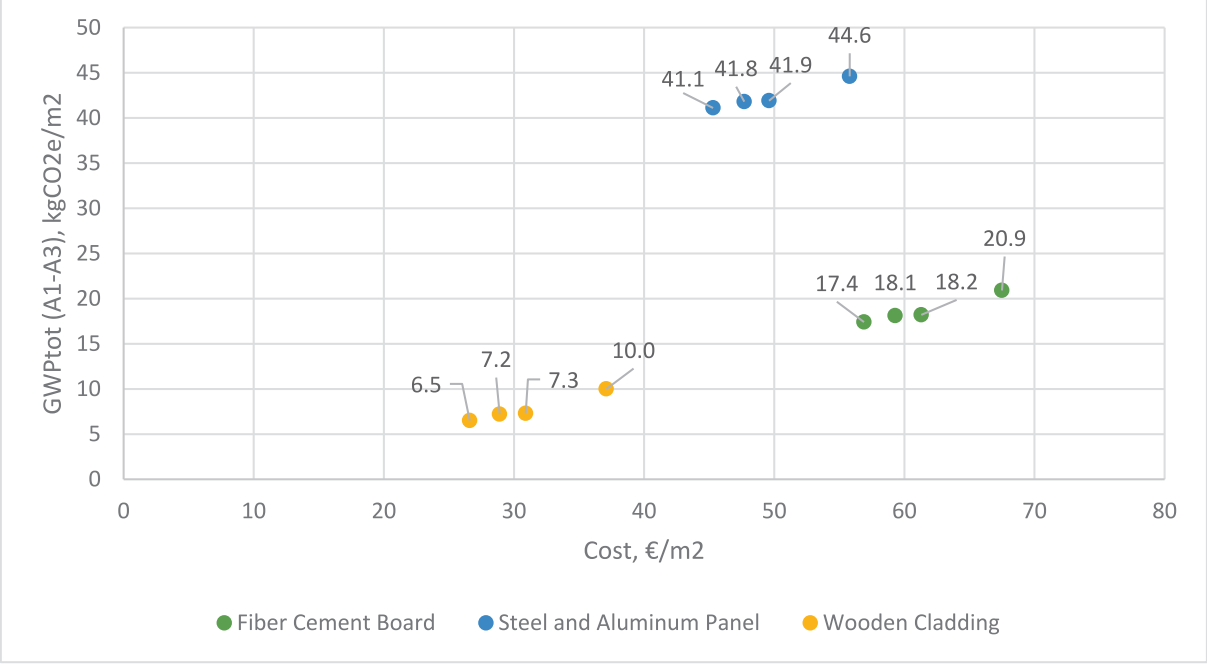


Fig. 4. Cost versus embodied carbon of wall systems with different exterior finish material.

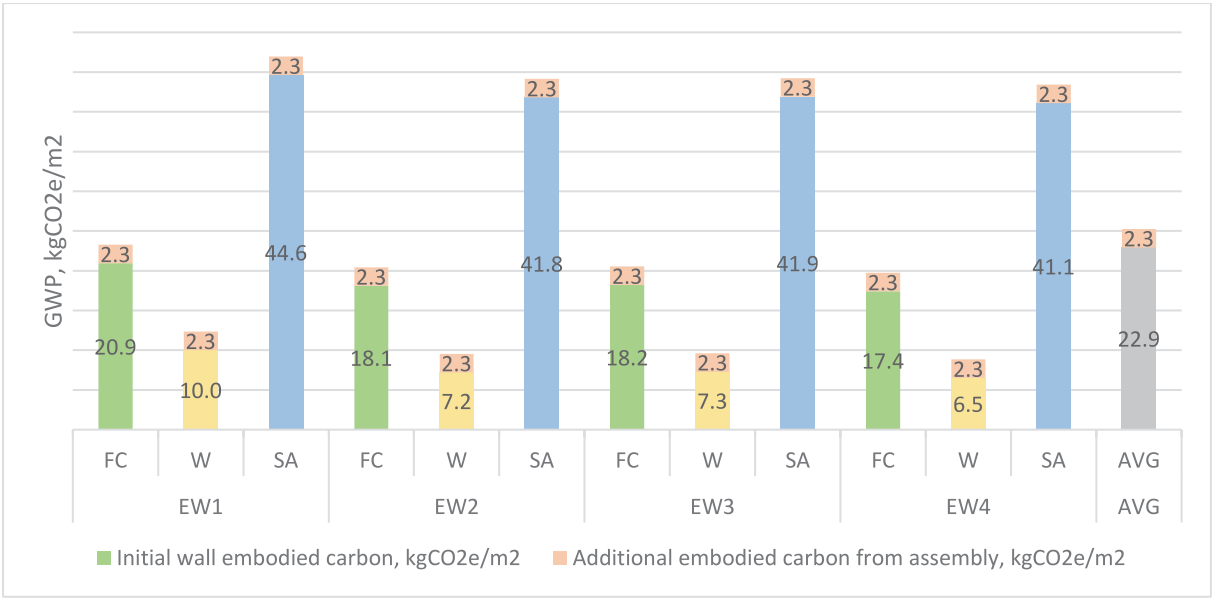


Fig. 5. Total embodied carbon in prefabricated external walls from material manufacturing and element preassembly.

Table 5
Energy performance of renovation packages.

No	Final electricity energy (heating, DHW, appliances, other), kWh/m^{2}a	Final heating energy (heating, DHW), kWh/m^{2}a	Primary electricity energy (heating, DHW, appliances, other), kWh/m^{2}a	Primary heating energy (heating, DHW), kWh/m^{2}a	PV self-consumption, kWh/m^{2}a PV self-consumption	Post-renovation final energy consumption, kWh/m2a	Post-renovation primary energy consumption, kWh/m^{2}a	Decrease in primary energy consumption vs pre-renovation, kWh/m^{2}a
1	47 (6, 8, 22, 11)	13 (7, 6)	83 (10, 15, 39, 19)	9 (5, 4)	6	61	92	62–86
2	35 (0, 0, 22, 13)	57 (24, 33)	60 (0, 0, 38, 22)	38 (16, 22)	6	93	98	56–80
3	35 (0, 0, 22, 13)	57 (24, 33)	60 (0, 0, 38, 22)	38 (16, 22)	6	93	97	57–81
4	47 (6, 8, 22, 11)	13 (7, 6)	83 (10, 15, 39, 19)	9 (5, 4)	6	61	92	62–86
5	47 (6, 8, 22, 11)	13 (7, 6)	85 (11, 15, 40, 19)	9 (5, 4)	6	61	92	62–86
6	35 (0, 0, 22, 13)	58 (25, 33)	60 (0, 0, 38, 22)	38 (16, 22)	6	94	98	56–80
7	35 (0, 0, 22, 13)	58 (25, 33)	60 (0, 0, 38, 22)	38 (16, 22)	6	94	98	56–80
8	47 (6, 8, 22, 11)	13 (7, 6)	85 (11, 15, 40, 19)	9 (5, 4)	6	61	93	69–85
9	47 (6, 8, 22, 11)	14 (8, 6)	97 (13, 17, 45, 22)	9 (5, 4)	0	62	105	49–73
10	35 (0, 0, 22, 13)	59 (26, 33)	71 (0, 0, 45, 26)	39 (17, 22)	0	96	111	43–67
11	35 (0, 0, 22, 13)	59 (26, 33)	71 (0, 0, 45, 26)	39 (17, 22)	0	95	110	44–68
12	47 (6, 8, 22, 11)	14 (8, 6)	97 (13, 17, 45, 22)	9 (5, 4)	0	62	105	49–73
13	48 (7, 8, 22, 11)	14 (8, 6)	99 (15, 17, 45, 22)	9 (5, 4)	0	63	107	47–71
14	35 (0, 0, 22, 13)	64 (31, 33)	71 (0, 0, 45, 26)	42 (20, 22)	0	100	114	40–64
15	35 (0, 0, 22, 13)	63 (30, 33)	71 (0, 0, 45, 26)	42 (20, 22)	0	99	114	40–64
16	49 (8, 8, 22, 11)	14 (8, 6)	99 (15, 17, 45, 22)	9 (5, 4)	0	63	108	46–70

and heating. On-site PV first covers the building's electric loads, only the remainder is purchased from the grid. Primary energy is calculated from the delivered electricity and district heat using the Estonian methodology for calculating the energy performance of buildings and converted to primary energy using national primary energy factors (PEF) (electricity 2.0; district heating 0.65). PV exports are shown separately and are excluded from consumption totals. In the end-use split, *heating* includes space heating and ventilation-air heating, *other* comprises lighting and ventilation fans.

For each package, cost (€/m2) over the building's net floor area, embodied carbon (GWP(A1 A3), kgCO_2e/m2a) and operational carbon (GWP(B6), kgCO_2e/m2a) per heated area of single building (3765 m^2) is calculated. For example, Package 1 (combines EW1 + R2 + FW + W + D + HS1 + VS1 + PV) achieves a primary energy consumption of 92 kWh/m^{2}a (a reduction of 62–86 kWh/m^{2}a down from a pre-renovation consumption of 154–178 kWh/m^{2}a) at a cost of 526 €/m^2 and with an embodied carbon of 1.89 kgCO_2e/m^{2}a and operational carbon of 30.11 kgCO_2e/m^{2}a.

The analysis of the 16 renovation packages presents a conflict between minimizing upfront investment and embodied carbon versus achieving long-term operational performance. Two distinct pathways are viable.

The first group of packages (9–16) does not include PV systems, which results in the lowest initial embodied carbon (1.04–1.13 kgCO_2e/m^{2}a). Within this set, a trade-off between initial cost and long-term performance is evident. Package 16 represents the minimum initial investment at 474 €/m^2, but this is associated with the highest operational emissions of any package analyzed. In contrast, Package 14 emerges as a strong balanced option. At 478 €/m^2, it is one of the lowest-cost packages, and its use of the mechanical ventilation and heating system (HS2, VS2) results in good operational performance (30.23 kgCO_2e/m^{2}a).

Packages with PV show a modest increase in A1–A3 and a larger reduction in B6 by displacing grid electricity. The net life-cycle effect depends on the grid emission factor (higher-carbon grids amplify the operational benefit). Analysis indicates that Package 3 achieves the best operational performance but is also the most expensive option at 530

Table 6
Description of renovation packages.

No	Description	Renovation package cost, €/m^2	Embodied carbon (A1-A3) GWP$_{tot}$, kgCO$_2$e/m^{2}a	Post-renovation operational carbon (B6) GWP$_{tot}$, kgCO$_2$e/m^{2}a
1	**EW1**, **R2**, FW, W, D, **HS1**, **VS1**, PV	526	1.89	30.11
2	**EW1**, **R1**, FW, W, D, **HS2**, **VS2**, PV	500	1.98	25.61
3	**EW1**, **R2**, FW, W, D, **HS2**, **VS2**, PV	530	1.94	25.59
4	**EW1**, **R1**, FW, W, D, **HS1**, **VS1**, PV	496	1.93	30.16
5	**EW2**, **R2**, FW, W, D, **HS1**, **VS1**, PV	518	1.87	30.30
6	**EW2**, **R1**, FW, W, D, **HS2**, **VS2**, PV	491	1.95	25.70
7	**EW2**, **R2**, FW, W, D, **HS2**, **VS2**, PV	522	1.92	25.68
8	**EW2**, **R1**, FW, W, D, **HS1**, **VS1**, PV	487	1.90	30.35
9	**EW3**, **R2**, FW, W, D, **HS1**, **VS1**	509	1.05	34.59
10	**EW3**, **R1**, FW, W, D, **HS2**, **VS2**	482	1.13	29.88
11	**EW3**, **R2**, FW, W, D, **HS2**, **VS2**	513	1.10	29.85
12	**EW3**, **R1**, FW, W, D, **HS1**, **VS1**	478	1.08	34.64
13	**EW4**, **R2**, FW, W, D, **HS1**, **VS1**	504	1.04	35.37
14	**EW4**, **R1**, FW, W, D, **HS2**, **VS2**	478	1.12	30.23
15	**EW4**, **R2**, FW, W, D, **HS2**, **VS2**	508	1.09	30.21
16	**EW4**, **R1**, FW, W, D, **HS1**, **VS1**	474	1.07	35.42

€/m^2. Other packages offer different compromises; for example, Package 2 provides the second-best operational performance at a more moderate cost, while Package 6 is identified as the most cost-effective PV-inclusive option (491 €/m^2) while still delivering high operational performance. The trade-offs balancing cost, embodied and operational carbon are illustrated in Fig. 6.

In summary, the selection of an optimal renovation package depends heavily on project-specific goals and priorities: 1) for the absolute lowest initial cost, Package 16 is the choice, accepting a high operational footprint; 2) for the most balanced performance without PV, Package 14 is a strong option, offering high operational efficiency at a low initial cost; 3) for a well-rounded PV-inclusive solution, Package 6 offers an effective compromise between cost and strong operational performance. These findings reinforce the need for an integrated approach in designing renovation strategies.

3.3. Construction stage: Duration and cost

The duration of the construction stage varies significantly depending on the selected renovation process strategy. Renovating four buildings one-after-another (Scenario 1) requires 22 weeks. Renovating two buildings concurrently (Scenario 2) halves the duration to 11 weeks, while renovating all four simultaneously (Scenario 3) reduces the duration to a little over 6 weeks (see Fig. 7).

After the completion of design and factory prefabrication, the on-site sequence is identical in all three scenarios: facade preparation, anchor placement, carrier-beam installation, roof-support-frame erection, installation of prefabricated façade and roof elements, joint sealing, and roof finishing. The same eight-person crew executes both facade preparation and roof-frame erection, relocating between buildings as soon as a roof frame is complete. This sequencing ensures a smooth workflow and maximizes productivity, particularly in Scenarios 2 and 3, minimizing overlap and delays.

To illustrate the financial composition of a deep renovation, Table 7 provides a detailed cost estimate for a representative renovation solution, Package 6.

To illustrate district-scale procurement and economies of scale, a 10 % reduction to direct materials and labor across the Table 7 sub-groups can be applied, while keeping some items unchanged (site overheads, client's reserve, and surveys). Under this assumption, the Package 6 construction total would decrease by €202,000 (−9.2 %), from €2.2 M (491 €/m2) to €2.0 M (446 €/m2). As fixed items are held constant, their share of total rises slightly.

Alongside bulk procurement, a second procurement lever is time on site: overheads scale with project duration. In Scenario 1, the four buildings are renovated sequentially over a total of seven months. This standard timeline leads to total overhead costs of €15.54 per m^2 with diesel machinery or €12.89 per m^2 with electric alternatives. In Scenario 2, renovating two buildings in parallel reduces the project duration to four months. This acceleration leads to cost efficiencies, with total overheads decreasing by approximately 3 % to €15.11 per m^2 for diesel machinery and €12.46 per m^2 for electric. Scenario 3, renovating all four buildings simultaneously, achieves the shortest duration of 2.5 months and is the most cost-effective strategy. The significant reduction in time-based costs (such as staff salaries and site office rental) outweighs the increased costs of logistical intensity (e.g., machinery transport). Consequently, overheads fall by approximately 3.4 % compared to the standard sequential approach, to €15.01 per m^2 for diesel machinery and €12.36 per m^2 for electric.

While the differences in overhead costs between the scenarios are modest, the analysis shows that acceleration of project timelines is beneficial: the most rapid approach (Scenario 3) is also the cheapest (see Table 8). It cuts the construction schedule by over 70 % compared to the standard sequential approach (Scenario 1) while also offering the largest overhead cost savings of over 3 %. Although the direct financial savings are not significant, the substantial non-financial benefits, including reduced resident disruption and accelerated project completion, provide a strong justification for adopting the accelerated strategy.

3.4. Construction stage: Carbon emissions

The choice of renovation management strategy in this study has a relatively small impact on the total on-site carbon emissions from construction (see Table 9). While the composition of emissions changes between scenarios, the totals remain almost flat. For example, using diesel machinery, the total emissions are 2.35 kgCO$_2$e/m^2 in Scenario 1, 2.34 kgCO$_2$e/m^2 in Scenario 2, and 2.36 kgCO$_2$e/m^2 in Scenario 3. This indicates that the time and cost benefits of the accelerated strategies do not come with a significant carbon penalty for the construction stage.

This stability in total emissions is due to two offsetting factors. As the project timeline is compressed, emissions from logistical intensity increase, for example, machinery transport emissions more than

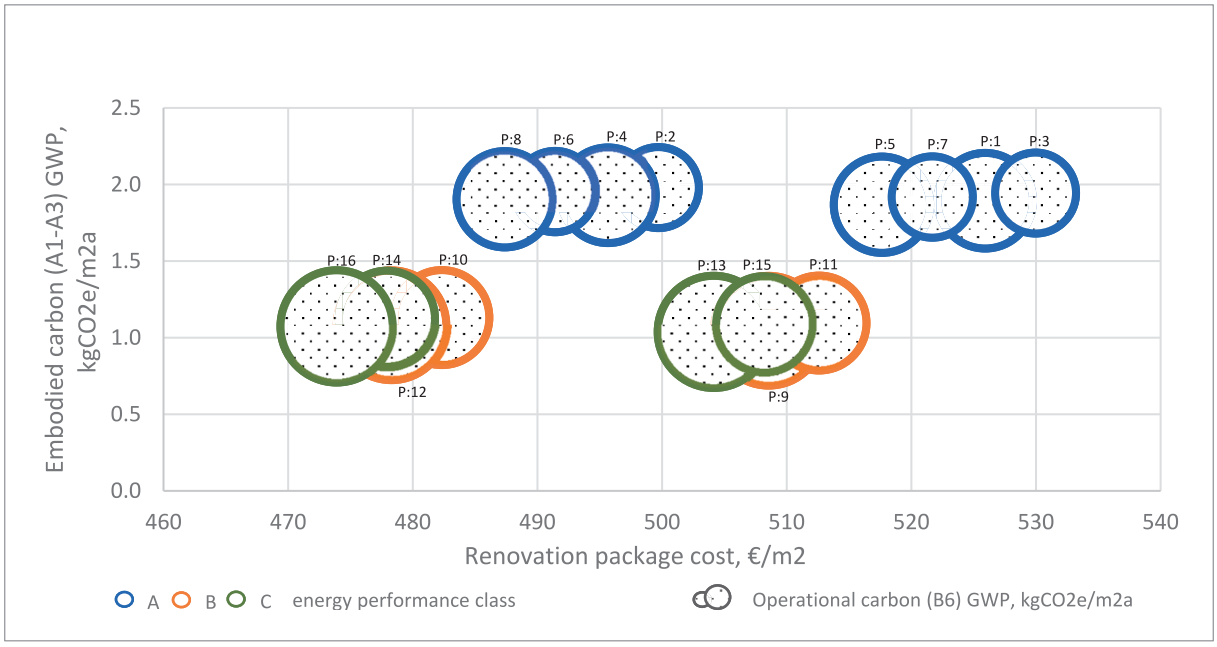


Fig. 6. Cost vs embodied and operational carbon trade-offs of the renovation packages. P – renovation package.

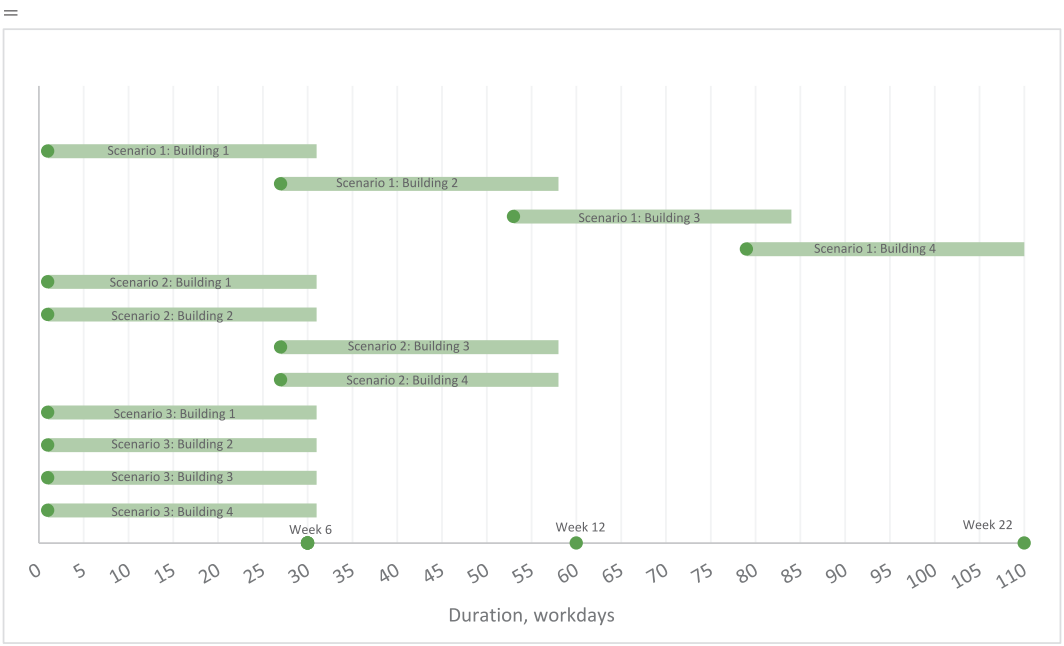


Fig. 7. Schedules of the prefabrication-related works of the three renovation scenarios.

quadruple from Scenario 1 to Scenario 3 (0.01 to 0.05 $kgCO_2e/m^2$). However, emissions from time-based resource use decrease. For example, office energy consumption emissions lower by over 18 % from Scenario 1 to Scenario 3 (0.16 to 0.13 $kgCO_2e/m^2$) due to the shorter duration. This is because the significant reduction in project duration has a greater impact than the increase in monthly resource intensity, resulting in lower overall energy consumption.

On-site emissions are reported for the current electricity mix. Under present factors, switching from diesel to electric machinery yields a modest reduction (~8% from ca 2.35 to 2.17 $kgCO_2e/m^2$) in Estonia. The climate benefit of electrification scales with grid decarbonization, which would also reduce operational (B6) and electricity-related embodied (A1-A3) components, however, a full decarbonization analysis lies outside the scope of this paper.

3.5. *Summary of product, construction and operational stage carbon emissions*

To provide a consolidated view of carbon emissions, Table 10 summarizes the GWP for the lifecycle stages A1-A5 and B6, using the balanced Renovation Package 6 and the most rapid construction strategy (Scenario 3, diesel) as a representative example.

The analysis breaks down the emissions into three key stages. The A1-A3 stages, which cover the embodied carbon of materials from "cradle-to-gate" amount to 1.95 $kgCO_2e/m^2a$. The factory external wall preassembly stage adds an additional 0.03 $kgCO_2e/m^2a$ to each

Table 7
Package 6 cost estimate of construction costs.

Cost sub-groups	Share of total cost, %	Cost (VAT excluded), €	Cost (VAT excluded), €/m²
Demolition, site preparation and formation	0.8	17,000	4
Substructure	1.4	30,000	7
Structure	26.0	576,000	128
Architectural/non-structural works	14.7	324,000	72
Services and equipment	30.1	666,000	148
External and ancillary works	18.7	413,000	92
Site overheads/general requirements	3.6	80,000	17
Client's reserve	4.8	106,000	23
Total		**2,212,000**	**491**

Table 8
Overhead costs per four buildings in the different management scenarios.

No	Overheads cost type	Sequential (Scenario 1), Cost (VAT excluded), €/m²	Two-at-a-time (Scenario 2), Cost (VAT excluded), €/m²	All-at-once (Scenario 3), Cost (VAT excluded), €/m²
1	Staff salaries	3.11	2.70	2.55
2	Site office	0.39	0.34	0.32
3	Office energy consumption	0.04	0.03	0.03
4	Machinery transport to/ from site	0.03	0.07	0.13
5a	Machinery, diesel	7.59	7.59	7.59
5b	Machinery, electric	4.93	4.93	4.93
6	Other	4.39	4.39	4.39
7a	**Total, diesel (per m² net area)**	**15.54**	**15.11**	**15.01**
7b	**Total, electric (per m² net area)**	**12.89**	**12.46**	**12.36**

Table 9
On-site carbon emissions in the different management scenarios.

No	On-site carbon emissions type	Sequential (Scenario 1), GWP, kgCO₂e/m²	Two-at-a-time (Scenario 2), GWP, kgCO₂e/m²	All-at-once (Scenario 3), GWP, kgCO₂e/m²
1	Office energy consumption	0.16	0.14	0.13
2	Machinery transport to/from site	0.01	0.02	0.05
3a	Machinery, diesel	2.18	2.18	2.18
3b	Machinery, electricity (today's carbon intensity)	2.00	2.00	2.00
3c	Machinery, electricity (potential carbon intensity, moderate scenario)	0.22	0.22	0.22
4a	**Total, diesel**	**2.35**	**2.34**	**2.36**

renovation package. Finally, the A4-A5 stages, which include transportation and on-site construction activities, contribute 0.59 $kgCO_2e/m^2a$. This results in a total upfront carbon investment for stages A1-A5 of 2.57 $kgCO_2e/m^2a$. This together with the operational energy carbon (B6) makes up 28.27 $kgCO_2e/m^2a$.

Table 10
Embodied and operational carbon emissions across A1-A5 and B6 stages.

Stage	Description	GWP, $kgCO_2e/m^2a$ per building	Share of total emissions, %
A1-A3	Renovation package 6	1.95	6.9
	Preassembly	0.03	0.1
A4-A5	Scenario 3, diesel	0.59	2.1
B6	Renovation package 6	25.70	90.9
Total	**Renovation package 6 + Scenario 3, diesel**	**28.27**	**100**

Table 10 reveals that operational emissions (B6) are the dominant factor, accounting for nearly 91 % of the total carbon footprint for this renovation over a 50-year lifespan. In contrast, all upfront emissions from the product and construction stages (A1-A5) combined make up just over 9 % of the total. Notably, the on-site construction activities (A4-A5), despite being a major focus of project management for time and cost, contribute only 2 % to the total lifecycle carbon. This highlights the importance of prioritizing long-term energy performance (B6), low-carbon material choices (A1-A3) and the decarbonization of the energy grid as these decisions have a greater impact on a building's overall carbon footprint than the on-site construction management scenario itself.

The outputs across cost, duration and embodied and operational carbon define a cost-time-carbon trade-off rather than a single optimal option. A context-specific recommendation requires setting priorities (weights) over these criteria. Where a concrete decision is needed, practitioners can utilize standard frameworks such as Multi-Criteria Decision Analysis (MCDA) [50]or Choosing By Advantages (CBA) [51].

4. Discussion

4.1. Interpretation of findings

The study finds that façade finish selection has a more pronounced effect on A1–A3 outcomes than insulation thickness, which varies only modestly across the systems. In the twelve wall types assessed, finish choice often accounts for most of the observed variation: fiber cement and metal panels tend to have higher upfront GWP and longer maintenance intervals, whereas wooden cladding shows lower A1–A3 and lower unit cost but requires periodic surface treatment. Finish selection is therefore a design decision that balances carbon and cost with expected upkeep.

The quantification of the added embodied carbon from the factory preassembly stage, an element frequently overlooked in lifecycle assessments, is a novel contribution to understanding the full carbon footprint of industrialized renovation. The analysis of the factory's energy consumption reveals that this process adds 2.33 $kgCO_2e/m2$ to the final wall elements, increasing their initial embodied carbon by an average of 12.8 %. This demonstrates that the manufacturing process itself, not just the raw materials, has a measurable impact that should be considered in a complete carbon footprint analysis.

Additionally, the use-stage effect of PV in the renovation packages is examined. The analysis shows that PV packages attain lower B6 despite higher A1–A3: the upfront embodied impact is typically outweighed by use-stage electricity reductions over the service life, with the balance improving as the grid carbon intensity increases. In practice, where policy or client priorities emphasize use-stage carbon, PV-enabled packages gain advantage, however LCA assessments should evaluate this trade-off with the local grid intensity factor [52].

The findings of this study offer a counterpoint to research that has identified minimal benefits in district-level renovation, such as the work

of Husiev et al. [25]. While they noted challenges in financial and technical capacity, this paper's analysis of an industrialized production model demonstrates that significant time efficiencies are achievable, reducing the duration of prefabrication related renovation works by over 70 % while simultaneously decreasing overhead costs by up to 3.4 %. The key finding that accelerating the renovation schedule is not only faster but requires no added cost also provides a strong case for scaling up deep renovations in a coordinated manner. The associated reduction in resident disruption at comparable overhead cost also addresses key social barriers to scaling up renovation [53]. Additionally, economies of scale can provide up to ~ 10 % cost reductions in district-level renovation, with benefits strongest where procurement is aggregated, designs are standardized and work is sequenced across sites.

This study also reveals critical nuances in the on-site impacts of construction management. The stability of the total on-site carbon footprint across all three management scenarios highlights a trade-off between logistical intensity and project duration. As the timeline is compressed, the increase in emissions from machinery transport is almost perfectly offset by the decrease in emissions from time-based resources like site offices. This indicates that from an on-site carbon perspective, the choice of management strategy is less critical than the source of energy. It should be noted, however, that the transport emissions are highly context-dependent and would vary based on a project's specific location and logistics.

The need for decarbonization is reflected in the analysis of construction machinery. With Estonia's current high-carbon electricity grid, the benefit of switching from diesel to electric equipment is minimal, reducing on-site emissions by only about 8 %. This finding underscores that the true, massive potential of electrification (>80 % emission reduction in the A4-A5 stages) is intrinsically linked to national energy policy and the planned phase-out of oil shale. This aligns with the findings of Lylykangas et al. [54].

4.2. Implications for policy and practice

The novelty of this research lies in its integrated approach, connecting product related information (A1-A3 stages) to the strategic implications of construction management (A4-A5 stages) and placing them within the context of long-term operational performance (B6 stage). For policymakers, the fact that the fastest renovation scenario is also the most cost-effective suggests that policies and funding mechanisms should not only incentivize deep energy savings but also support coordinated, multi-building projects. Financial incentives could be structured to favor projects that leverage economies of scale in both material procurement and project management, while prioritizing the decarbonization of national electricity grids as a foundation for meaningful emission reductions from construction. Once grid carbon intensity is significantly reduced, targeted support could accelerate the uptake of low-carbon construction machinery to fully realize the benefits of electrification.

For practitioners, the findings underscore the need for an integrated approach. The optimal renovation package is not a single technical solution but a strategic decision balancing upfront investment (initial cost and embodied carbon) with long-term performance (operational cost and carbon) and project delivery (time and risk). Where a single recommendation is needed, well-stablished decision-making frameworks (e.g., MCDA or CBA) could be applied directly to make a context-specific decision.

4.3. Limitations and future directions

This study also shows that challenges remain in implementing industrialized renovations at scale. The accelerated renovation pace, while financially advantageous, introduces significant operational risks, including potential supply chain bottlenecks, skilled labor shortages, and manufacturing capacity constraints. The condensed schedule also reduces flexibility, meaning unforeseen design changes could lead to expensive delays.

Furthermore, this analysis has two key limitations that point to areas for future research. First, it focuses on upfront costs and does not include a full life-cycle cost (LCC) analysis of long-term maintenance, which is particularly relevant when comparing wooden facades to more durable materials. Second, a direct comparative analysis with a traditional, non-prefabricated renovation was outside the scope of this paper. This study quantifies the added carbon from the factory preassembly process; however, these off-site emissions are not entirely new. They effectively displace the emissions that would have occurred on-site in a conventional build, such as those from extended machinery use and higher material waste. Therefore, a direction for future research is to conduct a full comparative lifecycle assessment. Such an analysis would quantify these "displaced" emissions to determine the true net environmental benefit of the industrialized approach.

Another direction for future research is to scale up the integrated model developed in this case study. The next phase will apply this methodology to the entire Estonian stock of Soviet-era apartment buildings to assess the national-level impacts of a large-scale, industrialized renovation program. This analysis would move beyond project-level trade-offs to quantify the broader socio-economic benefits, including the potential for job creation and economic stimulus as identified in the literature [21,22]. Furthermore, it would investigate how an industrialized strategy could help overcome the critical supply-side barriers, such as insufficient organizational capacity and skilled labor shortages [25] that currently hinder the EU's renovation goals.

5. Conclusions

This study set out to evaluate how industrialized renovation of multiple similar buildings in proximity affects cost, time efficiency, energy savings, and carbon emissions, with a focus on both product-stage material choices (A1–A3) and construction-stage management strategies (A4–A5), while considering long-term operational performance (B6). Using a case study of four apartment buildings in Tallinn, Estonia, the research compared 16 renovation packages and three construction management scenarios to address this question.

The research concludes that while the management strategy presents a clear, dominant solution, the choice of the renovation package involves a trade-off between upfront and long-term impacts. The results show that the packages without PV systems minimize initial embodied carbon but have higher operational emissions, whereas PV-inclusive packages achieve the best operational performance at the expense of higher upfront carbon. In construction management, the accelerated all-at-once renovation strategy reduced the duration of prefabrication related renovation works by over 70 % and lowering overhead costs by up to 3.4 %, without increasing on-site emissions in the construction stages, indicating that on-site carbon depends more on the energy source than the management scenario.

These findings confirm that the research aim has been met: the study provides an integrated, lifecycle-based framework that quantifies the trade-offs between cost, time and carbon emissions in district-level industrialized renovation and demonstrates that the optimal approach is a strategic balance rather than a single technical "best" option. The broader implication is that policy and funding mechanisms should not only incentivize deep energy savings but also support coordinated, multi-building renovations, while aligning with national grid decarbonization to unlock the full benefits of electrification.

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CRediT authorship contribution statement

Kädi-Riin Vendel: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Ergo Pikas:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Müge Tetik:** Writing – review & editing, Writing – original draft. **Lauri Koskela:** Writing – review & editing. **Jarek Kurnitski:** Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

References

[1] European Commission. (2021, December 15). *Renovation and decarbonisation of buildings* [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683.

[2] European Commission. (2020a). *A Renovation Wave for Europe—Greening our buildings, creating jobs, improving lives*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662.

[3] Pikas, E., Lõhmus, R., Koskela, L., Tetik, M., & Vendel, K.-R. (2024). *Carbon Emissions of Construction Operations in a Cold Climate*. https://doi.org/10.24928/2024/0228.

[4] M. Weigert, O. Melnyk, L. Winkler, J. Raab, Carbon Emissions of Construction Processes on Urban Construction Sites, Sustainability 14 (19) (2022), https://doi.org/10.3390/su141912947. Article 19.

[5] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings-towards the nearly zero energy building: a literature review, Build. Environ. 105 (2016) 267–282, https://doi.org/10.1016/j.buildenv.2016.05.040.

[6] P. Rajala, A. Ylä-Kujala, T. Sinkkonen, T. Kärri, Profitability in construction: how does building renovation business fare compared to new building business, Construction Management and Economics 40 (3) (2022) 223–237, https://doi.org/10.1080/01446193.2022.2032228.

[7] Yin, R. K. (2011). *Applications of Case Study Research*. SAGE.

[8] *EN 15978:2011—Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. (2011). iTeh Standards. https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011.

[9] European Parliament and Council. (2023, September 13). *Directive (EU) 2023/1791*. http://data.europa.eu/eli/dir/2023/1791/oj/eng.

[10] European Parliament and Council. (2024). *Directive (EU) 2024/1275*. https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng.

[11] O. Morck, M. Almeida, M. Ferreira, N. Brito, K.E. Thomsen, I. Østergaard, Shining examples Analysed within the EBC Annex 56 Project, Energy Procedia 78 (2015) 2334–2339, https://doi.org/10.1016/j.egypro.2015.11.393.

[12] J. Terés-Zubiaga, R. Bolliger, M.G. Almeida, R. Barbosa, J. Rose, K.E. Thomsen, E. Montero, R. Briones-Llorente, Cost-effective building renovation at district level combining energy efficiency & renewables – Methodology assessment proposed in IEA EBC Annex 75 and a demonstration case study, Energy and Buildings 224 (2020) 110280, https://doi.org/10.1016/j.enbuild.2020.110280.

[13] European Commission. (2020b). A Renovation Wave for Europe—Greening our buildings, creating jobs, improving lives [COM(2020) 662 final].

[14] J. Hirvonen, A. Saari, J. Jokisalo, R. Kosonen, Socio-economic impacts of large-scale deep energy retrofits in finnish apartment buildings, Journal of Cleaner Production 368 (2022) 133187, https://doi.org/10.1016/j.jclepro.2022.133187.

[15] S.R. Asaee, S. Nikoofard, V.I. Ugursal, I. Beausoleil-Morrison, Techno-economic assessment of photovoltaic (PV) and building integrated photovoltaic/thermal (BIPV/T) system retrofits in the Canadian housing stock, Energ. Buildings 152 (2017) 667–679, https://doi.org/10.1016/j.enbuild.2017.06.071.

[16] J. Hirvonen, J. Heljo, J. Jokisalo, A. Kurvinen, A. Saari, T. Niemelä, P. Sankelo, R. Kosonen, Emissions and power demand in optimal energy retrofit scenarios of the finnish building stock by 2050, Sustainable Cities and Society 70 (2021) 102896, https://doi.org/10.1016/j.scs.2021.102896.

[17] V. Hasik, E. Escott, R. Bates, S. Carlisle, B. Faircloth, M.M. Bilec, Comparative whole-building life cycle assessment of renovation and new construction, Building and Environment 161 (2019) 106218, https://doi.org/10.1016/j.buildenv.2019.106218.

[18] T. Joensuu, H. Edelman, A. Saari, Circular economy practices in the built environment, Journal of Cleaner Production 276 (2020) 124215, https://doi.org/10.1016/j.jclepro.2020.124215.

[19] Kuusk, K., Ilomets, S., Kalamees, T., Tuudak, S., & Luman, A. (2014). *Renovation vs. Demolition of an old apartment building: Energy use, economic and environmental analysis*.

[20] L. La Fleur, P. Rohdin, B. Moshfegh, Energy Renovation versus Demolition and Construction of a New Building—A Comparative Analysis of a Swedish Multi-Family Building, Energies 12 (11) (2019), https://doi.org/10.3390/en12112218. Article 11.

[21] D. Mikulić, S. Slijepčević, G. Buturac, Energy renovation of multi apartment buildings: Contributions to economy and climate changes, Energy and Buildings 224 (2020) 110247, https://doi.org/10.1016/j.enbuild.2020.110247.

[22] Pikas, E., Kurnitski, J., Liias, R., & Thalfeldt, M. (2015). *Quantification of economic benefits of renovation of apartment buildings as a basis for cost optimal 2030 energy efficiency strategies*.

[23] D. Streimikiene, T. Balezentis, Willingness to pay for Renovation of Multi-flat buildings and to Share the costs of Renovation, Energies 13 (11) (2020), https://doi.org/10.3390/en13112721. Article 11.

[24] E. Causse, M. Figuerira, B. Gutierrez, I. Panagiotopoulou, *European Property owners' readiness and capacity to renovate* (UIPI SURVEY FINAL REPORT), International Union of Property Owners. (2021). https://www.uipi.com/uipi-assesses-european-property-owners-capacity-and-willingness-to-renovate/.

[25] O. Husiev, A. Campos-Celador, M. Álvarez-Sanz, J. Terés-Zubiaga, Why district renovation is not leading the race? critical assessment of building renovation potential under different intervention levels, Energy and Buildings 295 (2023) 113288, https://doi.org/10.1016/j.enbuild.2023.113288.

[26] T. Prasauskas, D. Martuzevicius, T. Kalamees, K. Kuusk, V. Leivo, U. Haverinen-Shaughnessy, Effects of energy retrofits on indoor air quality in three northern European countries, Energy Procedia 96 (2016) 253–259.

[27] A. Hamburg, T. Kalamees, How well are energy performance objectives being achieved in renovated apartment buildings in Estonia? Energy and Buildings 199 (2019) 332–341.

[28] K. Kuusk, T. Kalamees, S. Link, S. Ilomets, A. Mikola, Case-study analysis of concrete large-panel apartment building at pre-and post low-budget energy-renovation, Journal of Civil Engineering and Management 23 (1) (2017) 67–75.

[29] J. Rose, K.E. Thomsen, O.C. Mørck, K. Kuusk, T. Kalamees, T. Mauring, The economic challenges of deep energy renovation-differences, similarities, and possible solutions in Northern Europe: Estonia and Denmark, ASHRAE Transactions 122 (1) (2016) 58–68.

[30] R. Galvin, Making the 'rebound effect' more useful for performance evaluation of thermal retrofits of existing homes: defining the 'energy savings deficit' and the 'energy performance gap', Energy and Buildings 69 (2014) 515–524, https://doi.org/10.1016/j.enbuild.2013.11.004.

[31] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research & Information 40 (3) (2012) 260–273.

[32] Ramallo-González, A. P. (2013). *Modelling, simulation and optimisation of low-energy buildings*.

[33] U. Ali, M.H. Shamsi, M. Bohacek, C. Hoare, K. Purcell, E. Mangina, J. O'Donnell, A data-driven approach to optimize urban scale energy retrofit decisions for residential buildings, Appl. Energy 267 (2020) 114861.

[34] Staniaszek, D., Kockat, J., Broer, R., & Álvarez, X. F. (2021). *The Road to Climate-Neutrality: Are National Long-Term Renovation Strategies Fit for 2050* (p. 51). Buildings Performance Institute Europe (BPIE). https://www.bpie.eu/publication/the-road-to-climate-neutrality-are-national-long-term-renovation-strategies-fit-for-2050/.

[35] A. Mastrucci, A. Marvuglia, E. Benetto, U. Leopold, A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale, Renewable and Sustainable Energy Reviews 126 (2020) 109834, https://doi.org/10.1016/j.rser.2020.109834.

[36] J. Rose, K.E. Thomsen, S. Domingo-Irigoyen, R. Bolliger, D. Venus, T. Konstantinou, E. Mlecnik, M. Almeida, R. Barbosa, J. Terés-Zubiaga, E. Johansson, H. Davidsson, M. Conci, T.D. Mora, S. Ferrari, F. Zagarella, A. Sanchez Ostiz, J. San Miguel-Bellod, A. Monge-Barrio, J.M. Hidalgo-Betanzos, Building renovation at district level – Lessons learned from international case studies, Sustainable Cities and Society 72 (2021) 103037, https://doi.org/10.1016/j.scs.2021.103037.

[37] S. Sareen, V. Albert-Seifried, L. Aelenei, F. Reda, G. Etminan, M.-B. Andreucci, M. Kuzmic, N. Maas, O. Seco, P. Civiero, S. Gohari, M. Hukkalainen, H.-M. Neumann, Ten questions concerning positive energy districts, Building and Environment 216 (2022) 109017, https://doi.org/10.1016/j.buildenv.2022.109017.

[38] L. Lihtmaa, T. Kalamees, Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe, Energy Strategy Reviews 51 (2024) 101282, https://doi.org/10.1016/j.esr.2023.101282.

[39] R. Barbosa, M. Almeida, R. Mateus, R. Briones-Llorente, Environmental Performance of a Cost-Effective Energy Renovation at the Neighbourhood Scale-the Case for Social Housing in Braga, Portugal. Sustainability 14 (2022) 1947, https://doi.org/10.3390/su14041947.

[40] *Methodology for calculating the energy performance of buildings*. (2015, January 7). Riigi Teataja. https://www.riigiteataja.ee/akt/107072020012?leiaKehtiv.

[41] M. L. Ojarand, "Lisasoojustuselementidega rekonstrueerimise analüüs ja tootearendus [The analysis and development of prefabricated reconstruction elements]," M.S. thesis, Dept. of Civil Engineering and Architecture, Tallinn

University of Technology (TalTech), Tallinn, Estonia, 2018. [Online]. Available: https://digikogu.taltech.ee/et/item/6128a65e-67e3-4484-a13d-402e44058fbd.
[42] E. Nigumann, T. Kalamees, K. Kuusk, P. Pihelo, Circular renovation of an apartment building with prefabricated additional insulation elements to nearly zero energy building, Journal of Sustainable Architecture and Civil Engineering 34 (1) (2024) 22–34, https://doi.org/10.5755/j01.sace.34.1.35674.
[43] E. Iliste, S. Lomp, E. Pikas, E. Arumägi, J. Hallik, K. Õiger, E.i. Kisel, I. Liiv, T. Kalamees, Heat loss characteristics of typology-based apartment building external walls for a digital twin-based renovation strategy tool, Journal of Physics: Conference Series 2654 (1) (2023) 012125, https://doi.org/10.1088/1742-6596/2654/1/012125.
[44] Kertsmik, K.-A., Kuusk, K., Lylykangas, K., & Kalamees, T. (2023). *Evaluation of renovation strategies: Cost optimal, CO_2e optimal, or total energy optimal?*.
[45] woodco. (2019, December 13). Wood Pellets and Wood Chip—What is Biomass Fuel? *Woodco*. https://www.woodco-energy.com/2019/12/13/what-are-wood-pellets/.
[46] P. Tang, D. Cass, A. Mukherjee, Investigating the effect of construction management strategies on project greenhouse gas emissions using interactive simulation, Journal of Cleaner Production 54 (2013) 78–88, https://doi.org/10.1016/j.jclepro.2013.03.046.
[47] Hendrickson, C., Haas, C., & Au, T. (2024). *Project Management for Construction (and Deconstruction)—Fundamental Concepts for Owners, Engineers, Architects and Builders*. Carl Thomas Michael Haas. https://ecampusontario.pressbooks.pub/projectmanagementforconstructionanddeconstruction/.
[48] European Environment Agency. (2024, June 14). *Greenhouse gas emission intensity of electricity generation in Europe*. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1.
[49] Graanul Invest, "Graanul Invest 2021 Sustainability Report," Aug. 2022. [Online]. Available: https://graanulinvest.com/wp-content/uploads/2022/08/graanul_invest_2021_sustainability_report.pdf.
[50] M. Cinelli, S.R. Coles, K. Kirwan, Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment, Ecol. Ind. 46 (2014) 138–148, https://doi.org/10.1016/j.ecolind.2014.06.011.
[51] P. Arroyo, I.D. Tommelein, G. Ballard, Selecting Globally Sustainable Materials: a Case Study using Choosing by Advantages, J. Constr. Eng. Manag. 142 (2) (2016) 05015015, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001041.
[52] G. Martinopoulos, Are rooftop photovoltaic systems a sustainable solution for Europe? a life cycle impact assessment and cost analysis, Applied Energy 257 (2020) 114035, https://doi.org/10.1016/j.apenergy.2019.114035.
[53] Vendel, K.-R., Pikas, E., Koskela, L., & Tetik, M. (2025). *Exploring Lean Principles in Large-scale Renovation: A Review of Socio-economic Impacts*. 1161–1172. https://iglc.net/papers/Details/2342.
[54] K. Lylykangas, K.-A. Kertsmik, D. Cerrone, P. Walke, K. Kuusk, T. Kalamees, Decarbonisation of Estonia's residential building stock, Energy and Buildings 346 (2025) 116193, https://doi.org/10.1016/j.enbuild.2025.116193.