What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?

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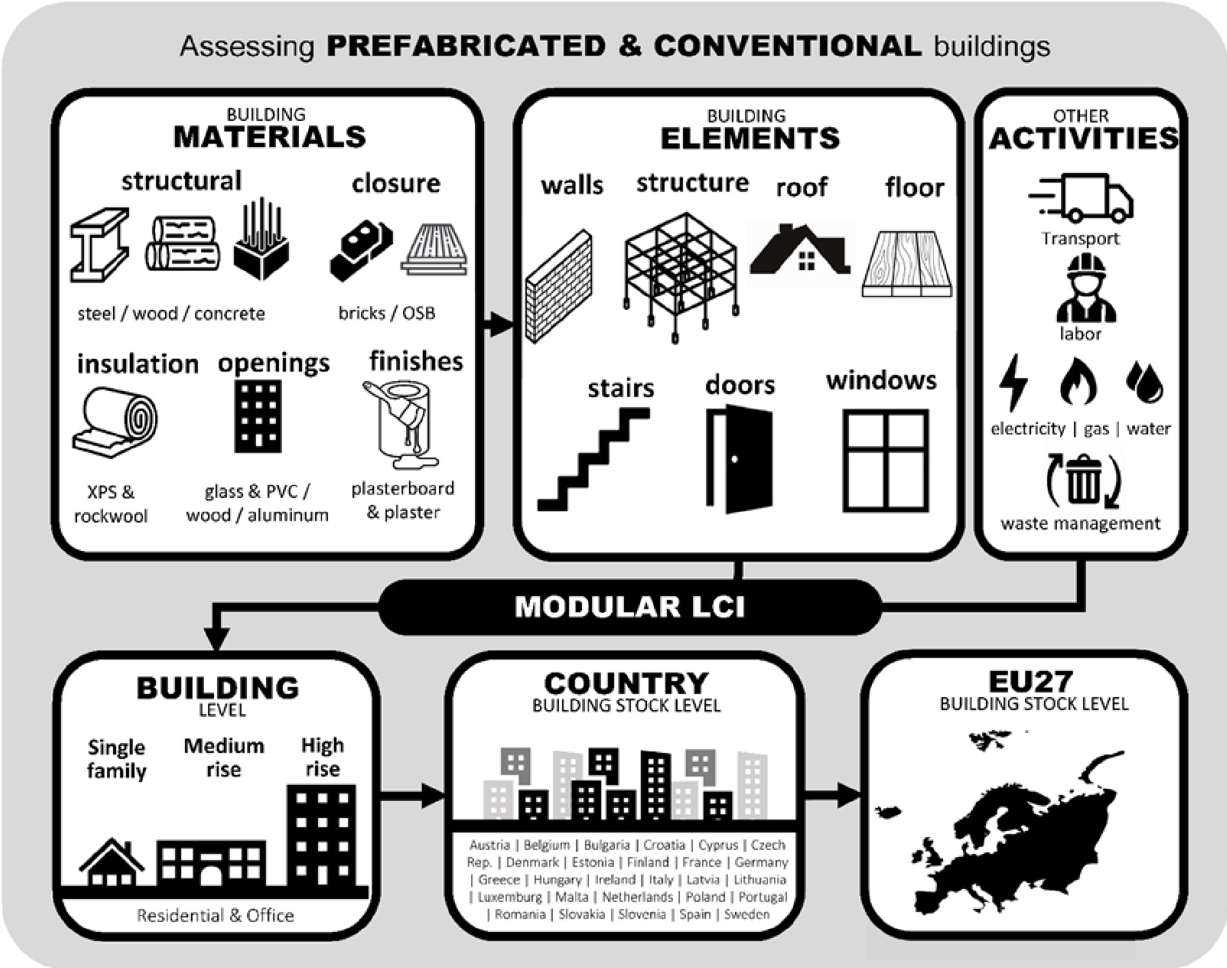
Abstract:

The European Union (EU-27) targets buildings' decarbonization by 2050, and prefabrication presents an opportunity to reduce buildings and construction sector impacts. A stock-based approach was developed to measure the influence of wide adoption of building prefabrication in the EU-27 building stock from 2020 to 2050. Impacts and costs of five typologies using conventional or prefabricated construction systems were assessed for three cities – Lisbon, Berlin, and Stockholm – and three insulation levels. Results were calculated at the building and country levels and then combined at the stock level. Global warming (GW) varies between 5kgCO_2eq/m^2 for prefabricated light steel framing (prefab_LSF) medium- or a high-rise in France and 85kgCO_2eq/m^2 for the conventional concrete single-family (SF) in Poland. Life cycle costs vary between around 900€/m^2 for multi-family buildings in prefabricated LSF in Bulgaria and over 11000€/m^2 for an SF in conventional concrete in Luxembourg. Prefabrication can further decrease building stock burdens up to 6% and reduce building stock costs up to 10%. The developed building stock model has proven to be a fast and reliable tool to forecast the market dynamics when introducing a technological innovation, such as prefabrication. Prefabrication can contribute to achieving the EU-27 targets and reduce construction costs, increasing the construction sector's productivity and sustainability.

Graphical abstract:



Keywords:

Building stock; Environmental Targets; Life-Cycle Costing; Life Cycle Assessment; Modular life cycle inventory; Prefabricated buildings.

Highlights:

- Life cycle impacts and costs of the European Union building stock from 2020 to 2050
- Building stock model combines a modular inventory and a BIM-based energy analysis
- Building stock model represented by 5 typologies, 3 structures, and 3 insulation levels
- Prefabrication can reduce buildings’ embodied (-40%) and end-of-life impacts (-90%)
- Prefabrication can decrease EU-27 buildings’ carbon emissions (-6%) and costs (-10%)

Abbreviations

BIM - buildings information modeling

CDW – construction and demolition waste

conv_RC – conventional reinforced concrete

ENTRANZE - policies to enforce the transition to nearly zero energy buildings in the EU-27

EPISCOPE - energy performance indicator tracking schemes for the continuous optimization of refurbishment processes in European housing stocks

EU – European Union

EU-27 – 27 countries of the European Union

GW – global warming

HR – high-rise residential

HO – high-rise office

IMPRO – buildings environmental improvement potentials of residential buildings

LCA – life cycle assessment

LCI – life cycle inventory

LEVEL(s) - a common EU framework of core sustainability indicators for office and residential buildings.

MR – medium-rise residential

MO – medium-rise office

NRE – non-renewable energy

prefab_LSF – prefabricated light steel framing

prefab_WF – prefabricated wood framing

SF – single-family house

TABULA - typology approach for building stock energy assessment

1. Introduction

Prefabrication has increasingly been applied in the construction industry [1–3]. Building prefabrication is based on manufacturing elements, panels, or modules in a plant that are then transported and assembled onsite [4]. Even though it is not a novel approach (first papers from the 90s [5,6]), recent innovations have been introduced into the construction sector that has accelerated building prefabrication, such as computer-aided design linked to computer-aided manufacturing (CAD-CAM linkage) [7,8], robotization of the construction process (leading to onsite building printing) [9,10], or reduced material use and increased materials recycling in construction (e.g., repurposed shipping containers or the use of waste-based materials) [11,12]. Moreover, prefabrication can respond to some market needs: i) to build faster (and quickly respond to housing needs, e.g., due to natural hazards or political instability), ii) reduce costs (relocating some manufacturing activities to places with lower labor- or energy-costs), iii) improve the construction sector productivity (due to mass production), and iv) reduce building burdens (by decreasing materials use and waste production) [13–15]. However, the benefits and challenges of the wide adoption of prefabrication need to be carefully assessed.

Life cycle assessment (LCA) has been used to assess and compare the environmental impacts of buildings and different construction technologies at the building scale [16]. Since LCA is focused on a single product for a specific lifetime, it cannot capture the transient effects of new technologies within a class of products over time. To-tackle this limitation, a fleet-based life-cycle (LC) approach was proposed combining the LCA methodology with fleet models, thus unveiling the dynamics of a set of products at use by describing the stocks and flows [17]. The fleet-based approach was applied to assess technological innovation, initially in vehicles or appliances [18] and more recently in buildings [19], being also referred to as a stock-based approach [20]. The building stock is a class of products (buildings) aggregated as a stock (the building stock) that is variable by the flow (e.g., demolition and renovation rates) over time. Prefabrication is a technological innovation that will alter stock overall performance and has not yet been validated.

The EU has set ambitious targets to tackle climate change and meet Paris Agreement targets [21]. By 2020, 70% of construction and demolition waste (CDW) should be deviated from landfills [22], energy efficiency must increase by 20%, and GHG emissions reduced by 20% [23]; by 2050 GHG emissions are targeted for an 80% reduction [23]. Previous research forecasted stock dynamics [24,25] and evaluated the impacts of building energy refurbishment [26], nearly zero-energy buildings (nZEB), and renewable energy systems adoption [27,28], and energy savings [29]. No previous research assessed the effect of prefabrication wide adoption. Prefabrication can decrease building stock impacts mainly by decreasing embodied and end-of-life (EoL) impacts of buildings [30,31], but costs may be a barrier [4,32]. The building stock model can unveil the impacts of introducing a new technological alternative to the building stock [24,26,33].

The main goal of this research is to analyze building prefabrication adoption's potential contribution to the EU's twin challenges of sustainability and affordability in the building sector [23]. The main research question is stated in the title of the manuscript: *what is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?* Present work compares equivalent buildings with similar energy performance: new prefabricated buildings with new conventional buildings. A stock-based approach combining archetypes, dynamic energy simulation, modular life cycle inventory (LCI), and a statistic-based stock aggregation was developed to measure the influence of wide adoption of building prefabrication in the EU-27 building stock impacts and costs from 2020 to 2050.

2. Materials and methods

One-third of buildings in the European Union (EU) are over 50 years old, and most of the building stock is energy inefficient. Buildings are responsible for more than one-third of energy consumption and CO_2 emissions in the EU [34]. Several research projects have been conducted to evaluate the environmental impacts of the building stock and identify improvement opportunities: i) IMPRO Buildings project (2006-2008) assessed the potential to decrease the EU-15 stock impacts by implementing refurbishment measures [35,36]; ii) TABULA (2009-2012) mapped residential building technologies and the following [37]; iii) EPISCOPE (2012-2014) aimed to assess refurbishment processes and forecast energy consumption in the future building stock models [29,38], and iv) ENTRANZE (2012-2014) sought to support nearly zero energy buildings (nZEB) and renewable energy sources for heating and cooling implementation [28,39]. Some studies forecasted the size of future stock [40], others focus on impacts [41]. Some evaluated a business as usual (BAU) scenario [42] and others alternative scenarios [26,43]. Previous research assessed energy efficiency measures and refurbishment scenarios, but none analyzed the influence of wide adoption of building prefabrication at the EU-27 building stock scale. Building stock background is presented in Appendix A of Supporting Information (SI).

A stock-based approach of combining BIM-LCA integration and statistical distributions was developed and implemented to better understand the cradle-to-grave impacts and costs of buildings (individually) and the building stock (as a whole) in each country and EU-27, from 2020-2050. This building stock approach aims to assess the influence of wide adoption of prefabrication to help decision-makers define future measures to achieve EU environmental targets. Figure 1 presents the stock-based approach developed to quantify the impacts and costs of the EU building stock over time and assess different scenarios considering the adoption of building prefabrication. Five buildings were modeled to represent the EU-27 building stock: single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO), and high-rise office (HO), representing the building stock in Europe (EU building stock characterized in table D.2 and D.3 of supporting information (SI)). Three different structural materials (steel, wood, and concrete) and three insulation levels were considered, summing up 45 archetypes. The operational energy use of these archetypes was calculated for three cities: Lisbon representing warm countries in zone 1 (Z1), Berlin representing moderate countries in zone 2 (Z2), and Stockholm representing cold countries in zone 3 (Z3). Climatic zones are based on climatic data (see table D.1 of SI), IMPRO study [35], and EU buildings observatory [45]. A modular life-cycle inventory was constructed to calculate the indicators of non-renewable energy (NRE), global warming (GW), and the cost of each archetype in each city. After, indicators were aggregated at the stock level using country-specific typology distribution (of typologies and structural materials) defining baseline. Future stocks were forecasted using stock dynamics (growth and replacement rates) and future hypothetic scenarios (considering prefabrication adoption) and then compared with baseline, thus identifying the improvement potential. Results are presented at the building, the country, and the EU-27 stock level.

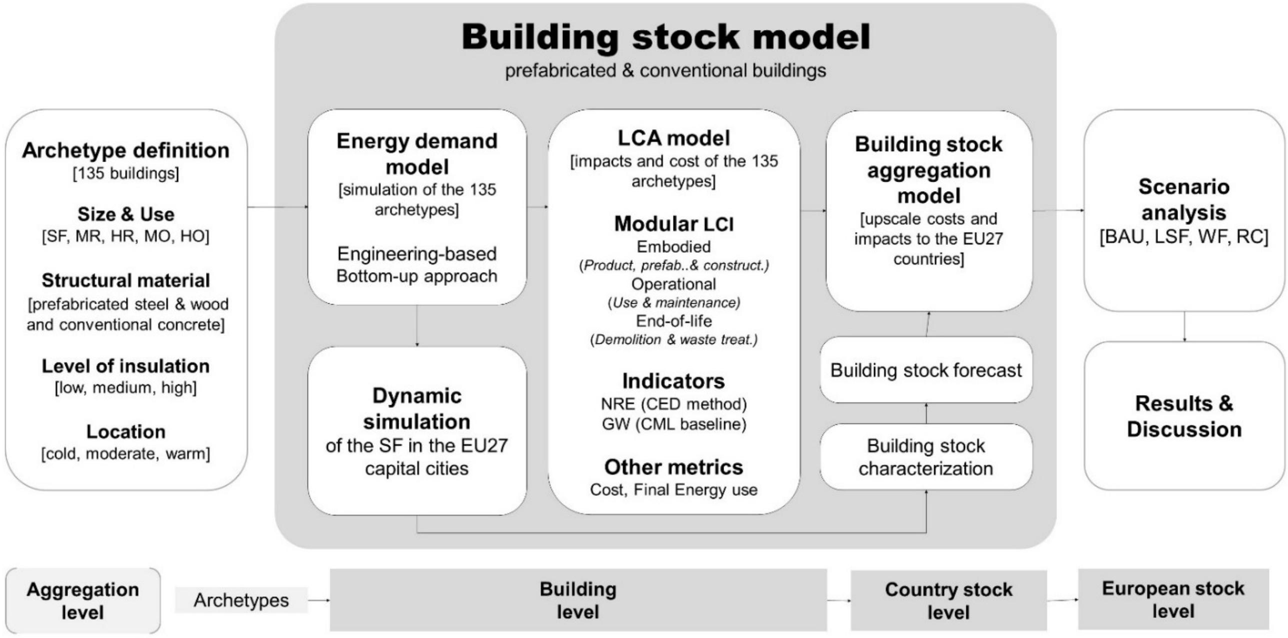
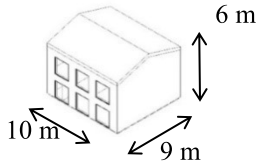
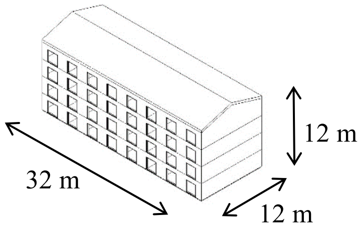
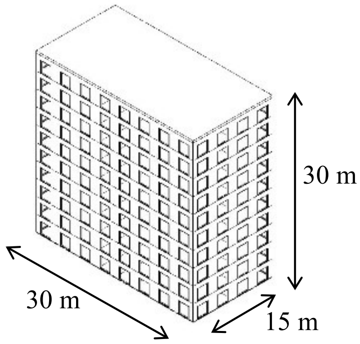
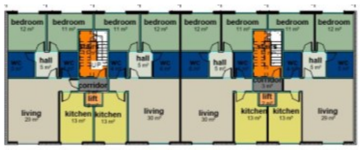
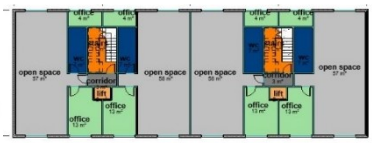
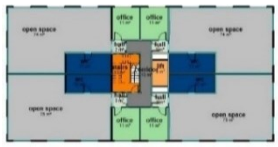


Fig 1. Stock-based methodological approach.

2.1 Archetype definition

The archetypes in this study represented the main typologies in the EU-27 building stock (further information on table D.2 of SI) and were based on previous work [26,40]. The three construction systems selected are usually used in the EU-27 construction sector: prefabricated light steel framing (prefab_LSF) and wood framing (prefab_WF), and conventional reinforced concrete (conv_RC). Structural material distribution per climatic zone is presented in table D.4 of SI and was used to build the business as usual (BAU) scenario. Table 1 presents archetypes' main characteristics: floorplan, main dimensions, and an axonometric view.

Table 1. Building stock archetypes characterization (based on IMPRO project, Nemry et al., 2010)

	Low rise	Medium rise	High rise
Axonometric view			
Dimensions (L·W·H)	10·9·6 m	32·12·12 m	30·15·30 m
Nr of floors	2- floors	4- floors	10- floors
Gross-floor area	180 m^2	1 536 m^2	4 500 m^2
Volume	540 m^3	4 608 m^3	13 500 m^3
Roof slope	30%	30%	0%
Window-to-wall ratio	30%	30%	30%
	single family (SF)	medium-rise residential (MR)	high-rise residential (HR)
Residential Floorplans			
Office Floorplans		medium-rise office (MO) 	high-rise office (HO) 

2.2 Building construction alternatives

Building prefabrication refers to the process of manufacturing building parts, elements, or modules at a plant and then transporting them to the final building site to be installed and assembled [46]. Having one extra phase (prefabrication at a plant), transportation stage (from plant to site), and performance (being based on lightweight construction), prefabrication impacts and costs need to be carefully balanced when compared with conventional building construction [34]. In this study, the two most commonly used prefabrication systems were analyzed: light steel framing (prefab_LSF), and wood framing (prefab_WF) structure with OSB panel walls, and a conventional reinforced concrete (conv_RC) structure with a brick siding. Table 2 describes the main construction elements (external wall, roof, internal wall, and windows) for the three constructive systems: prefabricated LSF and WF, and conventional RC (further details are presented in B.1 of SI presents). Three code complying insulation levels are considered: low, medium, and high; and three cities selected to represent different climatic zones: Stockholm (cold weather countries), Berlin (moderate weather countries), and Lisbon (warm weather countries). Table B.2 of SI presents the construction and site alternatives details.

Table 2. Construction elements characterization (further detailed in Table B1 of SI)

	Prefabricated		Conventional
	Prefab_LSF	Prefab_WF	Conv_RC
Exterior wall*	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) LSF profile (C 100·45·1,2 mm) Oriented strand board (15 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) Wood beam profile (100·45 mm) Oriented strand board (15 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Plaster (15 mm) Extruded polystyrene (variable: 100 / 60 / 30 mm) Waterproof membrane (2 mm) Reinforced concrete column (150·300 mm) Concrete masonry (150 mm) Plaster (15 mm)
Roof*	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) LSF truss (1.8 mm) Waterproof membrane (2 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) Wooden truss (70*50 mm) Waterproof membrane (2 mm) Rockwool (variable: 100 / 80 / 60 mm) Oriented strand board (15 mm) Plasterboard (12.5 mm)	Metal sheet (1.5 mm) Rockwool (variable: 100 / 80 / 60 mm) Metal sheet (1.5 mm) Concrete filling (60 mm) Vaulted concrete block Concrete beam Plaster (15 mm)
Interior wall	Plasterboard (12.5mm) Steel profile (48·70·0.55mm) Rockwool (70mm) Plasterboard (12.5 mm)	Plasterboard (12.5mm) Wooden profile (40·60mm) Rockwool (70mm) Plasterboard (12.5 mm)	Plaster (15 mm) Brick masonry (110mm) Plaster (15 mm)
Window	Double glazing Aluminum frame	Double glazing Wooden frame	Double glazing PVC frame

* Layers described from the exterior to the interior; and from high to low insulation level

2.3 Energy demand model

Energy consumption was calculated through dynamic energy simulation of the archetypes (SF, MR, HR, MO, HO; prefab_LSF, prefab_WF, and conv_RC) in the three cities (Lisbon, Berlin, and Stockholm) considering low, medium, and high insulation levels. Energy needs were calculated using a dynamic energy simulation software (EnergyPlus) linked to BIM modeling software (Revit 2020) and considering a split system with mechanical ventilation to meet cooling and heating needs. Interior lighting and equipment energy needs were based on average consumption per area. The five archetypes, with the three structural materials and the three insulation levels, were simulated in the three cities, summing up 135 alternatives. In addition, operational energy for the single-family (SF) with medium insulation level was calculated for all the EU-27 capital cities. The energy needs of the archetypes in all the remaining 24 capital cities were statistically calculated using typical energy needs variation within each climatic zone (among typologies and within structural materials) and using the SF as model calibration. Random archetypes were simulated in each city, and the difference to the estimated value was calculated and below 10%. The energy needs of both prefabricated designs are similar since the prefabricated buildings are lightweight buildings with similar thermal mass and thermal transmittance of the building envelope.

2.4 Life cycle model

The life cycle model follows the ISO 14040 [47] and CEN/TC 350 standards using the following phases: product stage (A1-A5); construction stage (A4-A5); use stage maintenance (B1-B5); use stage operation (B6-B7); end-of-life stage

(C1-C4); and benefits and loads beyond system boundaries (D). Waste recycling by waste type was included in the LC model, but modules, parts, or materials reuse was not considered. Water use was excluded and energy use calculated using dynamic energy simulation for all final locations. Two functional units were used: m^2 of built area and total building stock (of each country and the EU-27). The reference flow is defined by the building stock growth and replacement rate, and the boundary of the study is the EU-27 countries within the 2020-2050 timeframe. The selected indicators are non-renewable energy (NRE of CED impact assessment methods) and global warming (GW of CML baseline), as both are commonly used in building and building stocks assessments and are recommended by the environmental product declaration and JRC report [48]. Moreover, operational energy use and costs were also selected as both influence policy-making and individual owners' choices. Cost, GWP, and operational energy use are indicators proposed by Level(s) – the EU proposed framework to report buildings' sustainability using LCA [49].

2.4.1 Modular life cycle inventory

A modular LCI was developed to enable the rapid construction of the inventory for the 45 archetypes (presented in fig. 2). Building materials are assembled into building elements that, in addition to other activities (performed during construction, use, maintenance, and demolition), build up the life cycle inventory. Indicators and cost are allocated to each building element and activity using different units: building elements are defined per area (m^2 of walls, floors, and roof) or unit (number of doors and windows) during construction and maintenance (replacement rates based on life span); transport of workers by traveled distance (km), and transport of materials and waste by mass traveled distance (tkm); for electricity, gas and water use the time of manufacture, assemblage, construction and demolition (number of hours); and for use phase annual operational energy needs (to meet the heating and cooling needs, electric equipment use and lightening). In medium-rise and high-rise, both prefabricated systems consider an additional RC structural core (comprising the stairs and the walls around the stairs) as of current practice. Lights, appliances, HVAC equipment, foundations, cabinets, kitchen, and bathroom equipment, were excluded from the present analysis as they were considered to be similar among all the three alternatives. A modular cradle-to-grave LCA assessment was completed for all the alternatives.

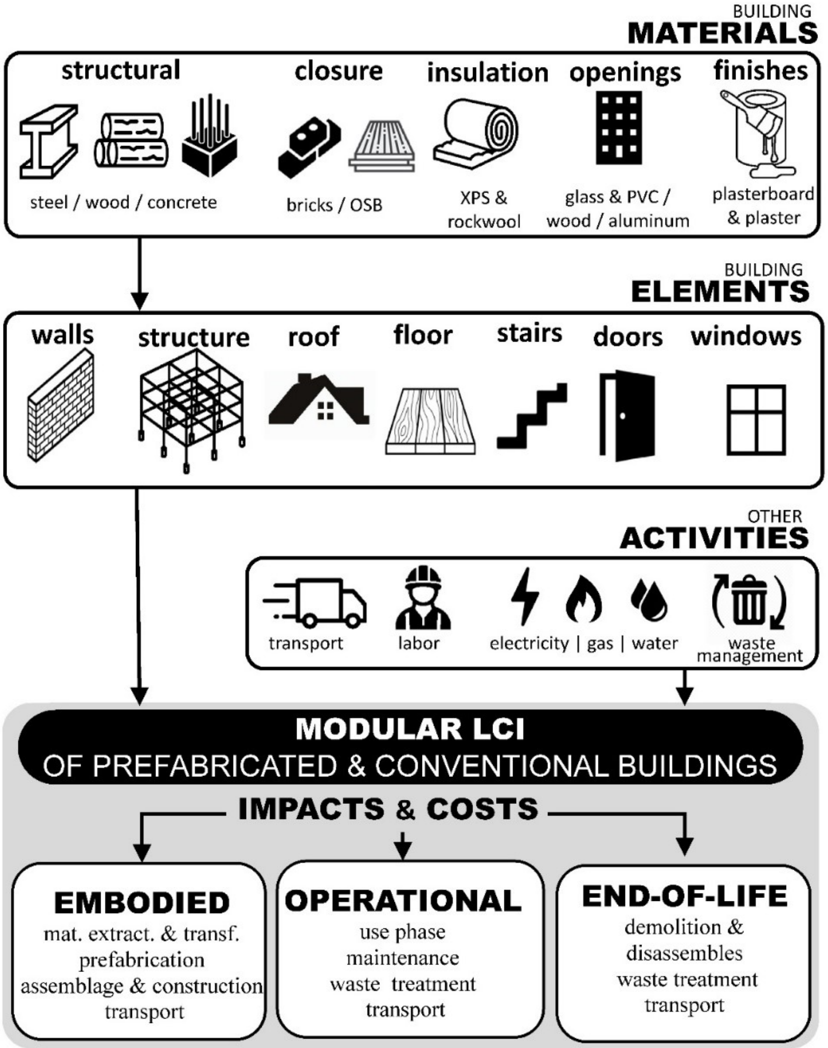


Fig 2. Modular life cycle inventory

The life cycle inventory is divided into three main stages: embodied, operational, and end-of-life phases. The embodied phase includes materials extraction and transformation, plant prefabrication, onsite assemblage and construction, and transport (of materials, prefab parts, and workers). The operational stage comprises the use phase needs; maintenance works, waste, and transport (of materials, waste, and workers). Finally, the end-of-life consists of demolition and disassembles works, waste treatment, and transport (of waste and workers). Waste is grouped according to the waste list [22], and impacts are calculated accordingly to each waste stream treatment strategy.

Table 3 presents the life cycle inventory of archetypes with a medium insulation level. A detailed inventory is presented in supporting information Table C1 – embodied stage LCI, C2 operational stage LCI, and C3 end-of-life stage LCI. The inventory shows the similarity among both prefabricated buildings and more significant differences with the conventional. Conventional RC is roughly four times heavier than prefabricated buildings (around 3.7 times heavier than prefab_WF and 4.2 times the prefab_LSF) with similar differences in demolition waste and equivalent transport of materials and waste. Conventional buildings have no prefabrication stage with no transport-, labor-, utilities-related burdens. However, during the construction stage conv_RC needs extra time and a higher number of workers, balancing (and even surpassing) prefabrication stage labor and time. Use stage differences between prefabricated and conventional buildings are less significant. Maintenance works of conventional buildings are slightly more complex (taking a little more time, labor, and materials) than both prefabricated. Operational energy tendency shows that prefabricated buildings with medium insulation levels use less energy with heating needs, and contrary, conventional RC uses less energy with cooling needs. This comes from the fact that conventional building is a heavyweight construction system, with higher inertia (less likely to overheat during the cooling season) and prefabricated buildings lightweight (easier to be heated during the heating season), and follows previous LR results [50]. Operational energy must be carefully analyzed in each location and using different insulation levels as buildings react differently to increased insulation level, in each location and using different construction systems (results are presented in section 3.2.1). Finally, at the EoL, the demolition of conventional and deconstructing prefabricated buildings was considered to take the same time and the number of workers, though benefits of prefabricated (mainly LSF reuse and recycling) will reduce buildings impacts and costs at EoL.

Table 3. Life cycle inventory of materials, waste and labor of the archetypes with medium insulation level (further detailed in Table C1, C2 and C3 of SI)

	A1-A5 PRODUCT & CONSTRUCTION STAGE								
	Materials (ton)			Offsite work (hr)			On site work (hr)		
	LSF	**WF**	**RC**	**LSF**	**WF**	**RC**	**LSF**	**WF**	**RC**
SF	35	41	152	1 848	1 848	-	1 848	1 848	14 784
MR	404	428	1 223	2 772	2 772	-	7 392	7 392	59 136
HR	963	1 034	2 827	3 696	3 696	-	22 176	22 176	129 024
MO	387	414	939	2 772	2 772	-	7 392	7 392	59 136
HO	899	963	2 440	3 696	3 696	-	22 176	22 176	177 408
	B1-B5 USE STAGE								
	Maintenance materials (ton)			Maintenance waste (ton)			Maintenance work (hr)		
	LSF	**WF**	**RC**	**LSF**	**WF**	**RC**	**LSF**	**WF**	**RC**
SF	22	22	31	22	22	31	385	385	578
MR	129	129	236	129	129	236	1 540	1 540	2 310
HR	289	289	507	289	289	507	3 465	3 465	5 198
MO	119	119	208	119	119	208	1 540	1 540	2 310
HO	244	244	358	244	244	358	3 465	3 465	5 198
	C1-C4 END OF LIFE STAGE & D BENEFITS & LOADS								
				Demolition waste (ton)			Demolition work (hr)		
				LSF	**WF**	**RC**	**LSF**	**WF**	**RC**
SF				35	41	152	70	70	70
MR				404	428	1 223	280	280	280
HR				963	1 034	2 827	630	630	630
MO				387	414	939	280	280	280
HO				899	963	2 440	630	630	630

NB: LSF – prefabricated LSF, WF – prefabricated wood-framing, RC – conventional reinforced concrete, SF – single-family house, MR – medium-rise building, HR – high-rise building, MO – medium-rise office, HO – high rise office.

Environmental impacts are calculated using the ecoinvent 3 database using NRE (CED method) and GW (CML baseline method) categories. In the absence of data on material production sources and destinations and the associated transportation routes, impacts of materials and transport are considered identical for all the different countries. By contrast, the specific electricity mix was considered for each EU-27 because this information is readily available. Costs were first calculated for Lisbon (Portugal) for all the five typologies, with different materials and insulation levels.

Materials costs are based on an open-access database [51], and transport, labor, energy, and waste costs were based on technical or statistical databases. Materials costs are calculated for the other two cities (Berlin and Stockholm) using a conversion factor based on the construction cost index [52]. Electricity, gas, water, and labor costs used were specific to each city and based on EU-27 country-specific statistics [53].

2.5 Stock aggregation model

Building stock dynamics comprises buildings construction, demolition, and refurbishment. New buildings will be constructed due to: i) stock size variation because of population fluctuation and; ii) buildings replacement as buildings are demolished at the end-of-life. Buildings' life span varies from 50 to 100 years, so the annual construction rate varies from 1.2-1.5%, as was previously considered in [41] and [25]. A fixed replacement rate of 1.2% was considered in the present work for the period 2020-2050, based on [54] and [41]. No data was found on building stock size projection, so the stock area had to be calculated based on available statistical data was from the last Census in 2011 [55]. A dynamic stock rate has been calculated by multiplying the population per building area per capita area in each EU-27 country; data were collected from Eurostat [56]. D.1 of SI presents EU-27 Building stock characterization in 2019 divided between residential (single-family, medium- and high-rise) and non-residential (medium and high rise). Further details are presented in SI Table D.1. EU-27 Building stock forecast for 2050 and Table D.3 EU-27 New buildings forecast from 2020 to 2050.

Residential area per capita varies between 21 m^2/capita (in Malta) and 54 m^2/capita (in Denmark). Service area per capita varies between 3 m^2/capita (in Romania) and 22 m^2/capita (in Denmark). Population from 2020-2050 will vary between +32% and -23%, as some countries' population is expected to increase (such as Malta and Ireland) while others will decrease (such as Latvia and Lithuania). This stock forecast model is based on the following assumptions: i) population variation determine building stock size for residential and office areas buildings; ii) the ratio of built area per person stays constant even though some studies have pointed out that area per person may increase; iii) the fact that some buildings may last beyond considered life span (such as heritage builds) was not considered. Further details are presented in SI Table D.4. The building area and population (2020-2050).

The operational energy of the single-family (SF) medium insulation house was calculated through dynamic energy simulation in the EU-27 capital cities. The operational energy of all the other archetypes in the EU-27 countries was calculated through a statistical correlation based on the calculated operational energy variation between each typology (from single-family to medium-rise residential, high-rise residential, medium-rise office, and high-rise office) and level of insulation (from medium to low or high level) within each climate zone (warm, moderate or cold weather.).

The statistical correlation error is below 10% and has been calibrated with the single-family house energy simulation. One hundred fifty-nine buildings were simulated (5 typologies, in 3 construction systems and 3 insulation levels, in 3 cities totalizing 135 plus 24 SF in each EU-27 capital), and the operational energy of the other 624 buildings was calculated based on statistics. The stock-based model considers operational impacts variation due to the electricity-mix impacts of each of the EU-27 countries.

The impacts and costs of the archetypes were calculated for each of the EU-27 countries based on statistics correlation (of construction, labor and electricity costs, and electricity mix impacts). Impacts at the country level were aggregated based on typology distribution and stock composition in terms of structural materials in each country. Typology distribution was based on statistical data, and stock composition in terms of structural materials was based on the new buildings defined in the IMPRO study [36] and assumed to represent the current construction practice in Europe.

3. Results

Results are presented at three different levels: at the EU-27 level (section 3.1), country-level (section 3.2), and building-level (section 3.3). Each aggregation level presents data with different resolutions that led to different conclusions, highlighting the importance of scope definition and aggregation level in building stock research.

3.1 Building stock-level

EU-27 building stock was characterized by size (built area), composition (typologies), and construction systems (structural materials). Impacts are forecasted from 2020 to 2050 in future scenarios (considering prefabrication adoption in section 3.1.2) and the business-as-usual scenario (in section 3.1.3). The distribution of the three structural materials across the EU-27 countries is described in table D.5 of SI (based on [44]) and was used to define the BAU scenario.

3.1.1 Size and composition

Figure 3 presents the EU-27 stock composition and forecast of the new building area. Around 70% of buildings in Europe are residential, half of them single-family houses (~50%), followed by multi-family houses (~20%). High-rise buildings (residential and non-residential) represent a small fraction of the stock (less than 5%). Around 60% of the new building area will be located in moderate weather countries (mainly in Germany and France) followed by warm weather countries (around 35%, mainly in Italy and Spain). In warm weather countries, all new buildings use RC structure; in moderate weather countries, 1/3 of single-family use WF and all the others RC; and in cold weather countries, half of SF and 2/3 of MF use WF, and all the others RC. Structural materials considered per climatic region and typology are detailed in SI, table D.1 - Structural material share per region for each archetype.

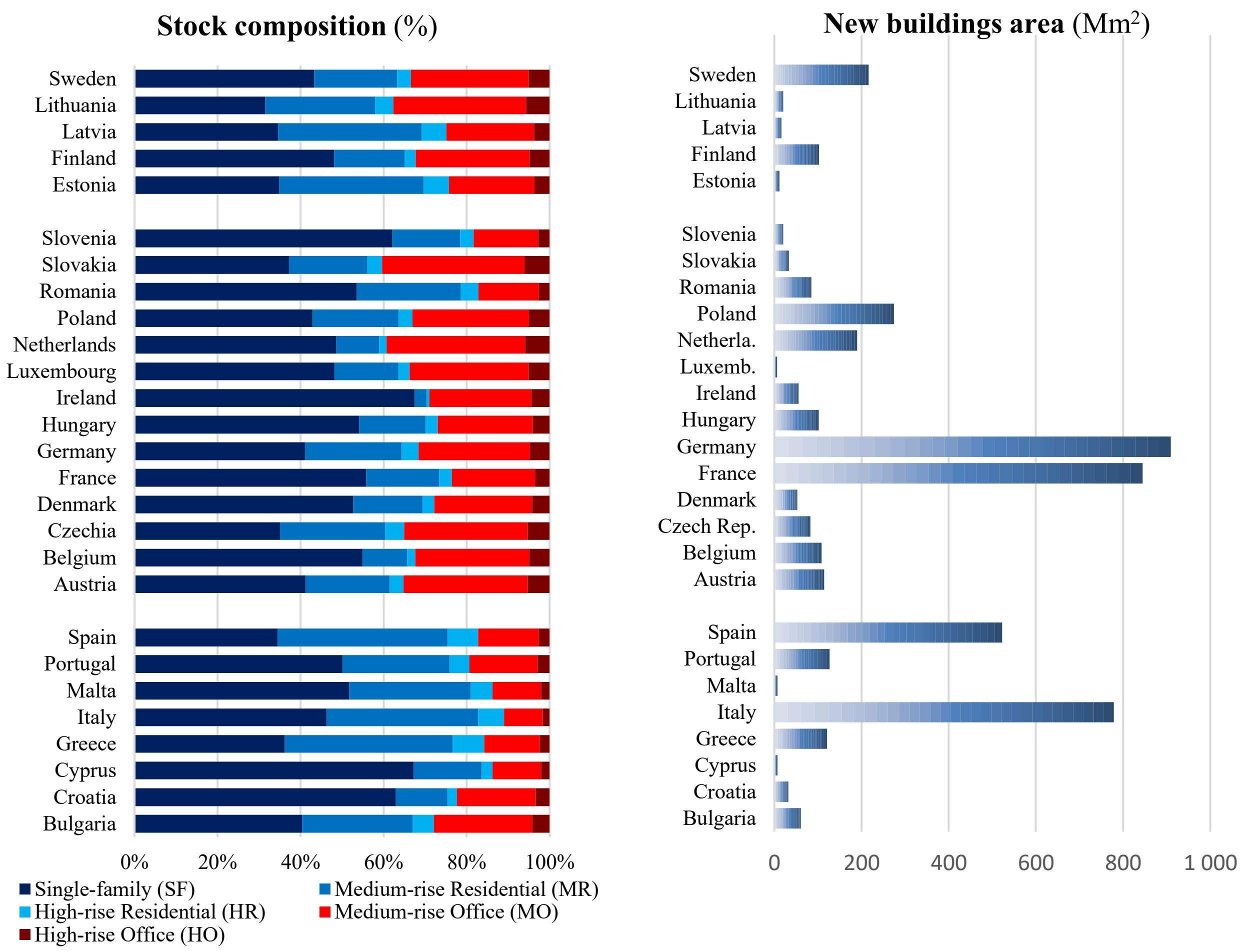


Fig 3 Stock composition (left) divided into single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO), and high-rise office (HO); and estimated new building area (right) per each EU-27 country from 2020 to 2050.

3.1.2 Future scenarios

Figure 4 presents EU-27 building stock total impacts, costs, and operational energy comparing the business as usual (BAU) scenarios with the alternative scenarios: hypothetical scenarios considering all new buildings are built in prefab_LSF, prefab_WF, or conv_RC. By 2050 prefabrication can decrease building stock GW by -6% (using prefab_LSF) or -4% (using prefab_WF) when compared to 2020, and NRE can be decreased by -4% (using prefab_LSF) or -3% (using prefab_WF). On the contrary, in the conv_RC scenario, impacts could increase by +1%. Buildings' costs can be decreased by -10% (using prefab_LSF) or -8% (using prefab_WF) compared with the BAU scenario. Operational energy use is identical for prefab_LSF and prefab_WF, and the reduction compared to BAU is insignificant (less than 1%).

Compared with the BAU, the variation in cost is the most significant since prefabricated buildings need less time and labor. By contrast, the variation in energy needs is the least significant as all the alternatives have roughly similar energy performance. The prefabricated building stock has similar reduction potential in GW and NRE categories. EU-27 building stock impacts, costs, and operational energy variation per m^2 of alternative scenarios compared with the business as usual (BAU) scenario are presented in figure E.1 of SI.

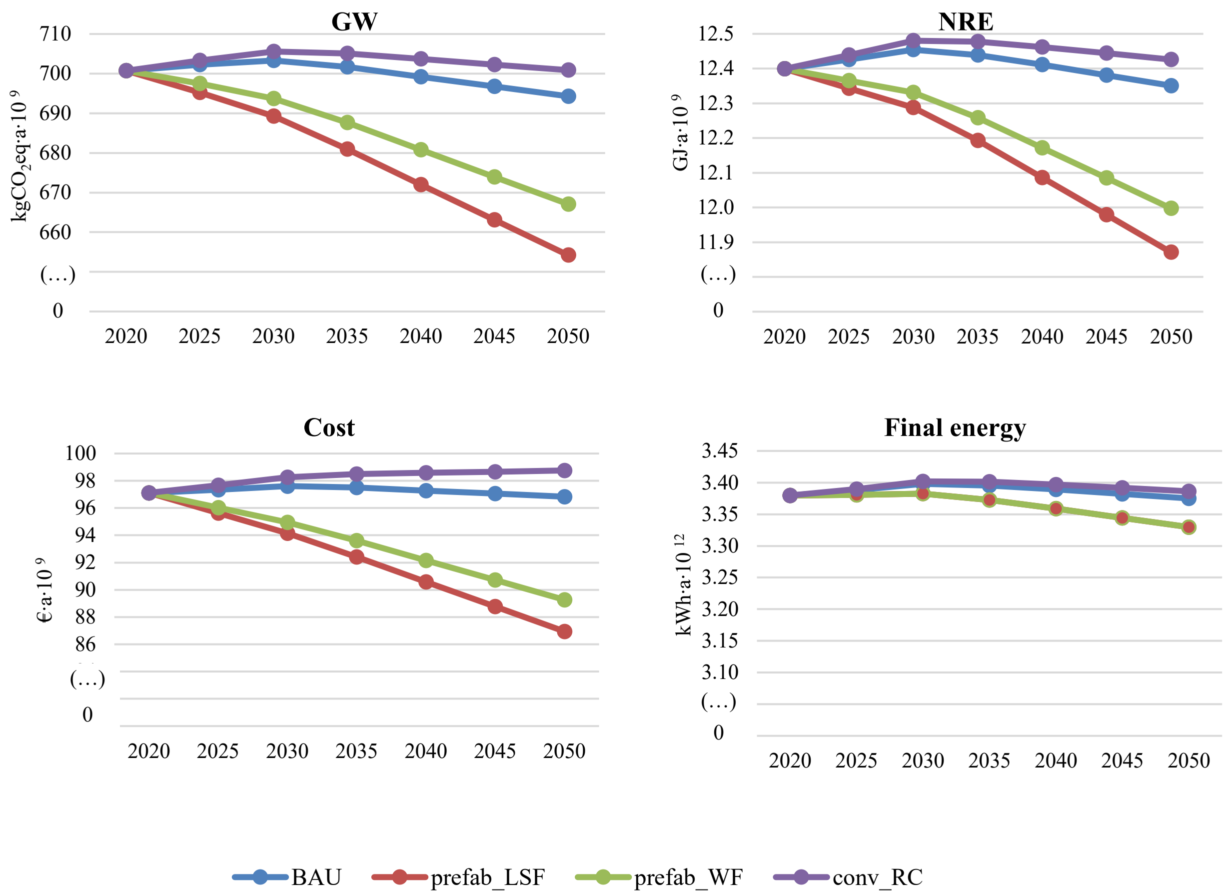


Fig. 4 EU-27 building stock total impacts, costs, and operational energy in business as usual (BAU) scenario and alternative scenarios: from 2020 to 2050, all new buildings are built in prefab_LSF, prefab_WF, or conv_RC (y-axes does not start in zero). Note that the y-axes show a fraction of the total scale.

3.1.3 Business as usual

Figure 5 presents building stock area and cost (left) and GW and operational energy (right) at the business-as-usual scenario (BAU). Aggregated impacts and costs of EU-27 building stock follow the building area curve that will pick around 2030 and is expected to decrease after. Both figures show that the total area of the building stock is the most critical aspect, as cost, energy, and GWP follow the building stock area growth. So even if buildings are more energy-efficient and have less embodied impacts, the building stock impacts will follow gross floor area growth because it is increasing at a significant rate. The built area will respond not only to the growing population but also to the increasing area-per-person ratio.

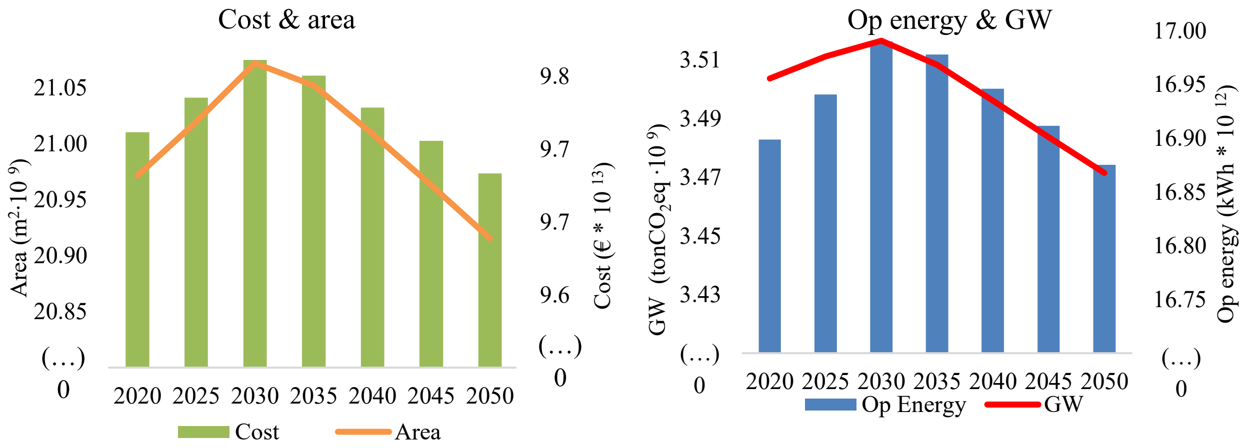


Fig. 5 EU-27 total building stock cost and area (left); and operational energy and GW (right). Note that the y-axes show a fraction of the total scale.

3.2 Country-level

Results are presented for each archetype in each of the 27 European countries grouped in three climatic zones: warm, moderate, and cold weather countries.

3.2.1 Operational energy

Figure 6 presents the operational energy per m^2 per year for prefabricated light steel framing (prefab_LSF), prefabricated wood framing (prefab_WF), and conventional reinforced concrete (conv_RC) buildings in EU-27 countries divided into single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO) and high-rise office (HO); with different insulation levels (low, medium, high). In the EU-27, the operational energy varies from 102-271 kWh/m^2·year (warm countries 118-237, moderate countries 102-231, and cold countries 134-271 kWh/m^2·year). In warm countries, insulation has a small influence on operational energy except for medium-rise residential (in prefab_LSF and prefab_WF) and high-rise office (in RC) that with lower insulation decreases the operational energy. The energy needs of conventional RC are more dependent on the insulation level, being a heavyweight construction system with a high thermal energy storage capacity of materials used in the building. Compared with other archetypes, high-rise office has higher energy needs in warm countries and single-family in moderate and cold countries; being this single-family with a concrete structure is highly dependent on the insulation (the higher the insulation level, the lower the operational energy).

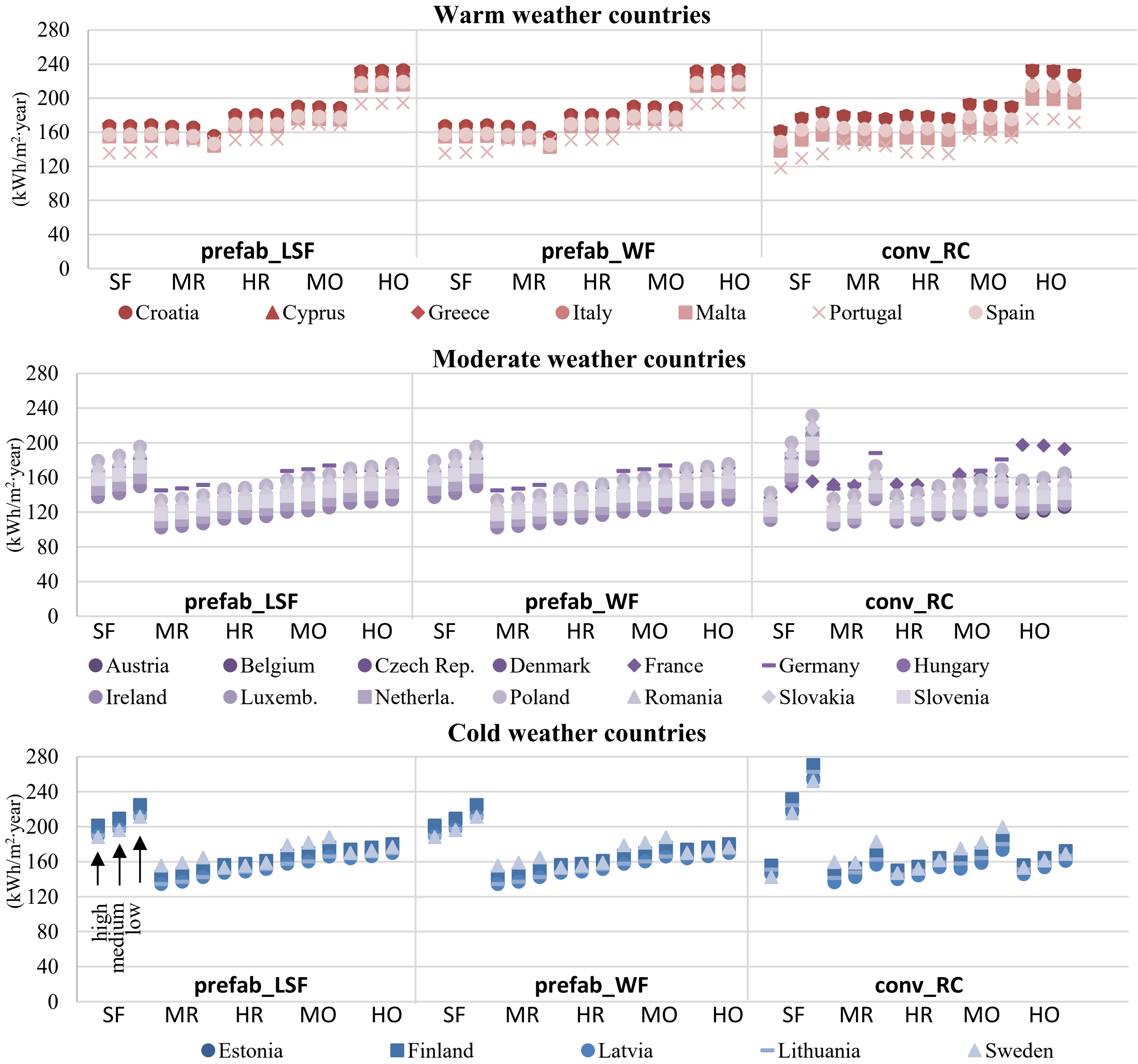


Fig. 6 Operational energy per m² for prefabricated light steel framing (prefab_LSF) and wooden framing (prefab_WF); and conventional reinforcing concrete (conv_RC) buildings in EU-27 countries divided into single-family (SF), medium-rise residential (MR), high-rise residential (HR), medium-rise office (MO) and high-rise office (HO); and high (left), medium (middle), and low insulation level (right). Operational energy per m² for each country are presented in table E1-E3 of supporting information.

3.2.2 Life cycle impacts

Figure 7 presents the GW per m² for prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO, and HO; with different insulation levels (low, medium, high). Total GW varies from 0,1-4,3 $tonCO_{2eq}/m^2$ (warm countries 1,1-3,5; moderate countries 0,1-4,3; and cold countries 0,3-3,5 $tonCO_{2eq}/m^2$). Impacts partially reproduce energy use variation (fig 5), with higher impacts for single-family (SF) houses. However, GW is more dependent on the emission factor of the electricity mix (e.g., with a high share of renewable or nuclear power) than on archetypes, construction materials, insulation level, or even weather. For example, the energy needs range of an SF in

France is 135-155 kWh/m^2·year, and the GW range is 420-820 kgCO_2eq·year. By contrast, in Hungary, Bulgaria, or Luxemburg they having roughly similar energy needs but have twice or three times the GW value (please see each country´s and archetypes' energy needs per m^2 in Table E.1-E3, and GW per m^2 in Table E.4-E6). The impact range is bigger within moderate and cold countries than in warm countries, though it is noticed that the moderate countries group is the largest. NRE impacts are presented in fig E.2 (Appendix E – Results) of SI.

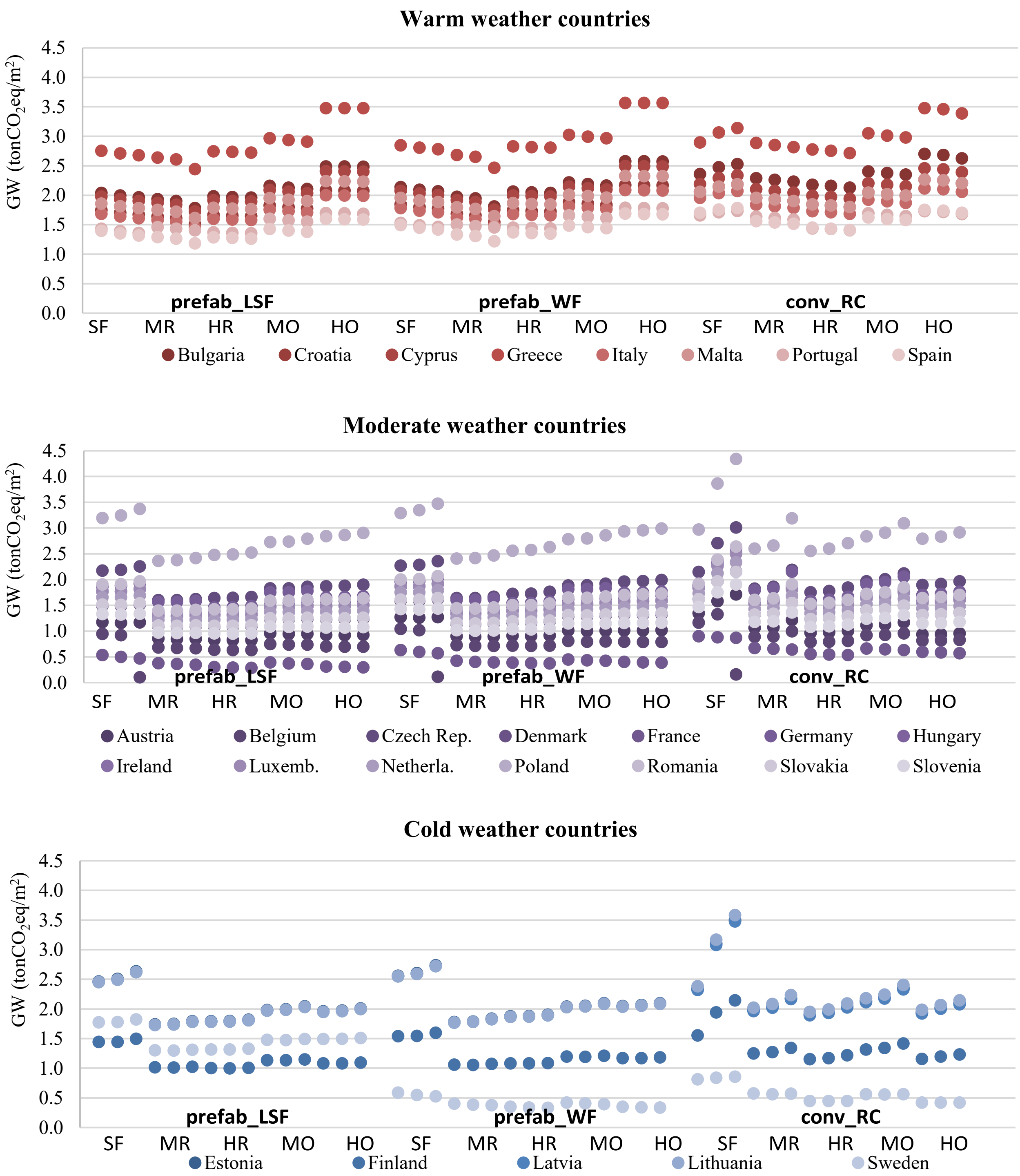
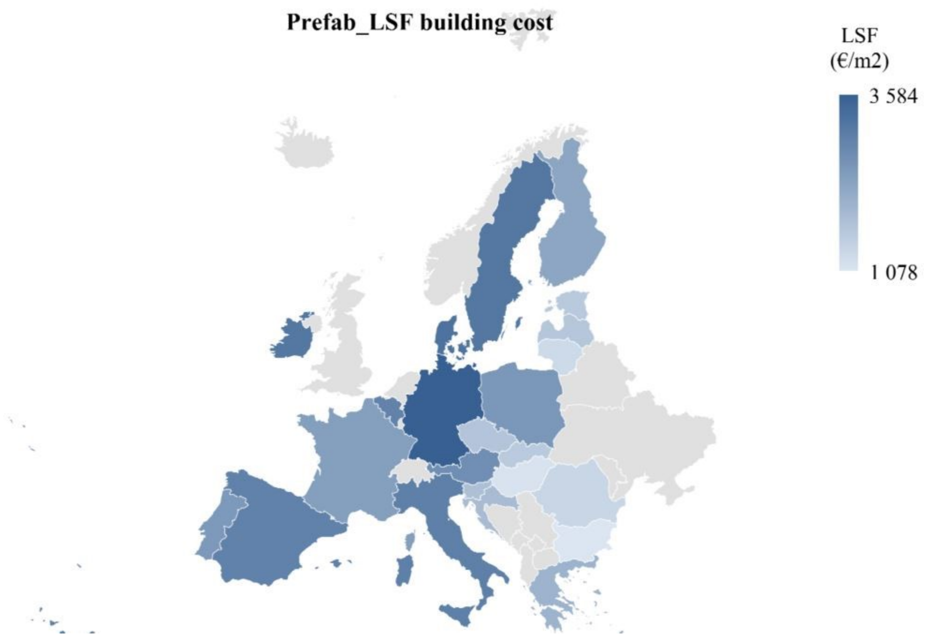
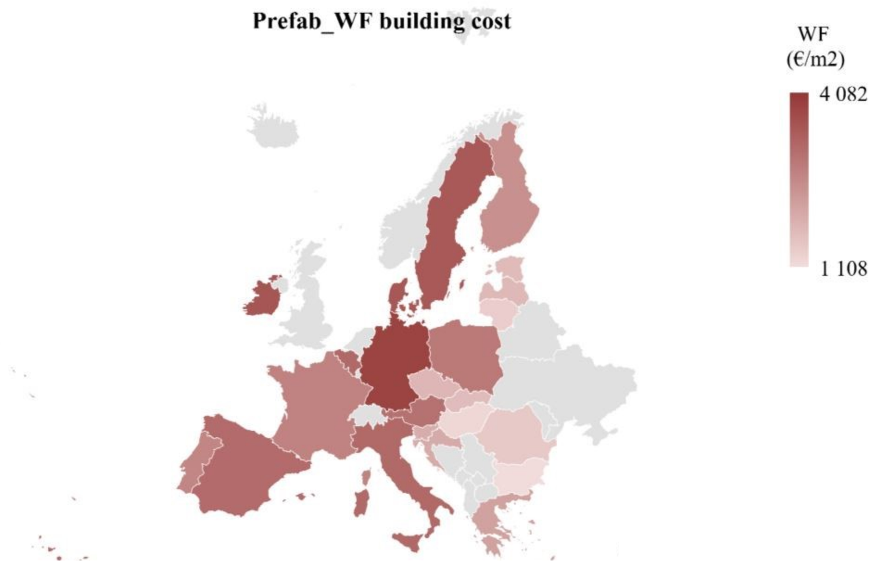


Fig. 7 GW per m^2 of prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO and HO, and insulation level. GW per m^2 for each country are presented in table E4-E6 of SI.

3.2.3 Life cycle cost

Figure 8 presents the average life cycle cost per m^2 for prefab_LSF, prefab_WF, and conv_RC buildings in the EU-27 countries. Cost range are 1.1-3.6 k€ / m^2 for prefab_LSF; 1.1-4.1k€ / m^2 for prefab_WF, and 1.2-6.0 k€ / m^2 for conv_RC. The conv_RC cost range is slightly higher than prefabricated solutions, but the three ranges overlap. Conv_RC buildings cost is more variable than both prefabricated as it is more dependent on each country-specific cost, namely labor and electricity cost.





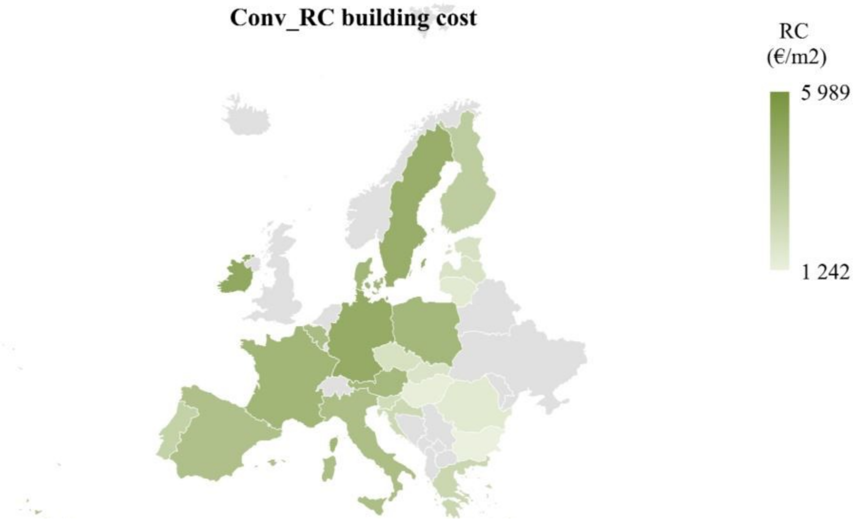


Fig. 8 Average total life cycle cost per m^2 for prefab_LSF (blue), prefab_WF (red), and conv_RC (green) buildings in EU-27 countries.

3.3 Building-level

Three cities were selected as case studies representing different climate zones within the EU territory: Lisbon (warm weather countries), Berlin (moderate weather countries), and Stockholm (cold weather countries). The five typologies with different materials and insulation levels were assessed in these three cities. This section presents detailed operational energy, environmental impacts, and costs of the archetypes in these three cities.

3.3.1 Operational energy

Figure 9 presents the final annual energy for each city, typology, structural material, and insulation level; divided into lighting and equipment, heating, and cooling. Operational energy roughly varies between 100-200 kWh/m^2·year. In Lisbon, the cooling needs are higher than the heating, and the opposite occurs in Stockholm. The insulation level influences more conv_RC buildings than prefab_LSF and prefab_WF, and single-family than all the other typologies.

In Lisbon, operational energy varies between 100 kWh/m^2·year (for single-family conv_RC high insulation) and 181 kWh/m^2·year (for high-rise office with prefab_LSF and prefab_WF). The insulation level does not influence operational energy except in single-family conv_RC buildings. In some typologies, conv_RC buildings use less energy than prefab_LSF and prefab_WF (especially highly insulated) by decreasing cooling needs. In Berlin, operational energy varies between 113 kWh/m^2·year (for single-family conv_RC high insulation) and 183 kWh/m^2·year (for single-family conv_RC low insulation). Operational energy can be the lowest in Berlin as buildings have lower cooling needs than in Lisbon and lower heating needs than in Stockholm. In Stockholm, operational energy varies between 123 kWh/m^2·year (for single-family conv_RC high insulation) and 213 kWh/m^2·year (for single-family conv_RC low insulation).

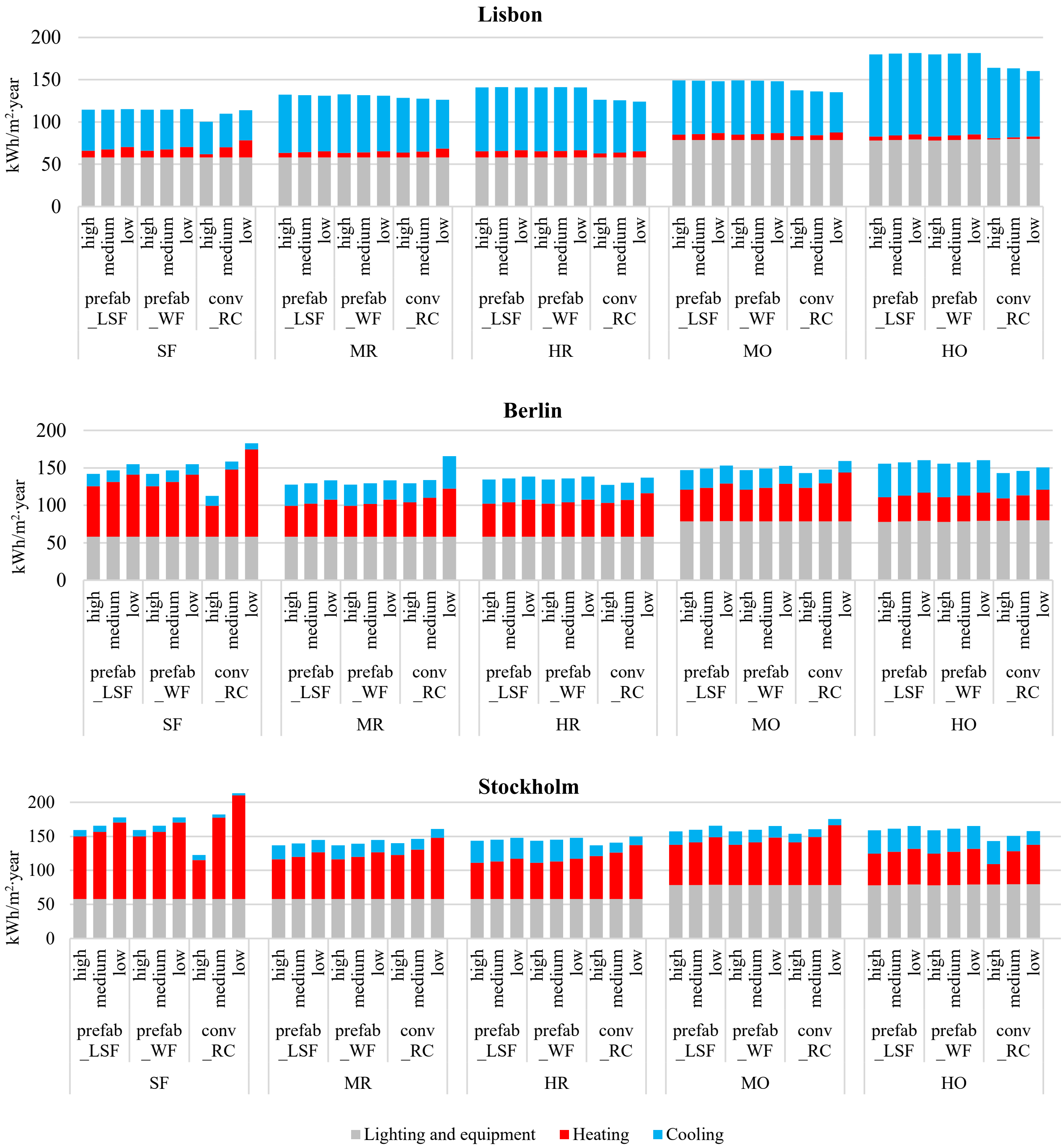


Fig. 9 Annual operational energy for each city, typology, structural material, and insulation level: divided by energy use.

3.3.2 Life cycle impacts

Figure 10 presents GW per m^2 for each archetype with medium insulation that varies between 3.2 and 20.5 tonCO_2eq/m^2. The highest values are for Berlin, Single-Family (SF) in conv_RC, and the lowest for Stockholm high-rise residential (HR) and high-rise office (HO) in prefab_LSF. Buildings in Stockholm have the lowest impacts due to Sweden's electricity mix, followed by Lisbon (slightly lower than Berlin) due to lower energy needs.

Operational impacts are the most significant (roughly 70-90%) followed by embodied impacts (10-30%), except for GW in Stockholm (operational 35-60%; embodied 40-65%). At the end-of-life, impacts can decrease down to less 10% (when using prefab_LSF) except for GW in Stockholm, decreasing down to less 45%. Within residential buildings, Single-Family (SF) generally has more impacts (more 5-40%) than the other typologies (except for conv_RC in Lisbon). Office buildings have up to +20% impacts of the residential buildings with identical volumetry (when comparing MO with MR and HO with HR).

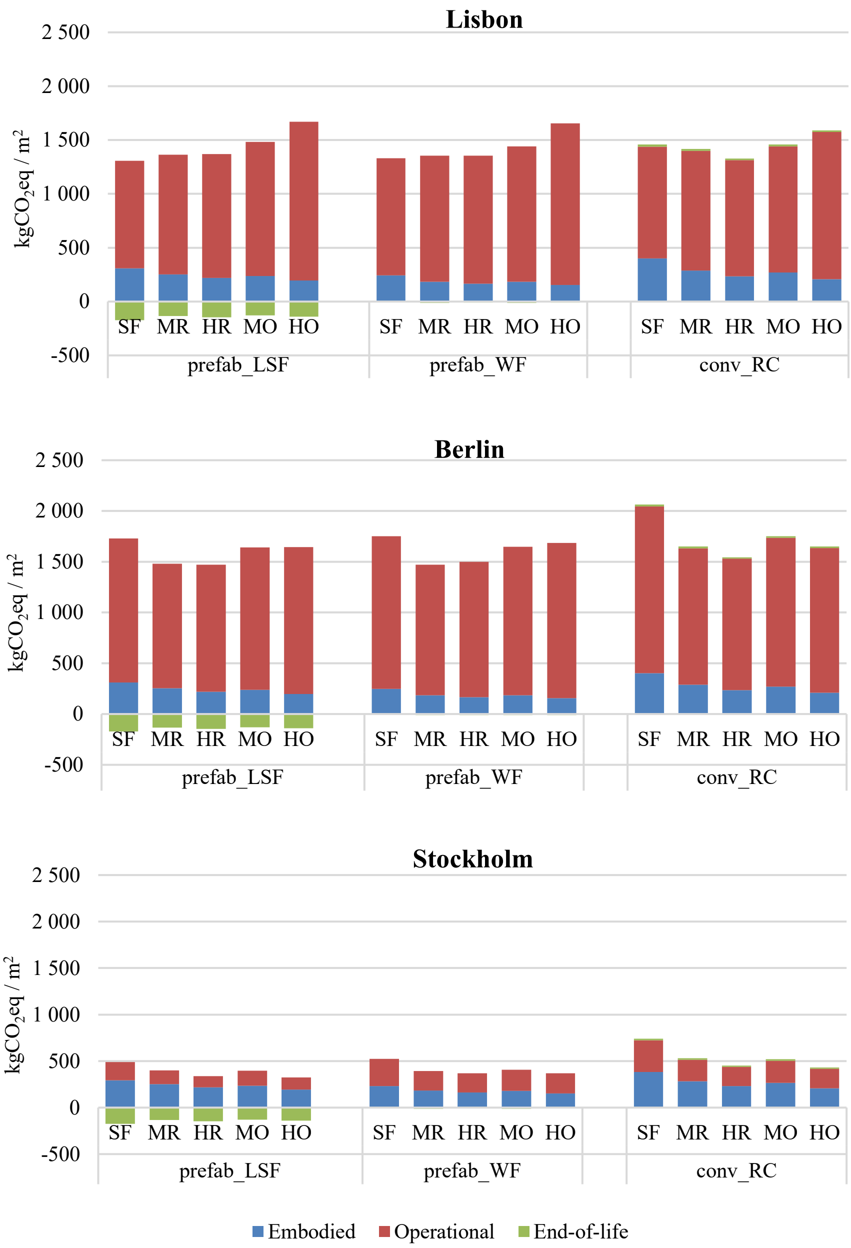


Fig. 10 GW per m^2 for each city, structural material, and typology: divided by life cycle phase.

3.3.3 Life cycle costs

Figure 11 presents the LC costs per m^2 for each archetype with medium insulation. Costs vary between 2.1-6.2 k€/m^2. The highest costs are for single-family (SF) in conv_RC in Berlin and Stockholm, and the lowest for residential buildings in prefab_LSF and prefab_WF in Lisbon.

Operational costs are the most significant (50-90%), followed by embodied costs (10-50%), with end-of-life costs negligible. SF in Berlin and Stockholm cost 20-40% more than the other typologies, and in Lisbon, SF cost 2-15% more. Office buildings in prefab_LSF and prefab_WF in Lisbon and Berlin cost 7-20% more than identical residential buildings (MO compared with MR and HO with HR). Each country's cost of living influences costs: mainly by the cost of electricity (increasing the costs of a single-family house that is more energy-intensive) and labor (increasing the costs of the more labor-intensive RC).

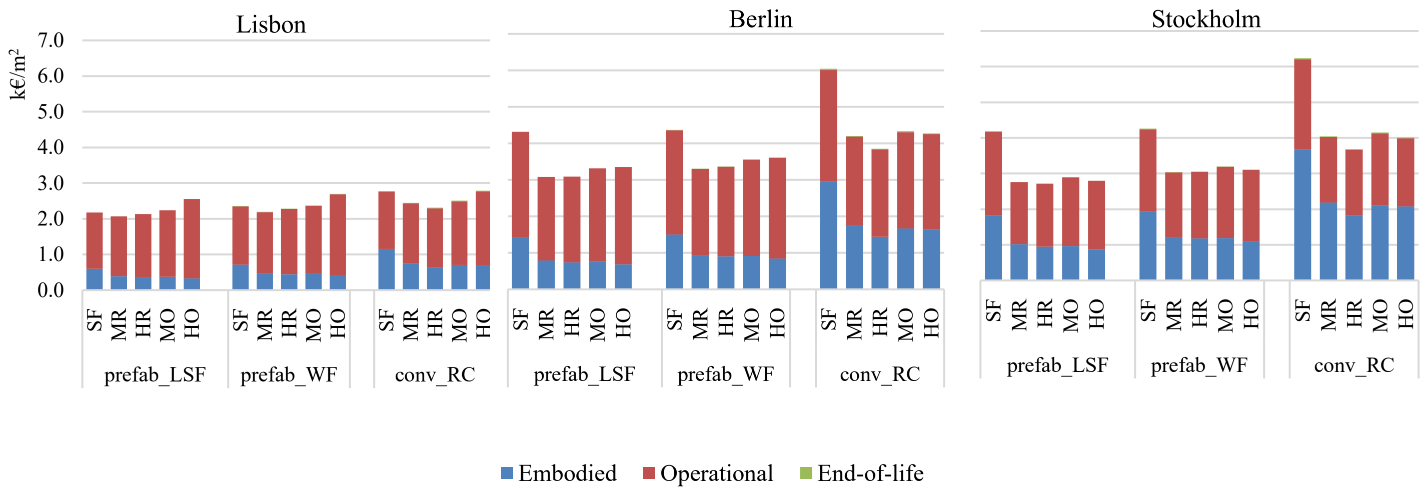


Fig. 11 Life cycle costs per m^2, per city, structural material, and archetype: divided by life cycle phase.

3.4 Contribution to EU-targets

The EU Commission considers that the "*built environment provides low-cost and short-term opportunities to reduce emissions*," setting a 90% reduction target by 2050 compared to 1990 levels [57]. Prefabricated and conventional buildings have similar operational performance, so the benefits of reducing the operational impacts of buildings (by replacing old inefficient buildings with new ones) were not considered, and the focus was given to embodied and EoL impacts reduction. New buildings reduce operational needs by 25-40% [44], and prefabrication can further reduce the impacts of buildings (reducing embodied and EoL impacts) by less 3-6%.

4 Discussion

Fig 12 presents current and previous work outcomes (detailed results are presented in Appendix F of SI). Results roughly fit previous work results range even though differences in scopes and system boundaries, impact categories, future scenarios, and main assumptions may lead to differences in results. Some studies present future impacts as a percentage of base case scenarios, making it difficult to draw conclusions among different studies and compare different environmental measures. All studies present more extensive ranges in all the categories at base case scenario due to higher variability and heterogeneity of the building stock, demonstrating how difficult it is to draw the baseline.

Compared with the IMPRO project [36], the present work presents a lower reduction potential for both GW and NRE. The difference arises from goal and scope definition. IMPRO assesses old buildings and, for most buildings, considers only refurbishment, excluding the construction stage. In IMPRO, reduction potentials for most archetypes and retrofitting measures are at least 20% (compared to 1990 baseline) [36], which are higher than the reduction potential of the present work. IMPRO compares new and old buildings, focusing on use phase efficiency. In contrast, the current work compares new buildings with similar operational performance, thus neglecting the reduction of the impact achieved by replacing old inefficient buildings with new energy-efficient ones. Operational energy is highly dependent on the study's main assumptions: construction type and performance (insulation and inertia), users' profile, energy uses and sources, HVAC systems, among other factors. The present work presents a slight operational energy reduction between current and future prefabricated scenario base cases (smaller than the IMPRO results).

LC costs were not assessed in previous works: IMPRO includes the refurbishment measures pay off, and ENTRANZE energy cost savings [28]. The range of LC costs in the base case scenario is wider than for future prefabricated scenarios, showing the higher variability of conventional buildings' cost than that of prefabricated buildings. New energy-efficient conventional buildings are compared with new energy-efficient prefabricated ones in this comprehensive life cycle cradle-to-grave assessment (comparing equivalent alternatives with similar energy performance). This work accounts for the core indicators (impacts, costs, and operational energy), thus enabling an objective comparison of equivalent alternatives in future building stock replacement and growth.

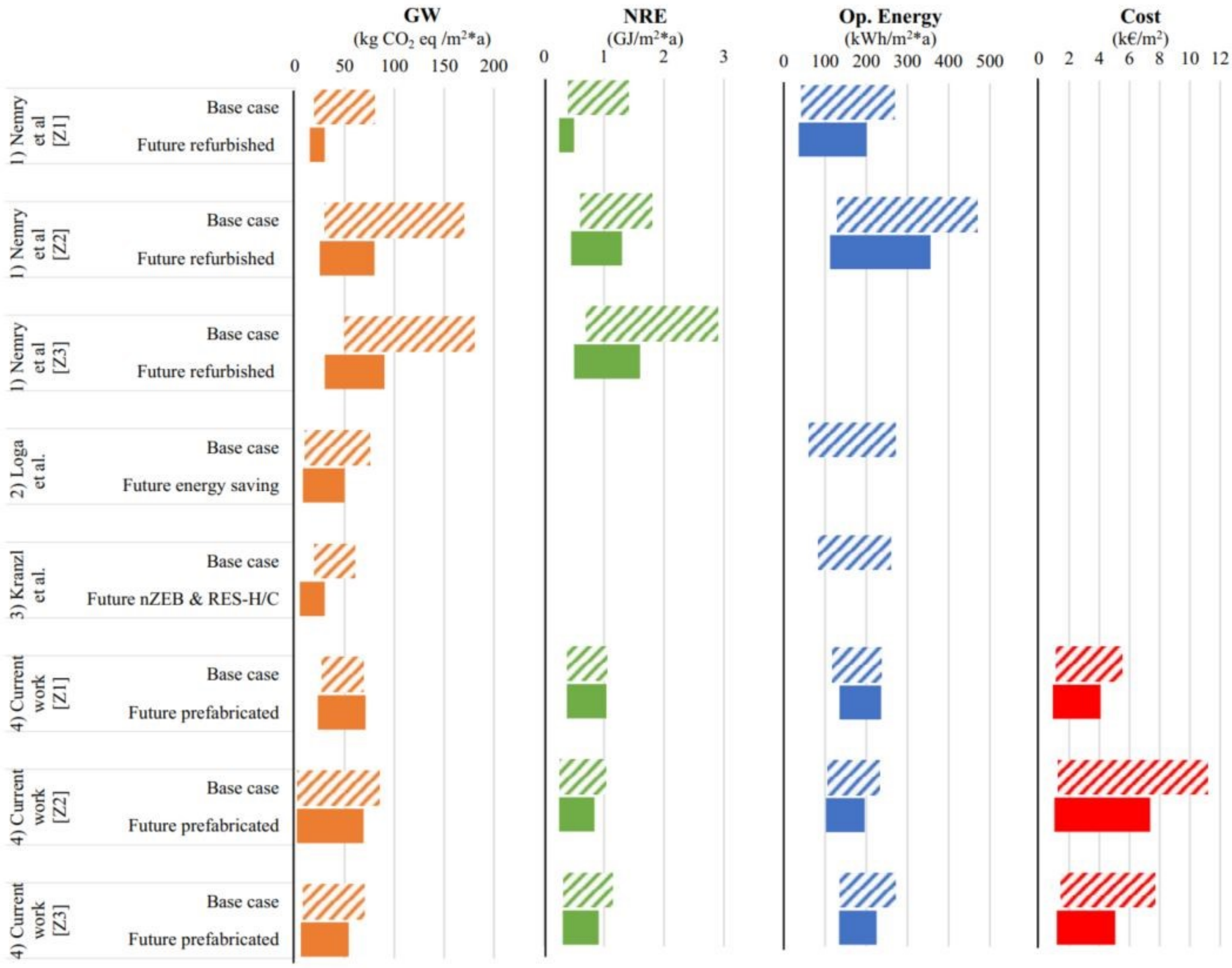


Fig. 12 Range of results for the base case and future scenarios for the different archetypes in current and previous works (results presented per area and year): 1) IMPRO project (2006-2008); 2) TABULA project (2009-2012) & EPISCOPE projects (2012-2014); 3) ENTRANZE project (2012-2014); and 4) current work. NB: Z1 warm-weather countries (HDD < 2200); Z2 moderate-weather countries (HDD 2200-3300), and Z3) cold-weather countries (HDD > 3300), adapted from [58].

The embodied impacts of prefabricated buildings are lower than conventional as a consequence of lightweight construction (using fewer and lighter materials) and an optimized construction system (taking less time, labor, and energy to be built) (see Table 3 and Section 2.4.1). As prefabricated buildings can be more easily disassembled and materials recycled, they have fewer impacts at EoL, producing less waste with higher reuse and recycling rates (which would enable a more circular economy). Prefabrication can decrease building stock costs by up to 10%, decreasing materials used, labor, and construction time. Prefabrication production could be relocated to countries with lower impacts and costs, although transport ought to be balanced. Finally, a reduced construction time could be translated to an accountable added value, a benefit ignored by the present study.

Results show that the country's electricity mix influences the impacts more (mainly GW) than the weather, construction materials, or insulation. The insulation level influences more heavyweight construction (conventional) than lightweight construction (prefabricated) and buildings in moderate or cold countries than in warm countries. Different conclusions can be drawn at different aggregation levels, as discussed by [20,59]. At the building stock level, prefab and BAU scenarios present similar operational impacts due to similar energy needs of buildings (prefabricated and conventional) with similar energy performance (less than 1% variation). However, at a country- or building-level, the operational impacts of alternatives are different, showing that a building stock analysis at different levels (building, country, and European stock level) can lead to different conclusions (e.g., preferable insulation level or construction system in each country; or what measure should be adopted to reduce the impact of each building type).

Prefabrication can reduce building stock impacts and costs, but in different ways than conventional buildings. Most of the buildings' impacts (50-90%) are due to the operation phase, and as alternatives have similar energy performances, the reduction potential is diminished. Nevertheless, prefabrication can reduce embodied (up to -40%), EoL (up to -90%), and LC impacts (up to -10%). Cost presents a higher variability, with LC costs varying among different countries in the most extreme case by an order of magnitude (e.g., LC cost in Luxembourg is ten times higher than in Bulgaria). This presents an opportunity to produce prefabricated buildings in countries with lower costs (labor, energy, materials), further decreasing costs, strengthening the domestic market, and leveraging prefabrication as an export product. Moreover, economies of scale were not considered and could enlarge the differences in costs and impacts between conventional and prefabricated.

The dynamic simulation tool integrated with BIM software is a quick method to assess the same building in different final locations. A modular LCI showed to be a rapid tool to build the LCI of buildings with the same construction system but with different forms, sizes, and final locations. The proposed modular LCI follows and expands the previously proposed component-based LCI [60]. Combining both approaches enabled the construction of a vast, reliable, and detailed database at a continental scale. The developed framework meets the initial goal to assess a technological innovation (building prefabrication) within a group of products in use (building stock), changeable by the flow (demolition and increasing rates) over time (from 2020 to 2050).

5. Conclusion

Prefabrication has been identified as a way to reduce the impacts of buildings. However, its wide adoption has not been previously assessed at the EU building stock scale. Results show that prefabrication alone cannot meet EU environmental targets but can (in addition to energy efficiency measures and the refurbishment of buildings) contribute to achieving the envisaged EU targets. Prefabrication presents an opportunity to reduce construction costs and increase sector productivity and sustainability.

The developed building stock model is a fast and reliable approach to forecast the market dynamics when introducing a new technological innovation. This framework combined a modular LCI with a BIM-based energy simulation, reducing LCA complexity and time needed. BIM methodology could also be used to build the LCI of buildings by associating cost and emission factors to each BIM element. Further developments include the integration of the modular LCI into the BIM software to balance embodied, operation, and EoL impacts and costs, enabling the assessment of buildings at the design stage by non-LCA experts. Both databases (cost and impacts) should be external and linked to the software to be easily updated to respond to regional and temporal variability.

Acknowledgments

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Appendix A – Building stock background

Previous studies have modeled current and future stock, aiming to predict its dynamics [40,43] and impacts [25,26,43]. Table A.1 sums up the different approaches in the building stock research field. The main research streams are: to evaluate stock performance, compare current and future scenarios, or model stock evolution over time [61]. Moreover, the primary purposes are benchmarking, assessing climate change mitigation strategies, or building a legal framework (Geraldi and Ghisi, 2020). Different temporal (short, medium and long) and spatial dimensions were used (regional, national or transnational), assessing (past, present and future) stocks; and different time dependency approaches: accounting (describes stock size and composition, and related materials and energy flow); static (focusing on the model on a precise moment in time, e.g., one year); or dynamic (capturing the evolution of building stock being input- or activity-driven, or stock-driven based). The technologies previously assessed were: i) building refurbishment [25,26]; ii) low energy or nZEB buildings [38]; and iii) no technology implementation with business as usual scenario [40].

Table A.1 Building stock modeling research

Streams of investigation [1]	Evaluating the environmental performance of the building stock	Comparing the current situation with a hypothetical future scenario (s)	Modeling the evolution of the building stock over time
Proposes of investigation [2]	Benchmarking	Climate change mitigation strategies	Building a legal framework
Technology implementation	None (business as usual)	Low energy buildings or nZEB	Renovation
Temporal dimension	Short temporal horizon	Medium temporal horizon	Long temporal horizon
Spatial dimension	Regional / urban	National	Transnational
Scenario analysis	Past	Present	Future
Stock type	Residential	Services and commercial	Industrial
Grouping approaches[3]	Supervised approach *Successive division of the dataset in a hierarchical structure of groups and subgroups defined manually*	Unsupervised approach *Clustering by applying an algorithm that group buildings according to multidimensional features (location, size, etc.)*	Semi-supervised *Labeled and unlabeled data are combined to improve grouping*
Time dependency	Accounting *Describes stock size and composition; and related materials and energy flows*	Static *Focus on the model at a precise moment in time (e.g., one year)*	Dynamic *Captures the evolution of building stock* *Input- or activity-driven (using construction or demolition rates)* *Stock-driven (service demand-provision concept based on population, size and type preferences, and mass balance eq)*

1) Based on [61]
2) Based on [20]
3) Based on [62]

Table A.2 presents the building stock model composition (based on Mastrucci et al. 2020): a) the energy demand model, b) the LCA model, and c) the stock aggregation model. The a) energy demand model assesses present and future operational energy needs of the building stock using dynamic (engineering-based), statistical, or hybrid approaches; by a top-down (statistical-based), bottom-up (inferring from a group of pre-assessed buildings), or a combined approach. The b) LCA models can use multiple approaches: attributional (when accounting for impacts) or consequential (when analyzing technologies implementation); process-based, input-output, or a hybrid LCA. The models have different system boundaries (most of them focusing on operational impacts) and functional units (FU) (e.g., total, per area, per inhabitant). Finally, the c) stock aggregation model combines and scales up results (from LCA and energy models) using archetypes (modeled buildings, e.g., Lavagna et al., 2018), building samples (actual building) that represent cohorts (e.g., Aelenei et al., 2016; Nemry et al., 2010), or a building-by-building approach based on GIS technologies (e.g., García-Pérez et al., 2018; Mastrucci et al., 2017). Each aggregation approach presents different constraints being the more detailed models (such as the building-by-building approach) generally applied to considerably narrower areas.

Table A.2 Building stock model: A) Energy demand model + B) LCA model + C) Stock aggregation model

A) ENERGY DEMAND MODEL

Energy model	Engineering-based approach Based on dynamic energy simulation (limited-range and able to account for impacts of new technologies)	Statistical approaches Based on statistical data (wide-range but unable to render differences within the stock)	Hybrid approach Combining both approaches
Energy data	Bottom-up Extrapolated from buildings or group of buildings	Top-down Energy consumption statistics correlated with socio-economic-technical drivers	

B) LCA MODEL

Functional unit	Absolute Total	Space-related Gross floor or living area	Per capita Inhabitant or dwelling
LCA approaches	Attributional	Consequential	
System boundaries	Embodied Including: *- Materials extraction and transformation* *- (Pre)fabrication* *- Assemblage and construction*	Operational Including: *- Buildings' use* *- Maintenance*	End-of-life Including: *- Demolition/disassembling* *- Waste treatment*
Data collection approaches	Process-based LCA	Input-output LCA	Hybrid LCA
Data resolution and scope	High resolution Detailed data typically in small scale studies (a narrower scope, e.g., neighborhood)	Low resolution More aggregated data typically in large scale studies (a broader scope, e.g., country level)	

C) STOCK AGGREGATION MODEL

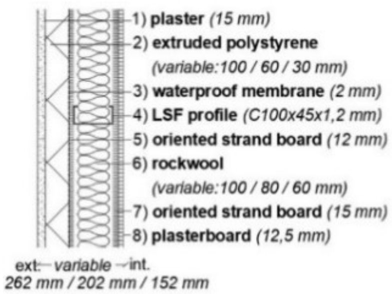
Building stock aggregation model	Archetypes Model representative buildings for each cluster at a specific region or type	Sample Pick a representative sample of actual buildings	Building-by-building Represents the entire population usually using GIS
Model characterization	Building related - Size and shape - Building envelope - Systems - Location and orientation	User related - Operation and maintenance - Users' profile - Indoor air quality	

Appendix B – Archetypes' definition

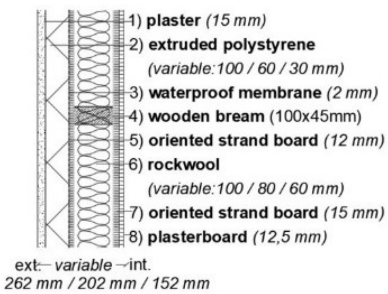
Table B.1 Construction details of the main elements (external wall, roof, internal wall, and windows) for the three constructive systems: prefabricated light steel framing (prefab_LSF) and wooden framing (prefab_WF); and conventional reinforcing concrete (conv_RC).

PREFABRICATED		CONVENTIONAL
Light steel framing (prefab_LSF)	Wood framing (prefab_WF)	Reinforced concrete (conv_RC)

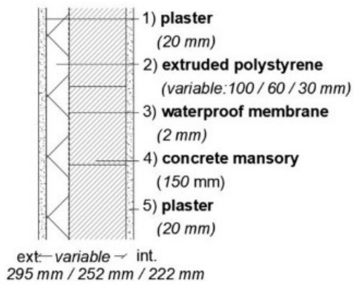
prefab_LSF Exterior wall



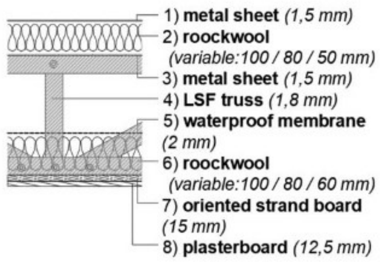
prefab_WF Exterior wall



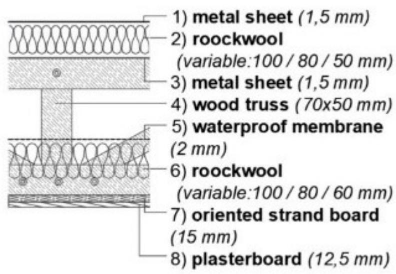
conv_RC Exterior wall



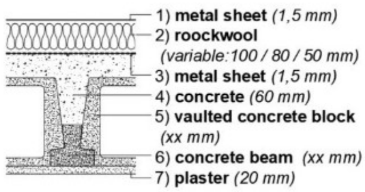
prefab_LSF Roof



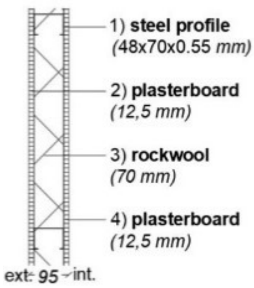
prefab_WF Roof



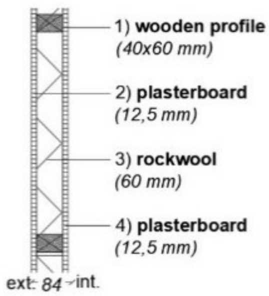
conv_RC Roof



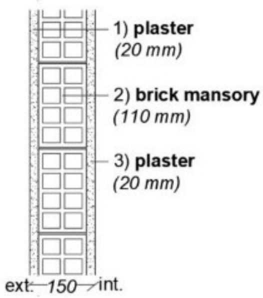
prefab_LSF Internal wall



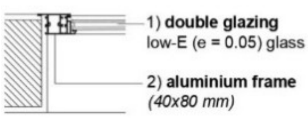
prefab_WF Internal wall



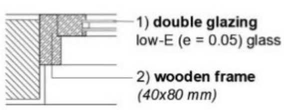
conv_RC Internal wall



Aluminium Window



Wood Window



PVC Window

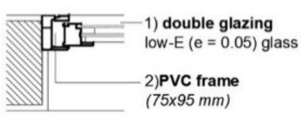


Table B.2 Construction and site alternatives

Building location	Warm	Moderate	Cold
City	Lisbon	Berlin	Stockholm
Heating degree days (HDD)	1109*	2801*	5120*
Cooling degrees days (CDD)	167*	46*	1*
Exterior wall insulation thickness	Low	Medium	High
Prefabricated (prefab_LSF & prefab_WF)	30+60 mm	60+80 mm	100+100 mm
Conventional (conv_RC)	30 mm	60 mm	100 mm
Roof insulation thickness	Low	Medium	High
Prefabricated (prefab_LSF & prefab_WF) roof	50+60 mm	80+80 mm	100+100 mm
Conventional (conv_RC) roof	50 mm	80 mm	100 mm

* Data from the 2019 year.

Appendix C– Life cycle supporting information

Table C.1. Life cycle inventory of embodied phase

A1-A3 RAW MATERIALS

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Exterior wall (kg)	SF	13 872 / 14 617 / 15 426	15 286 / 16 031 / 16 840	61 972 / 62 102 / 64 230
	MR & MO	59 793 / 62 925 / 66 329	64 281 / 67 413 / 70 817	260 610 / 261 153 / 270 102
	HR & HO	119 736 / 126 165 / 133 152	131 941 / 138 370 / 145 356	534 919 / 536 034 / 554 402
Roof (kg)	SF	5 934 / 6 659 / 7 194	7 561 / 8 278 / 8 853	30 400 / 30 690 / 30 980
	MR & MO	24 507 / 27 502 / 29 711	31 541 / 34 535 / 36 931	125 552 / 126 750 / 127 947
	HR & HO	27 356 / 30 698 / 33 164	35 207 / 38 549 / 41 223	140 144 / 141 481 / 142 818
Floor (kg)	SF	7 637	7 931	36 657
	MR & MO	61 601	68 955	295 700
	HR & HO	182 555	204 349	867 306
Interior wall (kg)	SF	2 583	3 846	16 586
	MR	56 233	57 902	334 732
	HR	119 278	132 497	765 962
	MO	41 700	46 322	53 067
	HO	59 868	66 300	383 283
Stairs (kg)	SF	636	617	3 050
	MR & MO	3 818	3 703	18 301
	HR & HO	5 727	5 554	27 451
Door (kg)	SF	288	288	288
	MR	3 888	3 888	3 888
	HR	9 000	9 000	9 000
	MO	1 440	1 440	1 440
	HO	4 680	4 680	4 680
Windows (kg)	SF	3 018	3 846	2 570
	MR & MO	16 124	20 509	13 705
	HR & HO	60 350	76 910	51 394
Concrete structural core (kg)	SF	-	-	-
	MR & MO	171 500	171 500	171 500
	HR & HO	428 750	428 750	428 750

A4 TRANSPORT TO PLANT

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Transport of materials (tkm)	SF	1 698 / 1 772/ 1 839	1 934 / 2 007 / 2 077	-
	MR	19 593 / 19 900 / 20 180	21 114 / 21 420 / 21 710	-
	HR	47 638 / 48 126 / 48 599	51 210 / 51 699 / 52 182	-
	MO	18 950 / 19 256 / 19 537	20 413 / 20 719 / 21 009	-
	HO	44 442 / 44 931 / 46 403	47 685 / 48 173 / 48 656	-
Transport of workers (km)	SF	2 640	2 640	-
	MR & MO	7 920	7 920	-
	HR & HO	21 120	21 120	-

A4 ON PLANT PREFABRICATION

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Electricity (kWh)	SF	12 000	12 000	-
	MR /MO	18 000	18 000	-
	HR /HO	24 000	24 000	-
Gas (kWh)	SF	2 200	2 200	-
	MR /MO	3 300	3 300	-
	HR /HO	4 400	4 400	-
Water (m3)	SF	66	66	-
	MR /MO	99	99	-
	HR /HO	132	132	-
Labor (hr)	SF	1 848	1 848	-
	MR /MO	2 772	2 772	-
	HR /HO	3 696	3 696	-

A4 TRANSPORT TO SITE

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Transport of materials and prefab parts	SF	33 967 / 35 437 / 36 781	38 684 / 40 147 / 41 530	151 523 / 152 942 / 154 360
	MR	391 869 / 397 995 / 403 608	422 280 / 428 406 / 434 205	1 223 987 / 1 225 728 / 1 235 874
	HR	952 753 / 962 524 / 971 977	1 024 209 / 1 033 980 / 1 043 640	2 833 926 / 2 836 378 / 2 856 083
	MO	378 996 / 385 122 / 390 735	408 525 / 414 378 / 420 177	1 154 232 / 1 155 973 / 1 166 120
	HO	888 841 / 898 612 / 908 065	953 693 / 963 464 / 973 124	2 446 926 / 2 449 378 / 2 469 083
Transport of workers	SF	8 800	8 800	17 600
	MR /MO	17 600	17 600	35 200
	HR /HO	35 200	35 200	70 400

A5 ASSEMBLAGE AND CONSTRUCTION

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Electricity (kWh)	SF	6 000	6 000	24 000
	MR /MO	12 000	12 000	48 000
	HR /HO	18 000	18 000	52 364
Gas (kWh)	SF	550	550	2 200
	MR /MO	1 100	1 100	4 400
	HR /HO	1 650	1 650	6 600
Water (m^3)	SF	17	17	66
	MR /MO	33	33	132
	HR /HO	50	50	144
Labor (hr)	SF	1 848	1 848	14 784
	MR /MO	7 392	7 392	59 136
	HR /HO	22 176	22 176	177 408

Table C.2. Life cycle inventory of operational phase

B2-B5 MAINTAINANCE, REPAIR, REPLACEMENT, REFURBISHMENT

Materials replacement	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Exterior wall (kg)	SF	7 497 / 7 691 / 7 950	7 497 / 7 691 / 7 950	11 708 / 11 837 / 12 160
	MR & MO	31 529 / 32 344 / 33 430	31 529 / 32 344 / 33 430	49 234 / 49 778 / 51 136
	HR & HO	64 714 / 66 387 / 68 618	64 714 / 66 387 / 68 618	101 057 / 102 172 / 104 960
Roof (kg)	SF	5 018 / 5 888 / 6 468	5 018 / 5 888 / 6 468	8 080 / 8 660 / 9 240
	MR & MO	20 724 / 24 317 / 26 713	20 724 / 24 317 / 26 713	33 370 / 35 766 / 38 161
	HR & HO	23 133 / 27 144 / 29 817	23 133 / 27 144 / 29 817	37 249 / 39 923 / 42 596
Floor (kg)	SF	1 798	1 798	463
	MR & MO	14 505	14 505	3 732
	HR & HO	42 987	42 987	11 059
Interior wall (kg)	SF	1 769	1 769	6 270
	MR	35 698	35 698	126 540
	HR	81 686	81 686	289 560
	MO	28 558	28 558	101 323
	HO	40 875	40 875	144 894
Stairs (kg)	SF	150	150	457
	MR & MO	899	899	2 741
	HR & HO	1 349	1 349	4 111
Door (kg)	SF	252	252	252
	MR	3 888	3 888	3 888
	HR	9 000	9 000	9 000
	MO	1 440	1 440	1 440
	HO	4 680	4 680	4 680
Windows (kg)	SF	3 018	3 846	2 570
	MR & MO	16 093	20 509	13 705
	HR & HO	60 350	76 910	51 394
Maintenance waste (kg)	SF	19 502 / 20 566 / 21 404	20 330 / 21 394 / 22 232	27 799 / 30 508 / 31 411
	MR	123 336 / 127 745 / 131 227	127 753 / 132 161 / 135 643	233 210 / 236 149 / 239 902
	HR	283 220 / 288 903 / 293 808	299 780 / 305 463 / 310 368	503 429 / 507 218 / 512 679
	MO	113 573 / 117 981 / 121 464	118 165 / 122 573 / 126 055	182 682 / 185 621 / 189 375
	HO	238 089 / 243 772 / 248 676	254 649 / 260 332 / 265 236	354 443 / 358 232 / 363 693
Transport	**archetype**	**prefab_LSF L / M / H**	**prefab_WF L / M / H**	**conv_RC L / M / H**
Transport of materials (tkm)	SF	975 /1 028 / 1 070	1 016 / 1 070 / 1 112	1 490 / 1 525 / 1 571
	MR	6 167 / 6 387 / 6 561	6 388 / 6 608 / 6 782	11 660 / 11 807 / 11 995
	HR	14 161 / 14 445 / 14 690	14 989 / 15 273 / 15 518	25 171 / 25 361 / 25 634
	MO	5 679 / 5 899 / 6 073	5 908 / 6 129 / 6 303	9 134 / 9 281 / 9 469
	HO	11 904 / 12 189 / 12 434	12 732 / 13 017 / 13 262	17 722 / 17 912 / 18 185
Transport of workers (km)	SF	300	300	300
	MR & MO	880	880	880
	HR & HO	1 980	1 980	1 980
Transport of waste (tkm)	SF	585 / 617 / 642	610 / 642 / 667	894 / 915 / 942
	MR	3 700 / 3 832 / 3 937	3 833 / 3 965 / 4 069	6 996 / 7 094 / 7 197
	HR	8 497 / 8 667 / 8 814	8 993 / 9 164 / 9 311	15 103 / 15 217 / 15 380
	MO	3 407 / 3 539 / 3 644	3 545 / 3 677 / 3 782	5 480 / 5 569 / 5 681
	HO	7 143 / 7 313 / 7 460	7 639 / 7 810 / 7 957	10 633 / 10 747 / 10 911

B6-B7 OPERATIONAL ENERGY USE

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Lisbon (kWh / year)	SF	22 856 / 22 664 / 22 586	22 856 / 22 664 / 22 585	19 756 / 21 608 / 22 447
	MR	216331 / 217 628 / 218 874	216 331 / 217 795 / 218 935	208 508 / 210 544 / 212 506
	HR	653 241 / 651 086 / 648 630	653 241 / 651 086 / 648 630	577 013 / 584 758 / 585 311
	MO	244 675 / 245 705 / 246 577	244 675 / 245 705 / 246 577	223 508 / 225 030 / 226 969
	HO	836 412 / 833 597 / 830 049	836 412 / 833 597 / 830 049	738 572 / 753 574 / 755 991
Berlin (kWh / year)	SF	30 5959 / 29 021 / 28 001	30 595 / 29 021 / 27 987	36 085 / 31 245 / 212 790
	MR	220 116 / 214 036 / 210 836	220 116 / 213 883 / 210 836	238 849 / 220 938 / 213 569
	HR	641 097 / 626 698 / 617 889	614 097 / 626 698 / 617 889	635 472 / 605 063 / 589 161
	MO	252 430 / 246 180 / 243 086	252 430 / 246 180 / 243 086	262 858 / 243 861 / 236 158
	HO	738 491 / 725 887 / 717 539	738 491 / 725 887 / 717 529	694 469 / 671 827 / 658 933
Stockholm (kWh / year)	SF	35 255 / 32 733 / 31 420	35 255 / 32 733 / 31 420	42 099 / 35 951 23 767
	MR	239 327 / 230 589 / 225 870	239 327 / 230 589 / 225 867	265 939 / 230 589 / 231 524
	HR	684 458 / 669 098 / 659 819	684 458 / 669 098 / 659 819	695 594 / 654 063 / 632 766
	MO	272 927 / 264 014 / 259 542	272 927 / 264 014 / 259 542	290 097 / 264 014 / 254 311
	HO	736 769 / 743 423 / 732 769	760 787 / 743 423 / 732 769	726 330 / 693 383 / 658 933

Table C.3. Life cycle inventory of end-of-life phase

C1-C4 DECONSTRUCTION / DEMOLITION

	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Electricity (kWh)	SF	1 364	1 364	1 364
	MR /MO	2 727	2 727	2 727
	HR /HO	4 091	4 091	4 091
Gas (kWh)	SF	125	125	125
	MR /MO	250	250	250
	HR /HO	375	375	375
Water (m3)	SF	4	4	4
	MR /MO	8	8	8
	HR /HO	11	11	11
Labor (hr)	SF	70	70	70
	MR /MO	280	280	280
	HR /HO	630	630	630
Transport	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Transport of workers (km)	SF	75	75	75
	MR & MO	300	300	300
	HR & HO	675	675	675
Transport of waste (tkm)	SF	1 019 / 1 063 / 1 103	1 161 / 1 204 / 1 246	4 546 / 4 558 / 4 631
	MR	11 756 / 11 940 / 12 108	12 668 / 12 852 / 13 026	36 720 / 36 772 / 37 076
	HR	28 583 / 28 876 / 29 159	30 726 / 31 019 / 31 309	85 018 / 52 091 / 85 682
	MO	11 370 / 11 554 / 11 722	12 248 / 12 431 / 12 605	34 627 / 34 679 / 34 984
	HO	26 665 / 26 958 / 27 242	28 611 / 28 904 / 973 124	73 408 / 73 481 / 74 072

D REUSE & RECYCLE

Waste management	archetype	prefab_LSF L / M / H	prefab_WF L / M / H	conv_RC L / M / H
Demolition waste (kg)	SF	33 922 / 35 392 / 36 781	38 684 / 40 147 / 41 530	153 328 / 153 747 / 154 360
	MR	391 683 / 397 809 / 403 608	422 280 / 428 406 / 434 205	1 231 577 / 1 233 318 / 1 235 874
	HR	952 546 / 962 317 / 971 977	1 024 209 / 1 033 980 / 1 043 640	2 849 506 / 2 851 958 / 2 856 083
	MO	378 810 / 384 936 / 390 735	408 252 / 414 378 / 420 177	1 161 823 / 1 163 564 / 1 166 120
	HO	888 633 / 898 404 / 908 065	953 693 / 963 464 / 973 124	2 462 506 / 2 464 958 / 2 469 083

Appendix D – Building stock characterization and population

Table D.1 EU-27 Building stock characterization in 2019

		area	heating & cooling degrees days		annual increase & replacement		building area				residential						non-residential			
							residential		non-residential		single-family		medium-rise		high-rise		medium-rise		high-rise	
	Countries	Mm²	HDD	CDD	incr. rate	replace.rate	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%
Z2	Austria	484	3 280	40	var.	1.2%	315	65%	170	35%	198	41%	98	20%	16	3%	144	30%	25	5%
Z2	Belgium	516	2 532	40	var	1.2%	348	67%	168	33%	285	55%	56	11%	10	2%	143	28%	25	5%
Z1	Bulgaria	240	2 153	164	var	1.2%	173	72%	67	28%	97	40%	64	27%	12	5%	57	24%	10	4%
Z1	Croatia	133	2 076	192	var	1.2%	104	78%	30	22%	84	63%	17	12%	3	2%	25	19%	4	3%
Z1	Cyprus	51	693	754	var	1.2%	44	86%	7	14%	34	67%	8	16%	1	3%	6	12%	1	2%
Z2	Czech Rep.	407	2 998	40	var	1.2%	264	65%	143	35%	143	35%	103	25%	18	5%	121	30%	21	5%
Z2	Denmark	446	3 027	2	var	1.2%	322	72%	124	28%	235	53%	74	17%	13	3%	105	24%	19	4%
Z3	Estonia	49	3 883	1	var	1.2%	37	76%	12	24%	17	35%	17	35%	3	6%	10	21%	2	4%
Z3	Finland	311	5 483	1	var	1.2%	211	68%	100	32%	150	48%	53	17%	8	3%	85	27%	15	5%
Z1	France	3 548	2 247	88	var	1.2%	2 713	76%	836	24%	1 980	56%	624	18%	109	3%	710	20%	125	4%
Z2	Germany	4 388	2 801	46	var	1.2%	3 002	68%	1 386	32%	1 801	41%	1 021	23%	180	4%	1 178	27%	208	5%
Z1	Greece	442	1 449	373	var	1.2%	373	84%	70	16%	160	36%	179	40%	34	8%	59	13%	10	2%
Z2	Hungary	391	2 381	150	var	1.2%	286	73%	105	27%	212	54%	63	16%	11	3%	90	23%	16	4%
Z2	Ireland	253	2 707	0	var	1.2%	179	71%	74	29%	172	68%	7	3%	2	1%	63	25%	11	4%
Z1	Italy	3 008	1 814	306	var	1.2%	2 678	89%	331	11%	1 392	46%	1 098	36%	187	6%	281	9%	50	2%
Z3	Latvia	68	3 623	3	var	1.2%	51	75%	17	25%	24	35%	24	35%	4	6%	14	21%	3	4%
Z3	Lithuania	112	3 391	12	var	1.2%	70	63%	42	37%	35	31%	29	26%	5	4%	36	32%	6	6%
Z2	Luxemburg	27	2 754	59	var	1.2%	18	66%	9	34%	13	48%	4	15%	1	3%	8	28%	1	5%
Z1	Malta	21	515	756	var	1.2%	18	86%	3	14%	11	52%	6	29%	1	5%	2	12%	0	2%
Z2	Netherlands	975	2 514	40	var	1.2%	592	61%	383	39%	474	49%	101	10%	18	2%	325	33%	57	6%
Z2	Poland	1 322	2 952	49	var	1.2%	886	67%	436	33%	567	43%	275	21%	44	3%	371	28%	65	5%
Z1	Portugal	496	1 109	167	var	1.2%	400	81%	96	19%	248	50%	128	26%	24	5%	81	16%	14	3%
Z2	Romania	466	2 568	124	var	1.2%	386	83%	79	17%	247	53%	116	25%	19	4%	67	14%	12	3%
Z2	Slovakia	172	2 899	65	var	1.2%	102	59%	70	41%	64	37%	33	19%	6	4%	59	34%	10	6%
Z2	Slovenia	90	2 601	73	var	1.2%	74	82%	17	18%	56	62%	15	16%	3	3%	14	16%	2	3%
Z1	Spain	1 950	1 671	248	var	1.2%	1 612	83%	338	17%	677	35%	806	41%	145	7%	287	15%	51	3%
Z3	Sweden	596	5 120	1	var	1.2%	397	67%	199	33%	258	43%	119	20%	20	3%	169	28%	30	5%
	EU-27	20 963	2 909	111		1.2%	15 654	73%	5 309	27%	9 635	47%	5 136	22%	899	4%	4 512	23%	796	4%

NB: Z1 warm-weather countries (HDD < 2200); Z2 moderate-weather countries (HDD 2200-3300), and Z3) cold-weather countries (HDD > 3300), adapted from Nemry & Uihlein (2008)

Table D.2 EU-27 Building stock forecast for 2050

		total building area in 2050				residential in 2050						non-residential in 2050			
		residential		non-residential		single-family		multi-family		high-rise		medium-rise		high-rise	
	Mm²	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%
Austria	510	332	65%	179	35%	209	41%	103	20%	17	3%	152	30%	27	5%
Belgium	516	348	67%	168	33%	285	55%	56	11%	10	2%	143	28%	25	5%
Bulgaria	250	180	72%	70	28%	101	40%	67	27%	13	5%	59	24%	10	4%
Croatia	133	104	78%	30	22%	84	63%	17	12%	3	2%	25	19%	4	3%
Cyprus	42	36	86%	6	14%	28	67%	7	16%	1	3%	5	12%	1	2%
Czech	407	264	65%	143	35%	143	35%	103	25%	18	5%	121	30%	21	5%
Denmark	379	274	72%	105	28%	200	53%	63	17%	11	3%	89	24%	16	4%
Estonia	49	37	76%	12	24%	17	35%	17	35%	3	6%	10	21%	2	4%
Finland	366	248	68%	118	32%	176	48%	62	17%	10	3%	100	27%	18	5%
France	3 548	2 713	76%	836	24%	1 980	56%	624	18%	109	3%	710	20%	125	4%
Germany	4 351	2 977	68%	1 374	32%	1 786	41%	1 012	23%	179	4%	1 168	27%	206	5%
Greece	442	373	84%	70	16%	160	36%	179	40%	34	8%	59	13%	10	2%
Hungary	410	300	73%	110	27%	222	54%	66	16%	12	3%	94	23%	17	4%
Ireland	253	179	71%	74	29%	172	68%	7	3%	2	1%	63	25%	11	4%
Italy	2 876	2 560	89%	316	11%	1 331	46%	1 050	36%	179	6%	269	9%	47	2%
Latvia	68	51	75%	17	25%	24	35%	24	35%	4	6%	14	21%	3	4%
Lithuania	109	68	63%	41	37%	34	31%	29	26%	5	4%	35	32%	6	6%
Luxemb.	27	18	66%	9	34%	13	48%	4	15%	1	3%	8	28%	1	5%
Malta	22	19	86%	3	14%	11	52%	6	29%	1	5%	3	12%	0	2%
Netherla.	975	592	61%	383	39%	474	49%	101	10%	18	2%	325	33%	57	6%
Poland	1 320	885	67%	436	33%	566	43%	274	21%	44	3%	370	28%	65	5%
Portugal	496	400	81%	96	19%	248	50%	128	26%	24	5%	81	16%	14	3%
Romania	419	348	83%	71	17%	223	53%	104	25%	17	4%	61	14%	11	3%
Slovakia	172	102	59%	70	41%	64	37%	33	19%	6	4%	59	34%	10	6%
Slovenia	86	71	82%	16	18%	54	62%	14	16%	3	3%	13	16%	2	3%
Spain	1 950	1 612	83%	338	17%	677	35%	806	41%	145	7%	287	15%	51	3%
Sweden	737	491	67%	246	33%	319	43%	147	20%	25	3%	209	28%	37	5%
EU-27	20 915	15 581	73%	5 335	27%	9 601	47%	5 102	22%	893	4%	4 534	23%	800	4%

Table D.3 EU-27 Forecasted new buildings from 2020 to 2050

		new building area 2020-2050				new residential 2020-2050						new non-residential 2020-2050			
		residential		non-residential		single-family		multi-family		high-rise		medium-rise		high-rise	
	Mm²	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%	Mm²	%
Austria	205	133	65%	72	35%	84	41%	41	20%	7	3%	61	30%	11	5%
Belgium	186	125	67%	60	33%	103	55%	20	11%	4	2%	51	28%	9	5%
Bulgaria	98	71	72%	27	28%	40	40%	26	27%	5	5%	23	24%	4	4%
Croatia	48	37	78%	11	22%	30	63%	6	12%	1	2%	9	19%	2	3%
Cyprus	8	7	86%	1	14%	6	67%	1	16%	0	3%	1	12%	0	2%
Czech	146	95	65%	51	35%	51	35%	37	25%	7	5%	44	30%	8	5%
Denmark	86	62	72%	24	28%	45	53%	14	17%	2	3%	20	24%	4	4%
Estonia	18	13	76%	4	24%	6	35%	6	35%	1	6%	4	21%	1	4%
Finland	176	119	68%	57	32%	85	48%	30	17%	5	3%	48	27%	9	5%
France	1 277	977	76%	301	24%	713	56%	225	18%	39	3%	256	20%	45	4%
Germany	1 553	1 063	68%	491	32%	638	41%	361	23%	64	4%	417	27%	74	5%
Greece	159	134	84%	25	16%	58	36%	64	40%	12	8%	21	13%	4	2%
Hungary	163	119	73%	44	27%	88	54%	26	16%	5	3%	37	23%	7	4%
Ireland	91	64	71%	27	29%	62	68%	3	3%	1	1%	23	25%	4	4%
Italy	940	837	89%	103	11%	435	46%	343	36%	59	6%	88	9%	16	2%
Latvia	25	18	75%	6	25%	9	35%	9	35%	1	6%	5	21%	1	4%
Lithuania	37	23	63%	14	37%	12	31%	10	26%	2	4%	12	32%	2	6%
Luxemb.	10	6	66%	3	34%	5	48%	1	15%	0	3%	3	28%	0	5%
Malta	9	7	86%	1	14%	4	52%	3	29%	0	5%	1	12%	0	2%
Netherla.	351	213	61%	138	39%	171	49%	36	10%	6	2%	117	33%	21	6%
Poland	477	319	67%	157	33%	204	43%	99	21%	16	3%	134	28%	24	5%
Portugal	179	144	81%	34	19%	89	50%	46	26%	9	5%	29	16%	5	3%
Romania	116	96	83%	20	17%	62	53%	29	25%	5	4%	17	14%	3	3%
Slovakia	62	37	59%	25	41%	23	37%	12	19%	2	4%	21	34%	4	6%
Slovenia	28	23	82%	5	18%	17	62%	5	16%	1	3%	4	16%	1	3%
Spain	702	580	83%	122	17%	244	35%	290	41%	52	7%	103	15%	18	3%
Sweden	378	252	67%	126	33%	163	43%	75	20%	13	3%	107	28%	19	5%
EU-27	7 528	5 578	73%	1 950	27%	3 446	47%	1 914	37%	318	4%	1 657	23%	292	4%

Table D.4. The building area and population (2020-2050)

EU-27	Area per hab[1] Residential (m^2/hab)	Service (m^2/hab)	Area in 2020 Residential (Mm^2)	Service (Mm^2)	Total (Mm^2)	Area in 2050 Total (Mm^2)	Population in 2020 (Million)	in 2050 (Million)	Population variation from 2020 to 2050 (%)
Austria	41	14	365	122	487	511	8.9	9.3	+ 5%
Belgium	35	10	406	112	518	537	11.5	11.9	+ 4%
Bulgaria	26	8	180	58	238	194	6.9	5.7	- 19%
Croatia	25	7	103	29	133	111	4.1	3.4	- 16%
Cyprus	49	10	43	9	52	61	0.9	1.0	+ 18%
Czechia	30	9	317	91	408	402	10.7	10.5	- 2%
Denmark	54	22	316	130	446	468	5.8	6.1	+ 5%
Estonia	28	9	37	12	49	46	1.3	1.3	- 6%
Finland	36	20	200	111	311	298	5.5	5.3	- 4%
France	39	14	2 605	953	3 558	3 707	67.2	70.0	+ 4%
Germany	39	13	3 274	1 120	4 394	4 369	83.1	82.7	- 1%
Greece	29	12	308	134	441	392	10.7	9.5	- 11%
Hungary	30	10	295	96	391	371	9.8	9.3	- 5%
Ireland	42	10	207	49	256	320	5.0	6.2	+ 25%
Italy	43	7	2 587	418	3 005	2 897	60.3	58.1	- 4%
Latvia	28	8	53	14	68	50	1.9	1.4	- 27%
Lithuania	31	9	86	26	112	86	2.8	2.1	- 23%
Luxembourg	34	10	21	6	27	34	0.6	0.8	+ 23%
Malta	33	10	17	5	22	28	0.5	0.7	+ 32%
Netherlands	38	18	669	313	982	1 024	17.4	18.1	+ 4%
Poland	25	10	937	383	1 321	1 187	37.9	34.1	- 10%
Portugal	39	10	397	100	497	453	10.3	9.4	- 9%
Romania	21	3	409	53	462	372	19.3	15.5	- 20%
Slovakia	25	7	134	38	172	162	5.5	5.2	- 6%
Slovenia	30	14	63	28	91	89	2.1	2.0	- 2%
Spain	34	8	1 608	359	1 966	2 051	47.3	49.4	+ 4%
Sweden	42	16	431	170	601	714	10.3	12.3	+ 19%

[1] Data from 2008 available in Enerdata (2008)

Table D.5. Structural materials share per region for each archetype

		SF	MR	HR	MO	HO
Warm weather countries	RC	100%	100%	100%	100%	100%
Moderate weather countries	WF	33%	-	-	-	-
	RC	67%	100%	100%	100%	100%
Cold weather countries	WF	50%	67%	-	67%	-
	RC	50%	33%	100%	33%	100%

Data based on new building defined on IMPRO study, ref [44]

Appendix E– Results

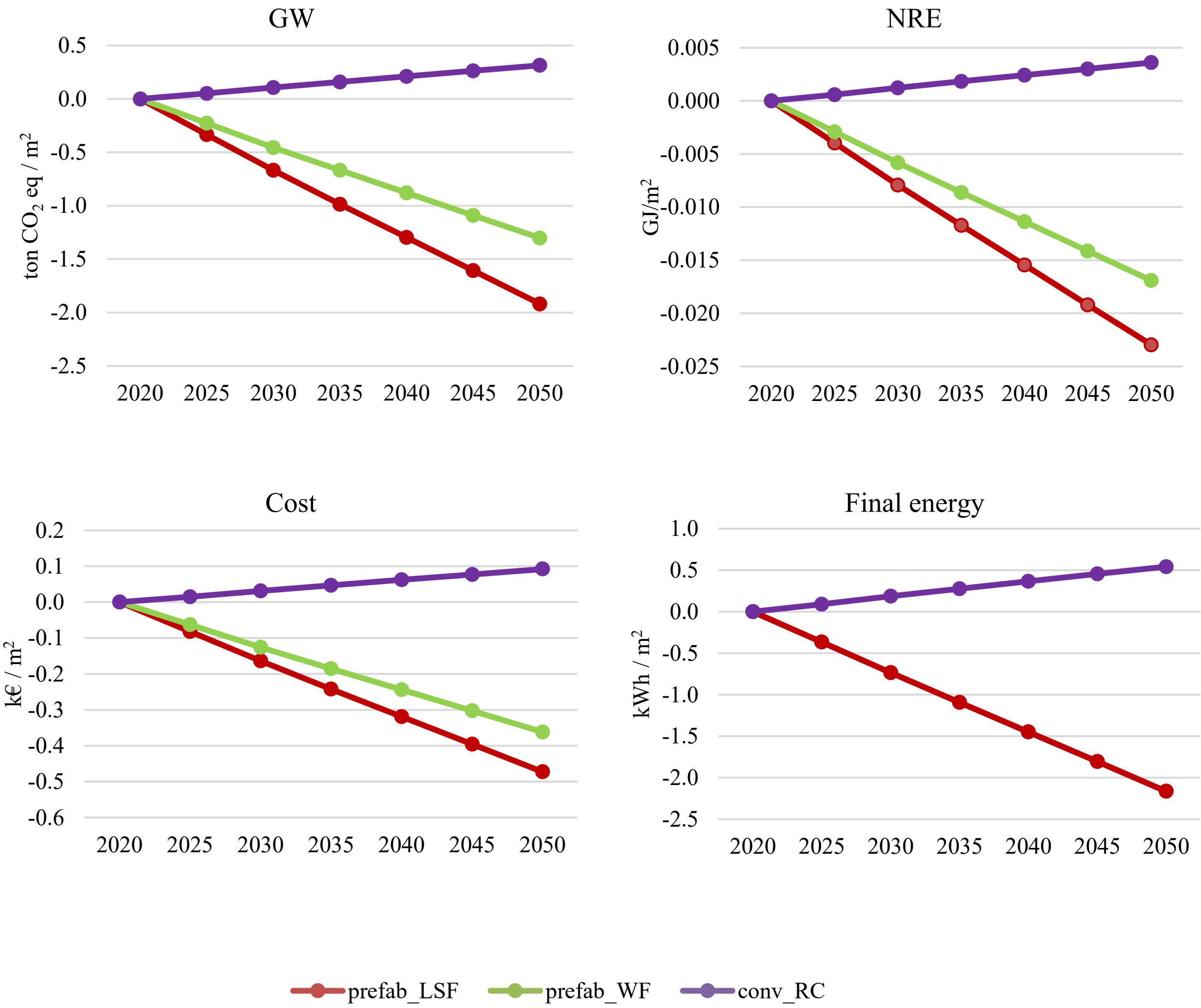


Fig. E.1 EU-27 building stock impacts, costs, and operational energy variation per m^2 of alternative scenarios compared with the business as usual (BAU) scenario: from 2020 to 2050. Alternative scenarios consider that all new buildings are built in prefab_LSF, prefab_WF, or conv_RC.

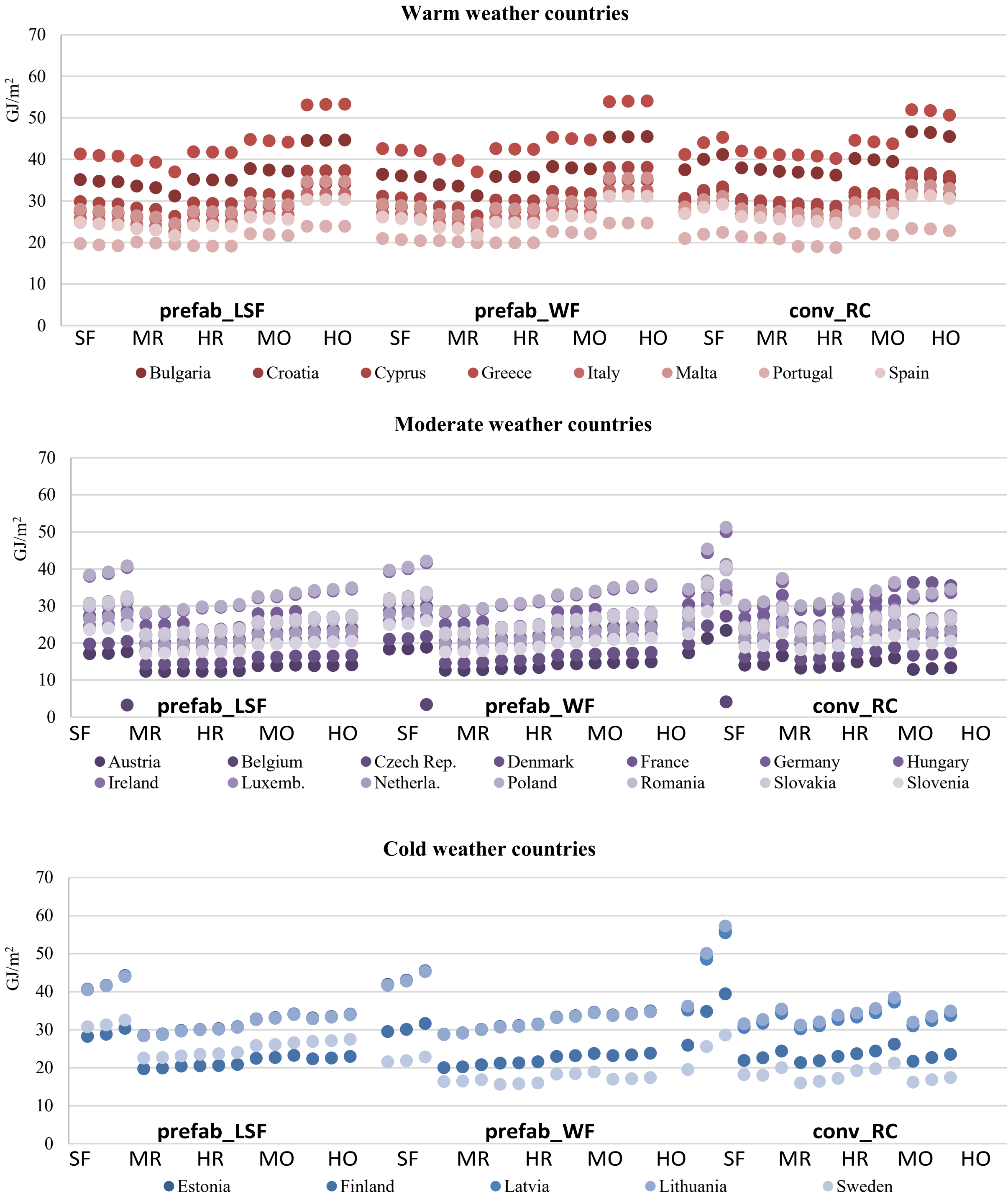


Fig. E.2 NRE per m² of prefab_LSF, prefab_WF, and conv_RC buildings in EU-27 countries divided into SF, MR, HR, MO and HO, and insulation level.

Table E.1 Energy needs per m^2 per year in each country for prefabricated LSF

				Prefab_LSF														
					SF			MR			HR			MO			HO	
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	157	**162**	171	117	119	122	128	130	132	138	140	144	149	151	154
2	**Belgium**	*2 532*	*40*	144	**149**	157	108	109	112	118	119	121	126	128	132	137	139	141
1	**Bulgaria**	*2 153*	*164*	169	**169**	170	168	167	157	182	182	182	192	191	191	234	235	236
1	**Croatia**	*2 076*	*192*	167	**167**	168	166	165	155	180	180	180	190	189	188	231	232	233
1	**Cyprus**	*693*	*754*	167	**167**	168	166	165	155	180	180	180	190	189	188	231	232	233
2	**Czech**	*2 998*	*40*	162	**167**	177	121	123	126	132	134	136	142	144	148	154	156	158
2	**Denmark**	*3 027*	*2*	162	**167**	176	121	123	126	132	134	136	142	144	148	154	156	158
3	**Estonia**	*3 883*	*1*	191	**198**	213	135	138	143	148	150	152	158	161	167	165	167	171
3	**Finland**	*5 483*	*1*	201	**209**	225	143	145	151	156	158	161	167	170	176	174	176	180
2	**France**	*2 247*	*88*	138	**142**	150	103	104	107	113	114	116	121	123	126	131	133	135
2	**Germany**	***2 801***	***46***	**168**	**174**	**183**	**145**	**147**	**152**	**144**	**146**	**149**	**167**	**170**	**174**	**167**	**169**	**172**
1	**Greece**	*1 449*	*373*	160	**160**	161	160	159	149	173	173	173	182	181	181	222	223	223
2	**Hungary**	*2 381*	*150*	165	**170**	180	123	125	128	135	136	139	145	147	151	157	159	161
2	**Ireland**	*2 707*	*0*	137	**142**	150	102	104	107	112	113	116	121	122	126	131	132	135
1	**Italy**	*1 814*	*306*	156	**156**	157	155	154	145	168	168	168	177	177	176	216	217	217
3	**Latvia**	*3 623*	*3*	190	**197**	212	135	137	142	147	149	152	158	160	166	164	166	170
3	**Lithuania**	*3 391*	*12*	190	**197**	212	135	137	142	147	149	152	158	160	166	164	166	170
2	**Luxemb.**	*2 754*	*59*	161	**166**	175	120	122	125	131	133	135	141	143	147	153	155	157
1	**Malta**	*515*	*756*	155	**155**	156	154	153	144	167	167	167	176	175	175	214	215	216
2	**Netherla.**	*2 514*	*40*	147	**152**	160	110	111	115	120	121	124	129	131	134	140	142	144
2	**Poland**	*2 952*	*49*	179	**185**	196	134	136	140	147	148	151	157	159	164	171	173	176
1	**Portugal**	***1 109***	***167***	**135**	**136**	**137**	**151**	**150**	**149**	**151**	**151**	**152**	**170**	**169**	**169**	**193**	**194**	**194**
2	**Romania**	*2 568*	*124*	175	**181**	191	131	133	136	143	145	147	154	156	160	167	169	172
2	**Slovakia**	*2 899*	*65*	169	**175**	185	126	128	132	138	140	143	149	151	155	161	163	166
2	**Slovenia**	*2 601*	*73*	158	**163**	172	118	120	123	129	130	133	139	141	144	150	152	155
1	**Spain**	*1 671*	*248*	157	**157**	158	157	156	146	169	169	169	179	178	177	218	219	219
3	**Sweden**	***5 120***	***1***	**188**	**196**	**211**	**156**	**159**	**165**	**153**	**155**	**159**	**179**	**182**	**188**	**170**	**173**	**177**

Table E.2 Energy needs per m^2 per year in each country for prefabricated WF

				Prefab_WF														
					SF			MR			HR			MO			HO	
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	157	**162**	171	117	119	122	128	130	134	138	140	144	149	151	154
2	**Belgium**	*2 532*	*40*	144	**149**	157	108	109	112	118	119	122	126	128	132	137	139	141
1	**Bulgaria**	*2 153*	*164*	169	**169**	170	168	168	156	182	182	182	192	191	191	234	235	236
1	**Croatia**	*2 076*	*192*	167	**167**	168	166	166	154	180	180	180	190	189	188	231	232	233
1	**Cyprus**	*693*	*754*	167	**167**	168	166	165	154	180	180	180	190	189	188	231	232	233
2	**Czech**	*2 998*	*40*	162	**167**	177	121	123	126	132	134	138	142	144	148	154	156	158
2	**Denmark**	*3 027*	*2*	162	**167**	176	121	122	126	132	134	137	142	144	148	154	156	158
3	**Estonia**	*3 883*	*1*	191	**198**	213	135	138	143	148	150	152	158	161	167	165	167	171
3	**Finland**	*5 483*	*1*	201	**209**	225	142	145	151	156	158	161	167	170	176	174	176	180
2	**France**	*2 247*	*88*	138	**142**	150	103	104	107	113	114	117	121	123	126	131	133	135
2	**Germany**	***2 801***	***46***	**168**	**174**	**183**	**145**	**147**	**152**	**144**	**146**	**149**	**167**	**170**	**174**	**167**	**169**	**172**
1	**Greece**	*1 449*	*373*	160	**160**	161	160	159	148	173	173	173	182	181	181	222	223	223
2	**Hungary**	*2 381*	*150*	165	**170**	180	123	125	128	135	136	140	145	147	151	157	159	161
2	**Ireland**	*2 707*	*0*	137	**142**	150	103	104	107	112	113	117	121	122	126	131	132	135
1	**Italy**	*1 814*	*306*	156	**156**	157	155	155	144	168	168	168	177	177	176	216	217	217
3	**Latvia**	*3 623*	*3*	190	**197**	212	134	137	142	147	149	152	158	160	166	164	166	170
3	**Lithuania**	*3 391*	*12*	190	**197**	212	134	137	142	147	149	152	158	160	166	164	166	170
2	**Luxemb.**	*2 754*	*59*	161	**166**	175	120	122	125	131	133	136	141	143	147	153	155	157
1	**Malta**	*515*	*756*	155	**155**	156	154	153	143	167	167	167	176	175	175	214	215	216
2	**Netherla.**	*2 514*	*40*	147	**152**	160	110	111	115	120	121	125	129	131	135	140	142	144
2	**Poland**	*2 952*	*49*	179	**185**	196	134	136	140	147	148	152	157	159	164	171	173	176
1	**Portugal**	***1 109***	***167***	**135**	**136**	**137**	**151**	**150**	**149**	**151**	**151**	**152**	**170**	**169**	**169**	**193**	**194**	**194**
2	**Romania**	*2 568*	*124*	175	**181**	191	131	133	136	143	145	149	154	156	160	167	169	172
2	**Slovakia**	*2 899*	*65*	169	**175**	185	126	128	132	138	140	144	149	151	155	161	163	166
2	**Slovenia**	*2 601*	*73*	158	**163**	172	118	120	123	129	130	134	139	141	145	150	152	155
1	**Spain**	*1 671*	*248*	157	**157**	158	157	156	145	169	169	169	179	178	177	218	219	219
3	**Sweden**	***5 120***	***1***	**188**	**196**	**211**	**156**	**159**	**165**	**153**	**155**	**159**	**179**	**182**	**188**	**170**	**173**	**177**

Table E.3 Energy needs per m² per year in each country for conventional RC

				Conv_RC													
				SF			MR			HR			MO			HO	
	country	*HDD*	*CDD*	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
2	**Austria**	*3 280*	*40*	122	**172**	198	116	120	148	120	122	129	130	134	145	120	122	126
2	**Belgium**	*2 532*	*40*	112	**157**	181	106	110	136	109	112	118	119	123	132	123	125	129
1	**Bulgaria**	*2 153*	*164*	165	**180**	187	183	181	179	183	182	180	197	195	193	237	237	232
1	**Croatia**	*2 076*	*192*	161	**176**	183	179	177	175	179	178	176	192	191	189	232	231	227
1	**Cyprus**	*693*	*754*	151	**166**	172	168	167	165	168	167	165	181	179	178	218	218	213
2	**Czech**	*2 998*	*40*	128	**180**	208	122	126	156	125	128	135	137	141	152	141	143	148
2	**Denmark**	*3 027*	*2*	129	**182**	210	123	127	157	126	129	136	138	142	153	142	144	149
3	**Estonia**	*3 883*	*1*	147	**219**	256	138	144	158	142	146	155	154	160	175	147	155	163
3	**Finland**	*5 483*	*1*	156	**231**	271	146	152	168	150	154	164	163	169	186	156	164	172
2	**France**	*2 247*	*88*	137	**150**	155	152	151	149	152	151	150	164	162	161	198	197	193
2	**Germany**	***2 801***	***46***	**130**	**187**	**216**	**147**	**152**	**188**	**137**	**141**	**148**	**163**	**168**	**181**	**153**	**156**	**161**
1	**Greece**	*1 449*	*373*	146	**159**	166	162	160	159	162	161	159	174	173	171	210	210	205
2	**Hungary**	*2 381*	*150*	129	**181**	209	122	127	157	126	129	136	137	142	153	142	144	149
2	**Ireland**	*2 707*	*0*	111	**156**	181	106	109	135	109	112	117	119	122	132	122	124	129
1	**Italy**	*1 814*	*306*	145	**159**	165	161	159	158	161	160	158	173	172	170	209	208	204
3	**Latvia**	*3 623*	*3*	146	**216**	253	136	143	157	140	144	154	152	158	174	146	154	161
3	**Lithuania**	*3 391*	*12*	151	**224**	262	141	148	162	145	150	159	158	164	180	151	159	167
2	**Luxemb.**	*2 754*	*59*	127	**179**	207	121	125	155	125	128	134	136	140	151	140	143	148
1	**Malta**	*515*	*756*	138	**151**	157	153	152	150	154	153	151	165	164	162	199	199	195
2	**Netherla.**	*2 514*	*40*	116	**163**	188	110	114	141	113	116	122	123	127	137	127	130	134
2	**Poland**	*2 952*	*49*	143	**200**	231	135	140	173	140	143	150	152	157	169	156	160	165
1	**Portugal**	***1 109***	*167*	118	129	134	146	145	144	136	136	134	156	155	154	176	175	172
2	**Romania**	*2 568*	*124*	137	**193**	222	130	135	167	134	137	144	146	151	163	150	153	159
2	**Slovakia**	*2 899*	*65*	133	**187**	215	126	130	161	130	133	140	141	146	157	146	149	154
2	**Slovenia**	*2 601*	*73*	123	**173**	199	117	121	149	120	123	129	131	135	146	135	138	142
1	**Spain**	*1 671*	*248*	149	**163**	169	165	164	162	165	165	162	178	176	175	214	214	210
3	**Sweden**	***5 120***	***1***	**142**	**215**	**252**	**159**	**159**	**183**	**147**	**152**	**162**	**175**	**182**	**200**	**153**	**161**	**169**

Table E.4 GW per m^2 per year in each country for prefabricated LSF

	Prefab_LSF														
	SF			MR			HR			MO			HO		
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 118	1 107	1 122	813	805	808	800	796	800	912	905	910	899	898	902
Belgium	886	867	100	640	629	627	610	604	605	709	698	698	678	674	675
Bulgaria	1 979	1 939	1 913	1 884	1 856	1 738	1 950	1 939	1 929	2 114	2 088	2 065	2 462	2 460	2 458
Croatia	1 687	1 647	1 619	1 593	1 567	1 466	1 635	1 624	1 614	1 782	1 757	1 735	2 057	2 054	2 051
Cyprus	1 919	1 879	1 852	1 824	1 796	1 682	1 884	1 873	1 864	2 045	2 020	1 997	2 378	2 377	2 374
Czech	2 114	2 136	2 208	1 556	1 559	1 583	1 614	1 618	1 638	1 786	1 790	1 820	1 846	1 856	1 877
Denmark	1 438	1 437	1 471	1 052	1 047	1 057	1 061	1 060	1 069	1 193	1 189	1 203	1 203	1 206	1 216
Estonia	2 404	2 449	2 581	1 692	1 704	1 749	1 763	1 769	1 792	1 939	1 953	2 002	1 934	1 949	1 983
Finland	1 386	1 390	1 443	970	968	984	972	970	978	1 094	1 092	1 111	1 054	1 057	1 070
France	477	445	422	334	319	308	276	267	261	350	334	324	289	280	275
Germany	**1 815**	**1 832**	**1 884**	**1 519**	**1 522**	**1 545**	**1 430**	**1 438**	**1 460**	**1 712**	**1 714**	**1 738**	**1 629**	**1 636**	**1 654**
Greece	2 691	2 651	2 628	2 593	2 561	2 400	2 716	2 705	2 695	2 923	2 894	2 868	3 447	3 449	3 450
Hungary	1 813	1 825	1 880	1 331	1 331	1 349	1 368	1 370	1 385	1 522	1 522	1 545	1 560	1 567	1 583
Ireland	1 708	1 716	1 765	1 253	1 251	1 266	1 282	1 283	1 296	1 430	1 429	1 449	1 459	1 465	1 479
Italy	1 625	1 585	1 557	1 532	1 506	1 409	1 568	1 557	1 548	1 711	1 687	1 665	1 972	1 968	1 965
Latvia	2 394	2 439	2 570	1 685	1 697	1 741	1 755	1 761	1 784	1 931	1 944	1 993	1 925	1 940	1 974
Lithuania	2 394	2 439	2 570	1 685	1 697	1 741	1 755	1 761	1 784	1 931	1 944	1 993	1 925	1 940	1 974
Luxemb.	1 714	1 722	1 771	1 257	1 256	1 271	1 286	1 287	1 301	1 435	1 434	1 454	1 465	1 470	1 485
Malta	1 798	1 758	1 731	1 704	1 677	1 570	1 755	1 744	1 735	1 908	1 884	1 861	2 212	2 209	2 206
Netherla.	1 597	1 601	1 644	1 170	1 167	1 180	1 191	1 191	1 203	1 332	1 330	1 348	1 354	1 358	1 371
Poland	3 138	3 193	3 325	2 320	2 335	2 380	2 451	2 464	2 499	2 685	2 700	2 756	2 820	2 842	2 880
Portugal	**1 371**	**1 335**	**1 310**	**1 413**	**1 388**	**1 365**	**1 338**	**1 332**	**1 327**	**1 556**	**1 534**	**1 512**	**1 669**	**1 665**	**1 661**
Romania	1 845	1 858	1 915	1 355	1 355	1 373	1 394	1 396	1 412	1 550	1 551	1 575	1 590	1 597	1 614
Slovakia	1 458	1 458	1 492	1 066	1 062	1 072	1 078	1 077	1 086	1 211	1 207	1 221	1 222	1 225	1 235
Slovenia	1 273	1 266	1 290	928	922	927	926	923	930	1 048	1 041	1 051	1 045	1 046	1 053
Spain	1 335	1 295	1 266	1 244	1 219	1 140	1 257	1 246	1 236	1 382	1 360	1 339	1 571	1 566	1 561
Sweden	**429**	**397**	**375**	**313**	**298**	**288**	**236**	**227**	**221**	**320**	**305**	**295**	**235**	**226**	**221**

Table E.5 GW per m^2 per year in each country for prefabricated WF

	Prefab_WF														
	SF			MR			HR			MO			HO		
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 226	1 216	1 234	868	859	865	889	885	897	980	972	981	993	992	997
Belgium	994	976	113	694	684	684	699	693	700	776	766	768	772	768	770
Bulgaria	2 087	2 049	2 025	1 939	1 913	1 780	2 038	2 028	2 019	2 181	2 156	2 135	2 556	2 555	2 553
Croatia	1 795	1 756	1 731	1 648	1 624	1 511	1 724	1 713	1 704	1 849	1 825	1 805	2 151	2 148	2 146
Cyprus	2 027	1 988	1 964	1 879	1 853	1 724	1 973	1 962	1 954	2 113	2 088	2 067	2 472	2 471	2 469
Czech	2 222	2 245	2 320	1 611	1 613	1 640	1 703	1 707	1 743	1 853	1 858	1 892	1 940	1 950	1 972
Denmark	1 546	1 547	1 583	1 106	1 102	1 114	1 150	1 149	1 169	1 260	1 257	1 273	1 297	1 300	1 311
Estonia	2 512	2 558	2 694	1 745	1 757	1 805	1 852	1 858	1 881	2 007	2 020	2 068	2 028	2 043	2 078
Finland	1 494	1 500	1 555	1 024	1 022	1 041	1 061	1 059	1 067	1 161	1 160	1 179	1 148	1 151	1 165
France	585	554	534	389	374	365	365	356	352	417	402	394	383	374	370
Germany	**1 922**	**1 941**	**1 996**	**1 574**	**1 576**	**1 602**	**1 519**	**1 527**	**1 550**	**1 779**	**1 782**	**1 808**	**1 723**	**1 730**	**1 748**
Greece	2 799	2 761	2 740	2 648	2 618	2 436	2 805	2 794	2 785	2 991	2 962	2 937	3 541	3 544	3 545
Hungary	1 921	1 934	1 992	1 386	1 385	1 406	1 457	1 459	1 488	1 590	1 590	1 617	1 654	1 661	1 678
Ireland	1 816	1 825	1 877	1 308	1 306	1 324	1 371	1 372	1 398	1 497	1 496	1 520	1 553	1 559	1 574
Italy	1 733	1 694	1 669	1 586	1 562	1 454	1 657	1 646	1 638	1 779	1 755	1 735	2 066	2 063	2 060
Latvia	2 502	2 548	2 682	1 738	1 750	1 798	1 844	1 850	1 873	1 998	2 012	2 060	2 019	2 034	2 069
Lithuania	2 502	2 548	2 682	1 738	1 750	1 798	1 844	1 850	1 873	1 998	2 012	2 060	2 019	2 034	2 069
Luxemb.	1 822	1 831	1 883	1 312	1 310	1 328	1 375	1 376	1 403	1 502	1 501	1 525	1 559	1 565	1 580
Malta	1 906	1 868	1 843	1 759	1 734	1 613	1 844	1 833	1 824	1 976	1 952	1 931	2 306	2 304	2 301
Netherla.	1 705	1 711	1 756	1 225	1 222	1 237	1 280	1 280	1 304	1 400	1 398	1 419	1 448	1 453	1 466
Poland	3 246	3 302	3 437	2 375	2 388	2 437	2 540	2 553	2 613	2 752	2 768	2 828	2 914	2 936	2 975
Portugal	**1 479**	**1 445**	**1 422**	**1 468**	**1 444**	**1 422**	**1 427**	**1 421**	**1 417**	**1 624**	**1 601**	**1 582**	**1 764**	**1 759**	**1 756**
Romania	1 953	1 967	2 027	1 410	1 410	1 431	1 483	1 485	1 515	1 618	1 619	1 646	1 684	1 692	1 709
Slovakia	1 566	1 567	1 605	1 121	1 117	1 129	1 167	1 166	1 186	1 278	1 275	1 292	1 316	1 319	1 330
Slovenia	1 381	1 375	1 402	983	976	985	1 015	1 012	1 028	1 115	1 109	1 122	1 139	1 140	1 148
Spain	1 443	1 405	1 378	1 298	1 276	1 187	1 346	1 335	1 326	1 450	1 427	1 409	1 665	1 661	1 656
Sweden	**537**	**506**	**487**	**367**	**353**	**345**	**325**	**316**	**311**	**388**	**373**	**365**	**329**	**321**	**316**

Table E.6 GW per m^2 per year in each country for conventional RC

	Convent_RC														
	SF			**MR**			**HR**			**MO**			**HO**		
country	high	med	low	high	med	low	high	med	low	high	med	low	high	med	low
Austria	1 275	1 513	1 642	1 014	1 024	1 170	938	946	973	1 068	1 080	1 127	909	914	930
Belgium	1 093	1 256	155	841	845	948	760	764	781	874	880	911	789	792	803
Bulgaria	2 282	2 403	2 456	2 237	2 209	2 179	2 145	2 128	2 097	2 357	2 327	2 302	2 670	2 655	2 600
Croatia	1 982	2 076	2 117	1 905	1 880	1 854	1 812	1 797	1 770	1 999	1 973	1 950	2 238	2 225	2 178
Cyprus	2 113	2 218	2 265	2 050	2 024	1 996	1 958	1 942	1 913	2 155	2 128	2 104	2 427	2 413	2 362
Czech	2 075	2 638	2 941	1 774	1 810	2 143	1 722	1 749	1 817	1 921	1 961	2 077	1 867	1 891	1 940
Denmark	1 548	1 897	2 085	1 273	1 292	1 502	1 206	1 220	1 261	1 359	1 381	1 451	1 289	1 301	1 330
Estonia	2 262	3 033	3 435	1 930	1 989	2 138	1 877	1 918	2 016	2 086	2 147	2 307	1 913	1 993	2 070
Finland	1 479	1 869	2 074	1 196	1 222	1 295	1 123	1 141	1 189	1 268	1 294	1 374	1 129	1 167	1 204
France	824	810	803	621	607	594	526	517	507	617	603	590	570	561	548
Germany	**1 817**	**2 309**	**2 563**	**1 745**	**1 780**	**2 106**	**1 555**	**1 581**	**1 640**	**1 866**	**1 904**	**2 014**	**1 676**	**1 697**	**1 738**
Greece	2 821	2 992	3 068	2 835	2 802	2 766	2 744	2 724	2 685	3 000	2 965	2 935	3 447	3 430	3 359
Hungary	1 823	2 283	2 531	1 534	1 562	1 836	1 475	1 495	1 551	1 652	1 683	1 777	1 590	1 608	1 648
Ireland	1 780	2 223	2 462	1 494	1 520	1 784	1 433	1 453	1 506	1 606	1 636	1 726	1 543	1 561	1 598
Italy	1 877	1 961	1 998	1 789	1 765	1 740	1 696	1 681	1 656	1 874	1 849	1 827	2 087	2 074	2 031
Latvia	2 245	3 007	3 406	1 914	1 972	2 120	1 861	1 901	1 998	2 068	2 128	2 287	1 896	1 975	2 051
Lithuania	2 306	3 098	3 512	1 972	2 032	2 185	1 920	1 961	2 062	2 132	2 195	2 360	1 957	2 039	2 118
Luxemb.	1 761	2 197	2 432	1 476	1 502	1 761	1 415	1 434	1 486	1 587	1 616	1 704	1 523	1 540	1 577
Malta	1 981	2 074	2 115	1 904	1 879	1 852	1 811	1 796	1 769	1 997	1 971	1 949	2 236	2 223	2 176
Netherla.	1 660	2 054	2 267	1 380	1 402	1 638	1 315	1 332	1 379	1 479	1 504	1 584	1 411	1 426	1 459
Poland	2 895	3 792	4 272	2 553	2 616	3 140	2 525	2 571	2 681	2 795	2 864	3 050	2 768	2 809	2 889
Portugal	**1 580**	**1 637**	**1 662**	**1 584**	**1 562**	**1 539**	**1 404**	**1 395**	**1 373**	**1 643**	**1 621**	**1 601**	**1 702**	**1 690**	**1 654**
Romania	1 847	2 318	2 571	1 558	1 586	1 866	1 499	1 520	1 577	1 678	1 711	1 806	1 617	1 636	1 676
Slovakia	1 546	1 895	2 083	1 272	1 291	1 500	1 204	1 219	1 260	1 358	1 379	1 449	1 287	1 299	1 328
Slovenia	1 395	1 682	1 837	1 128	1 142	1 316	1 056	1 067	1 100	1 196	1 213	1 269	1 120	1 130	1 153
Spain	1 625	1 685	1 712	1 509	1 488	1 465	1 416	1 403	1 381	1 573	1 551	1 531	1 724	1 712	1 676
Sweden	**735**	**768**	**786**	**524**	**512**	**523**	**417**	**414**	**416**	**515**	**510**	**515**	**394**	**394**	**393**

Appendix F– Literature review results comparison

Table F.1 Comparison of previous and current work

Previous works	Scenarios	GW (kg CO_2 eq/m^2 x year)	NRE (GJ/m^2 x year)	Cost (k€/m^2)	Energy (kWh/m^2 x year)	Area (m^{2}x10^6)	Population (10^6)	Scope & System boundary
[26] [1]	Base scenario (2003)	ZI* [20-80] Z2* [30-170] Z3* [50-180]	ZI [0.4-1.4] Z2 [0.6-1.8] Z3 [0.7-2.9]	Embodied cost: Aver. - 1 254 Germ. - 3 370 Spain - 2 951 Poland - 725	ZI [108-282] Z2 [181-310]	ZI- 6 378 Z2- 7 909 Z3- 624	ZI- 181 Z2- 252 Z3- 21	Scope: environmental improvement potentials of residential buildings. Boundary: EU-15, production and transport of building materials, refurbishment, heating and cooling, and waste management; and excludes the construction of existing buildings.
	Future scenario	ZI [15-30] Z2 [25-80] Z3 [30-90]	ZI [0.25-0.5] Z2 [0.45-1.3] Z3 [0.50-1.6]	-	Z1 [31-218] Z2 [92-114]	-	-	
[37] [2]	Base scenario (2012/15)	10-75	-	-	60-270	-	-	Scope: to enable an understanding of the structure and of the modernization processes of the building sector in different countries and learn from each other about successful energy-saving strategies Boundary: EU-20
	Future scenario (2050)	8-50	-	-	-	-	-	
[28] [3]	Base scenario (2000)	20-60	-	-	SF [124-260] MF [84-173] Office [103-260] School [98- 260]	-	-	Scope: support policy making by providing the required data, analysis, and guidelines to achieve a fast and strong penetration of nZEB and RES-H/C within the existing national building stocks. Boundary: 9 countries (from EU-28), buildings' use phase.
	Future scenario (2030)	5-30	-	-	-	-	-	
[45] [4]	Base scenario (from 2000)	-	-	-	Residential [47-308] Non-residential [131- 653]	-	-	Scope: provide a better understanding of the energy performance of the building sector through reliable, consistent, and comparable data Boundary: EU-28
Present work	Base scenario (2020)	ZI [27-69] Z2 [3-85] Z3 [8-70]	ZI [0.38 - 1.04] Z2 [0.26 - 1.03] Z3 [0.32 - 1.14]	ZI [1 125 - 5 474] Z2 [1 235 - 11 154] Z3 [1 442 - 7 677]	ZI [118-237] Z2 [106-231] Z3 [136-271]	Z1 - 6 343 Z2 - 13 484 Z3 - 1 136	ZI - 141 Z2 - 285 Z3 - 22	Scope: assess the cost and impacts reduction potential by introducing prefabrication in the building stock. Boundary: EU-27, residential and commercial buildings, cradle-to-grave.
	Future scenario (2050)	ZI [23-71] Z2 [2-69] Z3 [6-54]	ZI [0.38-1.08] Z2 [0.25-0.84] Z3 [0.31-0.91]	ZI [915 - 4 081] Z2 [1 020 - 7 370] Z3 [1 182 - 5 052]	ZI [135-236] Z2 [102-196] Z3 [134-225]	Z1 - 6 212 Z2 - 13 375 Z3 - 1 329	ZI - 137 Z2 - 282 Z3 - 22	

* ZI - warm-weather countries, Z2 - moderate-weather countries, Z3 - cold-weather countries (can include different countries in each study)

1) IMPRO (Buildings Environmental Improvement Potentials of Residential Buildings) project (2006-2008)
2) TABULA (Typology Approach for Building Stock Energy Assessment) project (2009-2012) & EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks) project (2012-2014)
3) ENTRANZE (Policies to Enforce the TRAnsition to Nearly Zero Energy Buildings in the EU-27) project (2012-2014)
4) EU building observatory database (2016-2020)