RENOVATING ITALY

THE ECONOMIC AND SOCIO-ENVIRONMENTAL IMPACTS OF ENERGY RENOVATION STRATEGIES FOR THE ITALIAN RESIDENTIAL BUILDING STOCK

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The Economic and Socio-environmental Impacts of Energy Renovation Strategies for the Italian Residential Building Stock

By

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Preface

This master thesis, the conclusive endeavour of a long journey, is dedicated to my family - who have always believed in me – and to my friends, colleagues and supervisors for their invaluable emotional, professional and academic support.

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Abstract

Buildings are a central element in our everyday private and social life, meeting some of our most basic needs such as shelter, sanitation and easy access to energy. However, these comforts do not come without a cost: European buildings alone consume 40% of the total final energy and are responsible for 36% of all CO_2 emission. In Italy, 60% of the residential building stock was built before the first national law on energy efficiency and in fact some 25% of it can be considered as being highly energy inefficient. In 30 years, many of these buildings will still be standing and this threatens to lock-in the Italian residential sector on its historical emission pathways.

Deep energy renovation is defined as the refurbishment of buildings that reduces their energy consumption by at least 75% and that encompasses more than 25% of their surface or market value. It represents the most ambitious of the renovation depths which entails the realization of state-of-the-art interventions on the building envelope and/or its technical building systems. As such, deep energy renovations were identified as the best technical solutions that could help cut the energy consumption of existing buildings in a drastic way. Nevertheless, the high capital costs, medium-to-long payback periods and the "invasive" nature of this kind of interventions have limited their adoption by private investors and hindered their effectiveness in delivering large-scale improvements in energy performance. It soon became clear that successful design and implementation of these ambitious strategies requires a multi-criteria evaluation based on technical as well as financial and socio-environmental considerations.

Building Stock and Energy Modelling (BSEMs) is the research field that investigates the effects of housing - and real estate development at large – on key societal aspects such as energy consumption, air pollution and economic viability. Its main application is to test the effectiveness of energy efficiency policies and strategies concerning new constructions (e.g. nZEBs) as well as existing buildings (e.g. energy renovation and refurbishment). Within this field, the NTNU dwelling stock energy model represents an MFA-based bottom up, dynamic and stock-driven model using a type-cohort-archetype segmentation of the building stock. It was developed for the study of long-term trends and strategies at the aggregated residential stock level with particular focus on the estimation of future renovation activity rates and the modelling of deep renovation strategies.

The present work represented a first attempt at integrating a new module for financial and environmentally-extended macroeconomic analysis into the NTNU model. This was based on two established techniques - namely Standard Economic Evaluation (SEE) and Environmentally-extended Input-Output Analysis (EEIOA) - originally combined to perform a simplified integrated assessment of the energy, monetary, carbon and employment implications of renovation strategies. The integrated assessment tool is tested on a case study on Italy with the aim of evaluating the relative and combined effectiveness of three basic renovation strategies: (i) Advanced renovation of the building envelope, (ii) extensive implementation of renewable energy technologies, and (iii) more frequent rates of renovation.

Results showed that, with a total investment of 78 G€ over the 2020-2050 period, the most ambitious deep renovation strategy could deliver 680 TWh worth of savings, cutting almost 350 $MtCO_2eq$. while generating an average of 100 thousand new full time equivalent jobs per year. All this while representing a financially attractive solution from the point of view of the private investors due a payback time of 6 years and net savings in the order of 23 k€ within a 30-year timeframe. Although advanced renovation of the building envelope was found to represent the cost-optimal

solution, all basic strategies (advanced renovation included) would fall short on one or more criteria resulting in only partial success. An increased renovation rate was found to be a must for achieving optimal results on all indicators and 2.7% average yearly rate seemed to be represent a good balance between the needed ambitiousness and feasibility.

The use of a simplified hybrid MFA-IOA approach has proven useful to underpin the trade-offs existing between energy renovation strategies and assess their comparative effectiveness. Despite the many uncertainties around such long-term evaluation, results were in line with most findings and recommendations from other shorter-term studies. In the field of IE, this underrepresented approach could represent an interesting alternative to LCA for large-scale multi-criteria assessments of energy efficiency strategies for residential building stocks.

Abbreviations

A-I	
AB	Apartment Block
AEEG	Authority for the Electrical Energy, Natural Gas and Water Network
BSEM	Building Stock and Energy Modelling
CO_2-eq	Carbon dioxide equivalent
COA	Cost-Optimal Assessment
CRESME	Centro Ricerche Economiche e Sociali per il Territorio ed il Mercato Edilizio
DHW	Domestic Hot Water
MR EE IOT	Multi-regional Environmentally Extended Input-Output Table
EEM	Energy Efficiency Measure
EED	Energy Efficiency Directive
ENEA	National Agency for new Technologies, Energy and Sustainable Development
EPBD	Energy Performance Directive of Buildings
EPC	Energy Performance Certificate
FTE	Full Time Equivaent
GC	Global Cost
GHG	Greenhouse Gas
GSE	Gestore Sistema Elettrico
HDD	Heating Degree Day
IEA	International Energy Agency
IEE	Intelligent Energy Europe
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Italian Institute for Environmental Protection and Research

K-Z	
LCCA	Life-Cycle Cost Assessment
LCA	Life-Cycle Assessment
MFA	Material Flow Analysis
MFH	Multi Family Houses
MS	Member State
NEEAP	National Energy Efficiency Action Plan
NPV	Net Present Value
nZEB	nearly Zero Energy Buildings
OECD	Organisation for Economic Cooperation and Development
PAEE	Piano d'Azione per l'Efficienza Energetica
PANZEB	Piano d'Azione Nazionale per gli nZEB
PBT	Payback Time
PES	Primary Energy Saving
RBS	Residential Building Stock
RES	Renewable Energy Source
ROI	Return on Investment
SEN	Strategia Energetica Nazionale
SFH	Single Family House
STREPIN	STrategia per la Riqualificazione Energetica del Parco Immobiliare Nazionale
TABULA	Typology Approach for Building Stock Energy Assessment
TBS	Technical Building System
TH	Terraced House
TOE	Tonnes of Oil Equivalent
VAT	Value Added Tax

NOMENCLATURE

Stock and Energy models nomenclature*

*All parameters are time-dependent

Symbol	UM	Name
SD	dw	Population's demand for dwellings
SD_s	dw	Number of dwellings per segment (s)
P	pp	Population size
PD	pp/dw	Dwelling occupancy
W	%	Share of dwellings being in each dwelling type
D_{dem}	dw	Number of demolished dwellings
D_{new}	dw	Number of new constructed dwellings
D_{ren}	dw	Number of renovated dwellings
ρ_{DEM}	-	Demolition function
L	-	Lifetime profile
CDF	-	Cumulative Density Function
ρ_{REN}	-	Renovation function
ρ_{REN_cycle}	-	Renovation profile
K	Integ.	Cyclic repetitions number
τ	Integ.	Dwelling renovation cycle
$SD_{ss,r}$	dw	Number of dwellings per subsegment(ss) and archetype (r)
$U_{s,ss}$	-	Share of segment s being in subsegment ss
A_{ss}	m^2/dw	Subsegment-specific average heated floor area
$SA_{ss,r}$	Mm^2/yr	Floor area of dwelling per subsegment and archetype
$e_{ss,r,(c)}$	kWh/m²/yr	Archetype-specific energy need intensities (by energy carrier c)
$EN_{ss,r}$	GWh/yr	Total energy need per archetype
$HP_{ss,r}$	GWh/yr	Archetype-specific Heat Pump contribution
$PV_{ss,r}$	GWh/yr	Archetype-specific Photovoltaics contribution
$\eta_{sys(ss,r)}$	%	Weighted average system efficiency
$DE_{ss,r}$	GWh/yr	Archetype- and subsegment-specific delivered energy
$c_{ss,r}$	%	Energy carriers split
$DE_{ss,r,c}$	GWh/yr	Archetype- and subsegment-specific delivered energy split by energy carrier
DE_c	GWh/yr	Total delivered energy by energy carrier
DE	GWh/yr	Total delivered energy
$De_{ss,r,c}$	kWh/m²/yr	Archetype- and subsegment-specific delivered energy intensity split by energy carrier

Summary equation sets*

*All parameters are time-dependent

Stock Model
$SD_s = (P/PD) * W$
$\Delta SD(i) = S(i) - S(i-1) = D_{new}(i) - D_{dem}(i)$
$D_{dem}(i) = D_0(i) + (\rho_{DEM} * D_{new})(i)$
$L = 1 - CDF(\rho_{DEM})$
$\rho_{REN\_cycle} = \sum_{k=1}^{K} \rho_{REN}(k) * L(\tau)$
$D_{ren}(i) = R_0(i) + (\rho_{REN_{cycle}} * D_{new})(i)$
Energy Model
$SD_{ss,r}(i) = U_{ss}(s) * SD_{s,r}(i)$
$SA_{ss,r} = SD_{ss,r} * A_{ss}$
$EN_{ss,r} = SA_{ss,r} * e_{ss,r}$
$DE_{ss,r} = (EN_{ss,r} - HP_{ss,r} - PV_{ss,r})/\eta_{ss,r}$
$DE_{ss,r,c} = c_{ss,r} * DE_{ss,r}$
$DE_c = \sum_r \sum_{s'} DE_{s',r,c}$
$DE = \sum_r \sum_{s'} \sum_c DE_{s',r,c}$
Environmental-Economic Model
$RI_{s',\tau,i} = \sum_{ss} SA_{ss,i} * Ri_{ss,\tau,i}$
$Ri_{ss,\tau,i} = C_{ss,i} + \sum_{i=1}^{\tau} (Ca_{(ss,i)} * f_{pv}(i)) - \sum_{j=1} V_{f,\tau}(j)$
$Ce_{s',c,i} = \sum_{ss} De_{ss,c,i} * \rho_{ss,c,i} * f_{pv_{(c,i)}}$
$\Delta y_{en}(c,i) = \sum_{s'} \alpha_{s',c,i} * Pef_c * \delta_c * y_c$
$\Delta y_{ren}(c,i) = \sum_{s'} (RI_{s,',c,i}^{scenario} - RI_{s',c,i}^{baseline}) * \delta_c$
$b'_{hh}(i) = \sum_c DE_{c,i} * Pef_c * \partial_c$
$\Delta r_{en}(i) = b' \, L \, \Delta y_{en}(i) + b_{hh}(i)$
$\Delta r_{ren}(i) = b' \, L \, \Delta y_{ren}(i)$

Environmentally-extended economic model nomenclature

Alphabetic order

Symbol	UM	Name
$C_{ss,i}$	€/m²	Initial renovation investment costs
$Ca_{ss,i}$	€/m²	Annual cost at year i (at nominal value)
$Cr_{ss,i}$	€/m²	Running costs (annual)
$Cm_{ss,i}$	€/m²	Maintenance costs (annual)
$Co_{ss,i}$	€/m²	Operation costs (annual)
$Cs_{ss,i}$	€/m²	Added costs including taxes and subsidies (annual)
$Cem_{ss,i}$	€/m²	Emission costs (annual)
$Cp_{ss,i}$	€/m²	Total periodic costs due to maintenance and disposal at year i
$Cp_{j,Tn,(i)}$	€/m²	Periodic costs for component j at time Tn (for year i)
$Cr_{j,Tn,(i)}$	€/m²	Replacement costs for component j at time Tn (for year i)
$Cd_{j,Tn,(i)}$	€/m²	Disposal costs for component j at time Tn (for year i)
$Ce_{ss,c,\tau}$	€/m²	Energy costs (within observation period τ)
$\Delta Ce_{ss,c,\tau}$	€/m²	Net energy cost/savings from energy carrier c in year i
$f_{pv}(i)$	Integ.	Present value factor for year i
$n_{(j)}$	Integ.	Number of replacements of component j within observation period T with T=τ corresponding to the renovation cycle
$Ri_{ss,i}$	€/m²	Unit cost of renovation investment for subsegment ss at year τ)
$RI_{ss,i}$	M€	"Global" cost of renovation investment for subsegment at year τ)
R	%	Market interest rate
$R_{R(i)}$	%	Real interest rate (for year i)
$R_{D(i)}$	%	Discount rate (for year i)
Re_c	%	Rate of evolution of prices for energy carrier c
Ri_i	%	Inflation rate (for year i)
T	Integ.	Calculation period (T=τ)
$T_n(j)$	Integ.	Lifespan duration of component j
T_0	Integ.	Starting year for calculation
$V_{(I,j)}$	€/m²	Present value of component j at year i
$V_{T\_f(j)}$	€/m²	Residual value of component j (corresponding to period T
$\rho_{s',c,i}$	€/kWh	Segment-specific energy price for energy carrier c at year i

Symbol	UM	Name
∂_c	tCO_2/GWh	Carrier-specific emission factors for the residential sector
Pef_c	-	Primary energy conversion factor for energy carrier c
δ_c	-	End-use coefficient for product/carrier c
$\alpha_{c,i}$	-	Coefficient of relative consumption for energy carrier c in year i
b'	Various units/M€	Direct emission coefficients vector
b'_{hh}	Various (CO_2eq., TJ, FTEeq.)	Direct emission vector
y_c	M€	Households final demand vector
$\Delta y_{ren}(c,i)$	M€	Stimulus of renovation activity for product c in year i
$\Delta y_{en}(c,i)$	M€	Stimulus of energy activity for product c in year i
L	-	Total coefficient or Leontief inverse matrix
$\Delta r_{en}(i)$	Various units (CO_2eq., TJ, FTEeq.)	Impact vector for energy activity
$\Delta r_{ren}(i)$	Various units (CO_2eq., TJ, FTEeq.)	Impact vector for renovation activity

1 INTRODUCTION

Globally and locally, buildings are a key element of everyday private and social life, defining how our societal need for shelter and housing is met in respect to the surrounding environment. They are probably the main human interface to the natural environment which influences the way we perceive and build it. Far from limited to their physical structure, the positive and negative effects of buildings stretch along the whole construction and energy industries. This reveals the complex challenge of a socio-economic and environmentally effective transition to an energy-efficient built environment. Building stock energy modelling (BSEM) is the research field that investigates the aggregated effects of housing - and real estate development at large – on key societal aspects such as energy consumption, air pollution and economic viability. Its main application is to test the effectiveness of energy efficiency policies and strategies concerning new constructions (e.g. nZEBs) as well as existing buildings (e.g. energy renovation and refurbishment). Hereafter, the rationale behind BSEM is presented and shortly framed into the European and Italian contexts and research efforts. Following, the research aim of the study is articulated into clear research questions and its characteristics benchmarked to those of other studies assessing the energy and economic performance of renovation options for the Italian residential building stock (RBSs).

Globally, buildings and the construction industry represent the largest energy-consuming sector. According to the IEA, in 2015 they accounted for 30% and 6% of global final energy consumption and 28% and 11% of total direct and indirect CO_2 emissions, respectively (IEA 2017a). Thank to continued adoption and enforcement of building energy codes and efficiency standards, the energy intensity of buildings (kWh/m^2) fell by a yearly 1.3% between 2010 and 2014 (IEA 2017b). Yet progress has not been fast enough to offset the increasing demand for residential energy services. Driven by improved access to energy, larger penetration of energy-consuming devices and rapid growth in floor area per capita; buildings energy demand has in fact increased at almost 3% per year since 2010. As a result, global building energy demand per capita has remained basically constant since 1990 at just less than 5 MWh per person per year (IEA 2017c). To invert these trends and keep 1.5°C-consistent pathways, the IPCC identified three key sectoral targets for buildings: 80-90% emissions reduction by 2050, fossil-free and near-zero energy new construction by 2020 and a 5% energy refurbishment rate per year for existing buildings in OECD countries (Babiker et al. 2018).

In Europe, where buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions, more than 40% of the RBS was constructed before the 1960s and almost 75% is considered energy inefficient. Further, due to their long life-time, some 75% of the constructions that will stand in 2050 have already been built today. Contextually, only 0.4-1.2% (depending on the country) of the housing stock is being renovated each year (EED 2012). This underperforming response to the long-term path dependencies that characterise the built environment, threaten to lock-in Europe on the global emissions pathways with repercussions on society that can last for decades (Krausmann et al. 2017, 2018; Lin et al. 2017). Investing in the maintenance and upgrade of the existing stock is therefore a necessity, but at the same time also a socioeconomic opportunity with the potential of cutting European energy consumption and CO_2 emissions by 5-6% while boosting the economy. In fact, with a 9% contribution to gross domestic product[1] and 7% to total workforce, the "narrow" construction industry directly employs 18 million people and represents an important pillar of the EU economy (EC 2016). The benefits of investing in EU-wide energy

[1] Looking beyond the value added on site and considering the whole supply chain, the "broad construction" industry typically makes out between 25-30% of national gross domestic products (Gruneberg and Folwell 2013).

renovation programmes have been investigated and discussed from an environmental/financial (EC 2014; BPIE 2011; Boermans et al. 2012) as well as from a labour (Meijer et al. 2012) perspective. However, an integrated analysis of these potential trade-offs and co-benefits has received much less attention.

In response to these opportunities and threats, the European Commission has deployed two main legislative instruments, namely the Directive on the Energy Performance of Buildings (EPBD 2002) and the Directive on the Energy Efficiency (EED 2012). As an adoption of the IPCC recommendations, under these directives EU Member States (MSs) are required to: (a) set minimum energy performance standards for new constructions and major renovations, (b) provide these buildings with an energy performance certificate (EPC), (c) increase the rate of renovations and (d) implement all new constructions after 2020 as nZEBs. This is expected to cut down buildings-related emissions by 80-95% by 2050 compared to 1990 levels (EC 2011). MSs are free to choose which energy efficiency measures (EEMs) and strategies to implement, as long as they comply with the overall goal stated in the directives. In the recent recast of the EPBD (EPBD recast 2010), a common cost-optimal assessment (COA) of EEMs was developed which required MSs to define reference building typologies that are representative in terms of climatic areas and functional characteristics. Nevertheless, beyond the initial harmonization efforts and regulations at the building level, a clear long-term strategy encompassing the whole building stock is still lacking. This is particularly true in regard to the speed and future ambition level (within or possibly as a successor of the cost-optimality principle) of the renovation effort (Boermans et al. 2012).

In Italy, more than 60% of the dwelling stock is older than 45 years and thus built before the first national law of 1976 on energy savings. Of this building segment, more than 25% has a very high unit consumption ranging between 160 kWh/m^2 and above 220 kWh/m^2 and it shows an urgent need for maintenance and upgrade (Madonna and Vincenzo 2014). In turn, the renovation activity has remained relatively low at an average 0.5% per year for deep renovation projects (Costanzo et al. 2016). In line with the European average, Italian buildings consume some 42% of total final energy consumption, of which residential buildings represent the 28%. For this category, the fuel mix is dominated by gas (>50%), followed by biomass and electricity, which together provide 90% of the energy need in dwellings. Between 1990-2016, the dependency on natural gas for domestic heating including electricity generation increased at 1.5% per year reaching over 90% and against a European average of 70% (ADEME 2018). In 2016, this translated into about 17.5 Mtoe of imported natural gas just for residential purposes (including the natural gas share in electricity use), corresponding to a €13.6 billion expenditure (ARERA 2018). As a result of an ageing and natural gas-dependent housing stock, in 2016 emissions from the Italian residential almost touched 50 Mt. As a policy response to this challenge, the fourth National Energy Efficiency Action Plan (NEEAP) has identified renovation of existing buildings as a key investment strategy for compliance with the EU emission targets as well as for revitalizing the national construction industry (PAEE 2017; ECSO 2018).

Building Stock Energy Models (BSEMs) are an established tool for supporting political decision-making in the formulation of long-term strategies in this field (Kavgic et al. 2010). They are used to assess the required energy-saving potential in a diverse and changing building stock at different scales and to evaluate multiple aspects of different renovation strategies, including their cost-effectiveness (Brøgger and Wittchen 2018). To inform the translation of EU directives into NEEAPs, individual MSs have employed building stock energy models mostly focusing on the evaluation of energy refurbishment options for the RBS at the national level. In this context, the approach based on building typologies was applied, for instance, by Dascalaki et al (2011) in Greece; by Mata et al. (2013) in Sweden, by Ahern et al. (2013) in Ireland, by McKenna et al (2013) in Germany or by Sandberg et al. (2017) in Norway. This branch of studies focuses on the estimation of direct energy, carbon and/or financial impacts of renovation options which are supported by a careful characterization of the housing stock and its development. However, in these studies supply chain (indirect) or rebound (induced) effects are in most cases neglected. On the other extreme are studies that offsets a less accurate representation of the RBS with a more comprehensive impact assessment, for instance by computing carbon and labour footprints. This approach was applied, for instance, by Ürge-Vorsatz et al. (2010) in Hungary, by Cellura et al. (2013) in Italy, by Oliveira et al. (2014) in Portugal or by Mikulić et al. (2016) in Croatia.

Nevertheless, there is lack of intermediate-level studies focusing on the interplay of environmental, social and economic impacts related to renovation strategies at the national level. The key feature of this underrepresented approach is to couple a model-based estimation of the RBS and its energy consumption over time, with an assessment of the monetary aspect of the selected strategies and their implications from an individual and societal perspective.

1.1 Research Aim

The goal of this research is to investigate the development of the Italian dwelling stock and its energy performance under a baseline plus six different renovation scenarios towards 2050, evaluate their financial feasibility from a consumer perspective and finally to assess their direct and indirect carbon and labour impacts on the national economy.

The research questions addressed in this thesis are the following:

1. ***What is the relative and combined effectiveness of improved energy efficiency due to (a) more ambitious and (b) frequent renovation and (c) increased use of local renewable energy sources on improving the energy performance of the Italian dwelling stock towards 2050?***

    i. *What is the past and present composition of the Italian residential building stock?*

    ii. *How is the Italian dwelling stock expected to evolve in terms of size and composition as a result of future construction, demolition and renovation activities?*

    iii. *How is the Italian dwelling stock expected to evolve in terms of energy efficiency standard and use of local renewable energy sources?*

2. ***What is the cost of investments under the modelled energy renovation scenarios and which one of them delivers the best economic performance?***

    i. *What are the renovation and energy costs of each scenario and how are they expected to evolve towards 2050?*

    ii. *What scenarios have the financial and macroeconomic investment cost and how does this relate to their financial viability?*

3. ***What is the relation between economic performance and socio-environmental effectiveness of the modelled energy renovation scenarios?***

    i. *How can investment costs be coupled with employment and environmental data to estimate the direct and indirect carbon and labour impacts of the renovation strategies?*

    ii. *How do scenarios perform in terms of GHG emissions reduction and employment creation and how do these relate to their economic performance?*

To facilitate the implementation of successful climate-change mitigation policies, it is crucial to better understand the dynamic and complex nature of the future housing stock energy system. Building upon principles from the field of industrial ecology, this set of research questions aims at reflecting an integrated analytical approach based on a system perspective, which is deemed essential to capture such complexity. A key feature of this approach is an evaluation based on multiple criteria that should be able to highlight potential trade-offs and co-benefits of implementing the proposed strategies. In this study, the four criteria against which renovation are evaluated are: energy, carbon, money and employment. Energy consumption and carbon equivalent emissions are used as criteria for environmental impact, monetary investments and returns for financial viability and employment generation for socio-economic impact. The combined performance of a renovation strategy on these four criteria will be measured by a set of 10 indicators that, together, will define its "system" effectiveness.

It can be stated that the general effectiveness of a renovation strategy ultimately depends on two factors: the energy consumption pre- and post-renovation and the size and quality of the investment. In turn, the energy demand of a dwelling stock depends at least on: (i) the size and composition of the dwelling stock, (ii) the energy-efficiency state of the buildings, (iii) outdoor climate, (iv) the energy mix and efficiencies of the energy distribution and conversion technologies, (v) the use of local energy sources and (vi) the user behaviour. On the other hand, the renovation investment mostly depends on: (vii) the cost of the EEMs, (viii) the consumption bundle of the overall investment, (ix) the timing and (x) the economic perspective taken. All these factors will change over time due to, for instance, demographic or price development trends and the temporal changes must be examined in scenario analyses. Additionally, the scenarios can be considered independently or in comparison to a base-line case which can influence the outcomes.

As in most models, the characterization and quantification of variables depends on the parameters selected to describe them. In this study, stock development is driven by socio-demographic and "lifestyle" parameters while its composition is determined by physical characteristics of buildings such as lifetime, age-cohort or typology. The energy intensity of the heated floor area, generation and distribution efficiencies, energy mix, contribution from local RES and climate factors are the main explaining factors for the building stock energy demand. The unit costs of renovation investments, their "consumption basket", market factors and intensities of socio-environmental impacts are the key parameters used in the environmental-economic model. Bringing all these elements together, the length of the renovation cycle is a key modelling element that defines the renovation rate of a strategy, thereby influencing its stock composition, energy performance and size of the renovation investment. Different combinations of these parameters are used to model renovation scenarios and simulate the potential development paths of strategies for the renovation of the Italian RBS. Table 1 summarizes the key modelling elements made use of in this study.

Table 1. Key modelling parameters used in this study

Key stock parameters	Key energy parameters	Key environmental-economic parameters	Dwelling types	Age-cohorts	Scenarios
Population	Average heated floor area per dwelling	Renovation unit costs	Single Family Houses (SFH)	1801-1920	Baseline
Persons/dwelling type	Energy need intensities	Energy prices	Multi Family Houses (MFH)	1921-1945	Advanced renovation
Mean building lifetime and standard deviation	Residential energy mix	Investment "consumption bundle"	Terraced Houses (TH)	1946-1960	Frequent renovation
Share of historical buildings	Weighted system efficiency	Market interest and price development rates	Apartment Blocks (AB)	1961-1975	Extensive HP and PV use
Renovation cycle	HP and PV contribution	GHG intensities		1976-1990	Advanced renovation + extensive HP and PV
	Climate adaptation factors			1991-2005	Minimizing energy need
				2006-2020	Minimizing delivered energy
				2021-2050	

1.2 Building Stock Energy Modelling

While many countries have set targets for reducing energy use and GHG emissions, there is high uncertainty on whether the enabling policies are suitable to reach them within the specified timeframes. As acknowledged by Vásquez et al. (2015): "Models used to inform building policies often do not account for the different boundary conditions related to socio-economic development, climate, composition and age structure of the existing building stock, and lifetime expectancy, which hinders effective strategy development and realistic target setting". At the individual building level, state-of-the-art tools for decision-making support rely on life cycle assessment (LCA), economic input-output LCA, and hybrid LCA (Anderson et al. 2015). Nevertheless, these methods alone are unsuitable for upscaling to the national or regional levels and thus for evaluating the gap between targets and expected outcome from policies (Mastrucci et al. 2017). Models on the energy use and environmental impacts of building stocks need to be able to handle the heterogeneous nature of the stock by decomposing it into its essential dimensions, describing them and eventually re-composing them for aggregated assessment. This is the specific domain of BSEMs.

Building stocks and their energy use have a considerable body of literature of which a complete review is beyond the scope of this work. Both Kavgic and colleagues (2010) and Brøgger & Wittchen (2018) differentiate between top-down and bottom-up models. While top-down approaches derive the energy consumption from aggregated macroeconomic statistical data (e.g. income, fuel prices or energy intensities), bottom-up models try to combine disaggregated building physics data (e.g. surface of building elements, thermal properties or the energy efficiency of space heating system) and estimate the delivered energy consumption using an energy performance calculation method. Vasquez and colleagues (2016) propose a classification of existing bottom-up models based on dimensions and approaches from MFA, distinguishing between three model typologies: accounting, input- or activity-driven and stock-driven.

Accounting models aim at quantifying the stock size and composition but are not intended to investigate the drivers of stock development and its energy consumption. Quasi-stationary and dynamic models employ a range of driving variables to explain stocks evolution over time, for one single or multiple years respectively. They can be further classified into input- or activity-driven, when they make use of construction, demolition or renovation rates based on historical or recent trends; or stock-driven, when using a service demand/provision concept (Müller 2005). In the latter, time-changing factors such as population and lifestyle parameters (e.g. floor area per capita or dwelling occupancy) drive the demand for new houses, which is modelled after mass-balance principles together with the demolition and renovation activities. These, in turn, are defined by using probability functions depending from the lifetime of one or more dwelling typologies.

The NTNU dwelling stock energy model (Sandberg et al. 2017) is a bottom-up, dynamic and stock-driven model based on the so-called "Archetype approach". Building archetypes or "representative buildings" consist of building groups that have largely homogeneous characteristics in terms of construction typology, age-period and renovation state (e.g. a terraced house built between 1961-1975 in a standard renovation state) also called renovation "archetype". This result in a so-called Type-Cohort-Archetype (TCA) stock segmentation that has proven useful for modelling renovation strategies for dwellings' combinations with very diverse energy performances, hence enhancing the overall accuracy of the calculation. At the core of the "archetype approach" is the idea of composing a representative sample of the national building stock by means of such synthetic buildings, calculate their individual energy demand and then extrapolate it to the whole stock (Vásquez et al. 2016; Brøgger and Wittchen 2018). This modelling approach has been widely discussed (Filogamo et al.

2014; Mata et al. 2014) and applied in the scientific literature (Ballarini et al. 2014; Csoknyai et al., 2016; Florio & Teissier, 2015).

Robust building stock and energy models that are able to account for the heterogeneity of buildings and factors affecting their energy performance are therefore essential for informing decision makers about the effectiveness of different policies. This information can be leveraged for (i) realizing current goals, (ii) defining more realistic goals, (iii) prioritizing climate change mitigation strategies, and (iv) avoiding misinformation and fragmented actions and policies that lead to weaker results in the long run (Vásquez et al. 2015).

1.3 THIS STUDY IN CONTEXT

This study builds on the dwelling stock energy model developed by NTNU and extends it with a new module for financial and environmentally-extended macroeconomic analysis, hereafter referred to as simply "environmentally-extended economic model". Its conceptual outline, mathematical formulation and application to the Italian case study are original contributions of this work and are described in depth in Chapter 3. In this Chapter, the model is contextualized within the state-of-the-art in BSEM by comparing its key characteristics with those of studies with similar research scope and aim.

Compared to previous works on the impacts of energy renovation strategies for the Italian RBS, as shown in **Table 2**, this study employs a different approach relying on dynamic, stock-driven and segmented dwelling stock modelling. Compared to the single year studies of Ciulla et al. (2016) and Ballarini et al. (2017) and the dynamic approaches of Corrado et al. (2016) and Cellura et al. (2013); here renovation, construction and demolition activities are estimated as natural needs during the ageing process of the stock in contrast to extrapolated activity rates based on historical or recent trends. Differently from the other bottom-up studies, the impact assessment includes supply chain (indirect) effects which are typically addressed in top-down studies like the one based on households' expenditure by Cellura et al. (2013). Rebound (or induced) impacts stemming from the possible re-spending of the energy savings on other products are not covered. For the first time in a case study on Italy, employment effects were included as an indicator of socio-economic performance, a central item of the National Energy Strategy (SEN 2017) and the Strategy for the Energy Refurbishment of the National Buildings Stock (STREPIN 2015) developed by the Italian National Agency for New technologies, Energy and Sustainable Economic Development (ENEA).

Stock segmentation is based on age-type combinations developed within the IEE-TABULA project (Loga et al. 2016, 2014). Estimation of the energy performance relies on pre-calculated energy need intensities from TABULA rather than from algorithms specified in technical standards as in Corrado et al. (2016) and Ballarini et al. (2017), software-based simulations as in Ciulla et al. (2016) or official statistics as in Cellura et al. (2013). It is important to specify that the TABULA energy need intensities are themselves calculated according to the Italian technical specification UNI/TS 11300 series (Ente Nazionale Italiano di Unificazione 2014a, 2014b, 2010, 2016a, 2016b). The advantage of directly using energy intensities is that the energy analysis is simplified in its calculation because all geometrical (e.g. S/V ratio), building envelope (e.g. U-values) and climatic (e.g. HDD) parameters are already accounted for in the final figure. The disadvantage is that the number of renovation options and climatic areas is limited to those cases for which the energy need intensities were pre-calculated.

Compared to the in-depth studies of Madonna & Vincenzo (2014) and Capozza et al. (2014), this work has a much lower detail on the characteristics of each renovation option as well as building type. The key difference is that while the studies by Madonna & Vincenzo (2014) and Capozza et al. (2014) - but also Ballarini et al (2017) – focus on a single year assessment of carefully represented combinations of interventions, this work is centred around a high-level analysis of long-terms strategies. Where the other studies have the primary goal of establishing legally binding cost-optimal levels for a set of buildings, this work's main effort is to evaluate the effectiveness of general renovation pathways at the aggregated stock level. Consequently, where the other studies ask for more precise characterization and modelling of geometric, thermophysical and technological characteristics of buildings and renovation options, this work asks for the collection of the best available historical data and future projection and to reduce the uncertainty of time-dependent variables.

Table 2. Comparison of main parameters considered in this study and five selected peer-reviewed papers.

Item	This study	Corrado et al.	Ciulla et al.	Ballarini et al.	Cellura et al.	Madonna & Vincenzo; Capozza et al.
Year of completion	2019	2016	2016	2017	2013	2014
Geographical scope	National	Regional	National	National	National	National
Model approach	Dynamic MFA-IOA	Dynamic	Static	Static	Dynamic IOA-LCA	Static
Model type	Bottom-up Stock-driven	Bottom-up Activity-driven	Bottom-up Simulation	Bottom-up Building typology	Top-down expenditure	Bottom-up Building typology
Dwelling typologies	4 TABULA	3 TABULA + CENED	1	4 TABULA	–	4 TABULA
Cohorts	8	7	2 (historical <1919)	6	–	7
Climate areas	1 (E) HDD-weighted	1 (E)	4 (B, C, D, E)	5 (B, C, D, E, F)	–	5 (B, C, D, E, F)
Energy performance calculation	Energy need intensities (TABULA)	Quasi-steady state (UNI/TS 11300)	Dynamic (TRNSYS 17)	Quasi-steady state (UNI/TS 11300)	National Statistics (ENEA)	Quasi-steady state (UNI/TS 11300)
Renovation options	3 ("Deep renovations" only)	6	8	7	4	6-13
Environmental performance indicators	DES, CO_2, PBT	PES, CO_2	PES	PES	PES, CO_2	PES, CO_2
Socioeconomic performance indicators	GC, PBT, FTE-jobs	GC	PBT	GC, PBT	–	GC, CBR, PBT
Impact assessment (tier)	Direct and Indirect	Direct	Direct	Direct	Direct, Indirect and Induced	Direct
Scenarios	6	3	4	-	-	-

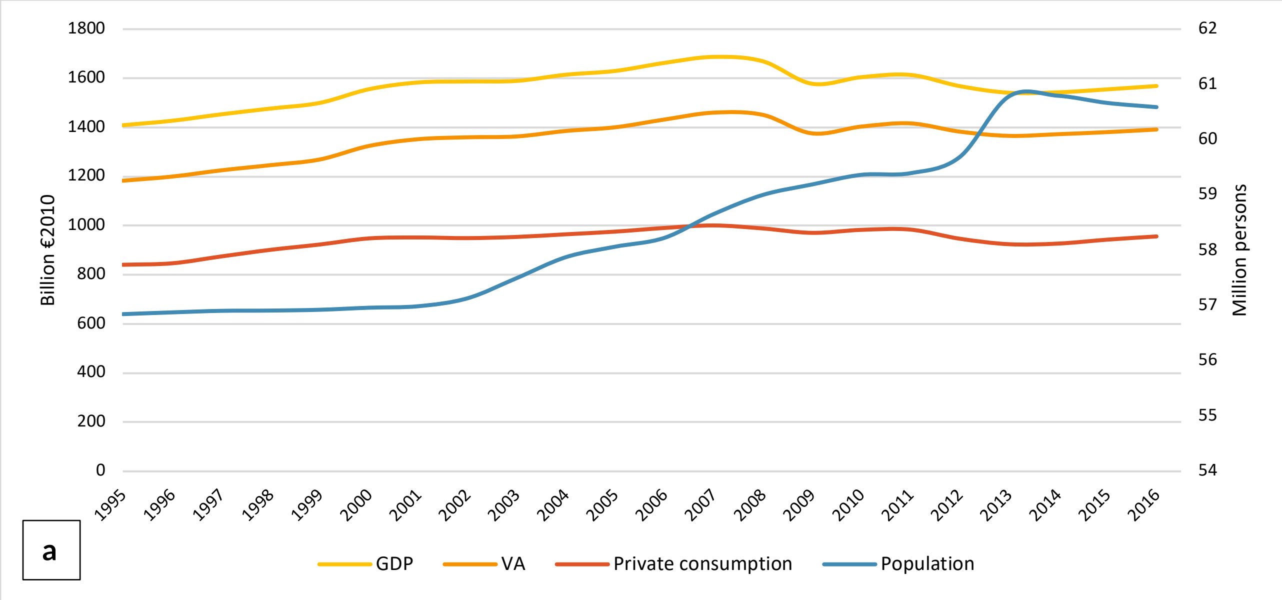
2 The Italian context

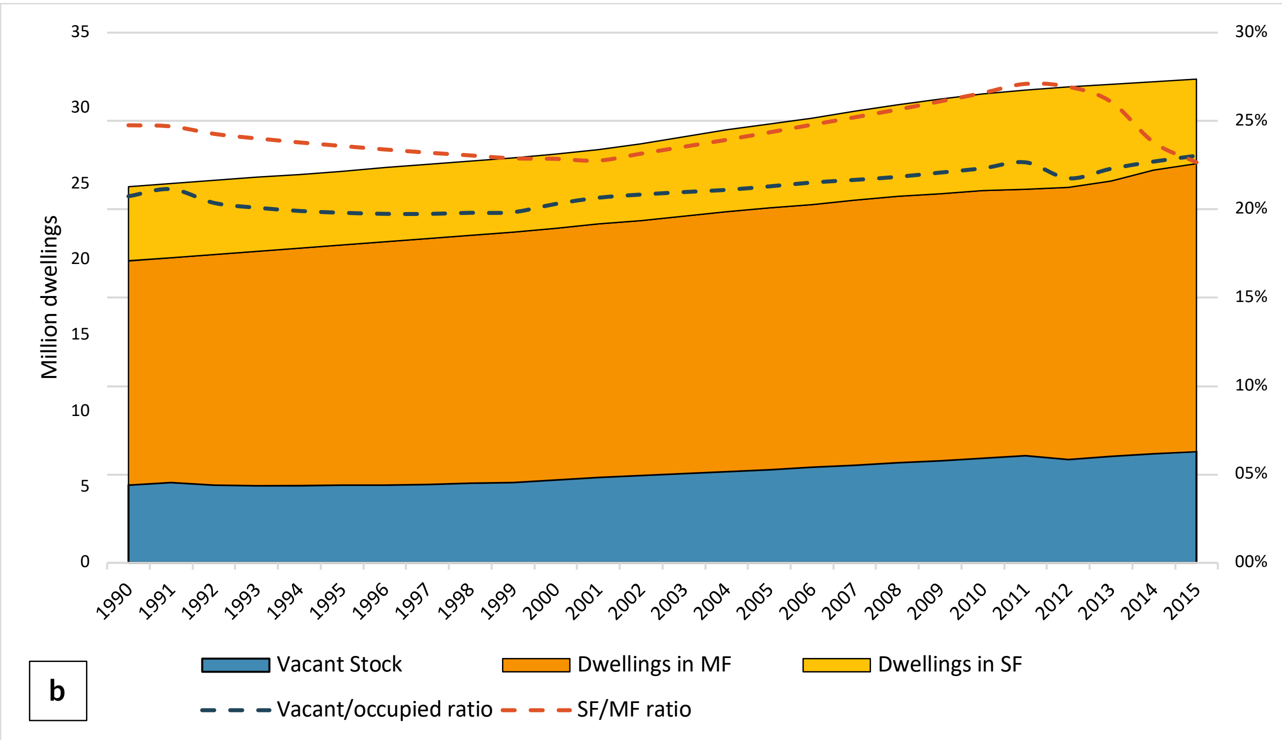
Achieving energy savings in buildings is a complex process that requires policy making in this field a meaningful understanding of several characteristics of the building stock. Reducing the energy demand requires the deployment of effective policies which in turn makes it necessary to understand what affects stakeholders' decision-making processes, the key characteristics of the building stock, the impact of current policies and more. EU legislation has set out an ambitious legal framework for improving the energy performance of European buildings. This challenges MSs to implement it through efficient regulations and policies, building codes and attractive financial programmes addressing the many barriers existing today. An overview of the challenges and barriers around energy efficiency renovation projects, the European and regulatory framework, the financial programmes and the co-benefits of renovation is provided in **Appendices** (Sections A, B, C and D).

Together with transport, industry and agriculture; "buildings and construction" is one of the four end-use macro-sectors under which Europe's energy consumption is split. It is composed of two main building categories: residential and non-residential buildings. Compared to the residential sector, non-residential buildings are more heterogeneous and are commonly referred to buildings in the service or tertiary sector. This study focuses on residential buildings, which in Europe and Italy represent 25% and 27% of total final energy consumption, respectively. An overview of the energy and carbon performance of the European and Italian building stock is provided in the Sections E, F and G of the **Appendices**. Figures are presented for all MSs for which data is available and special attention is given to the comparison between the Italian and average EU performances. Statistics show that Italian residential buildings are characterized by energy and carbon intensities close to the European average at 174.5 kWh/m2/yr. and 3 tCO2/dw/yr. respectively, but above average when normalizing them to the average European climate (226 kWh/m2). Moreover, Italy was the only MS where, between 2000-2015, the energy intensity of dwellings increased (+2.4%). As opposed to this trend, the activity rate for deep renovations is estimated at a low 0.5% per year. Section H of the **Appendices** offers more insights into how renovations are defined, classified and measured within the European context and provide some additional statistic on renovation acitivity in Italy.

In this Chapter, the geo-climatic and socio-economic context of Italy in relation to its RBS are briefly illustrated. The country is situated between the 35° and 47° north parallel and presents a considerable coastal profile (7.458 km) with a mix of hilly (41.6%), mountain (35.2%) and plain (23.2%) landscape. This translates into a very differentiated climate, ranging from subtropical Mediterranean in the south (with 40°C high peaks) to continental temperate in the north (up to -20°C low peaks). The global solar radiation ranges from 1.214 to 1.679 kWh/m2 with an average of 1.471 kWh/m2. Italy is the 8th global economic power by GDP and has a typically western economic structure in terms of value added from the primary, secondary and tertiary sectors (STREPIN 2015). **Figure 1a** and **Figure 1b** summarise a few selected key socio-economic and RBS trends taken from statistics. *Note that all the statistics presented in this section are not used as direct input data (see Chapter 4), but rather as data points for calibration of the dwelling stock and energy model results.*

Figure 1. a) Trends of key socio-economic indicators, 1995-2016; **b)** Number of dwellings in MFH, SFH and vacant (left axis) and share of dwellings in SFH, MFH and vacant over total dwellings (right axis) *Source: ODYSSEE-MURE database, EUROSTAT database*





2.1 Regulatory and Legislative Framework

Italy has fully complied with the requirements established in the European *"Climate and Energy Package"* for the objectives expected by 2020. In terms of GHG emissions reduction, the Italian commitment is based on a reduction target of 18% overall, 21% for the ETS sectors (Emissions Trading System, in particular the generation of electricity) and 13% in the sectors not covered by the ETS, compared to 2005. According to the last data by ENEA, compared to the 2011-2020 target set out in the third NEEAP (2013), the energy savings achieved in 2017 amounted to just over 8 Mtoe/yr, equivalent to almost 52% of the final target. As can be seen from **Table 3**, approximately 37% of these savings derive from the obligation scheme of the White Certificates and over a quarter from tax relief (Iorio and Federici 2018). The latter accounts for more than half of the total savings from residential, which is the only sector that has already reached its target for 2020.

Table 3. Achieved energy savings by end-use sector for the period 2011-2017 and expected for 2020 (final energy, Mtoe/yr) according to the 2014 NEEAP. *Source:* (Iorio and Federici 2018)

Sector / Measure	White Certificates	Tax Relief *	Conto Termico	Impresa 4.0 National Plan *	European Reguations and High-Speed Rail	Italian Legislative Decrees 192/05 and 26/6/15 **	Energy savings		Achieved target (%)
							Achieved in 2017	Expected by 2020 (final energy)	
Residential	**0.71**	**2.08**	-	-	-	**0.85**	**3.64**	**3.67**	**99.2%**
Services	0.15	0.02	0.005	-	-	0.04	0.22	1.23	17.5%
Industry	2.1	0.03	-	0.3	-	0.07	2.5	5.1	49%
Transport	0.01	-	-	-	1.68	-	1.69	5.5	30.7%
Total	2.97	2.13	0.005	0.3	1.68	0.96	8.05	15.5	51.9%

Notes:
* Estimate for the year 2017
** Estimate for the period Jan-Sept 2017 The residential sector includes the savings from the replacement of large household appliances as well

The "Italian Energy Strategy" (SEN 2013) set more ambitious targets in 2020 compared to those of the "Climate and Energy Package" of the European Commission. Its main aim is to strengthen energy efficiency policies by facilitating the measures with the best cost-effectiveness ratio in order to achieve the 2020 and further targets. Four high-level objectives are foreseen in 2020: (a) to reduce the energy costs by aligning the prices to European levels, (b) to exceed the targets set by the "package 20-20-20", (c) to increase the security of energy supply, and (d) to boost growth and jobs through new investments. Following the most recent *"Clean Energy for All European"* package presented by the European Commission in 2016, the latest Italian Energy Strategy (SEN 2017) confirms the key role of energy efficiency and mobilises extensive additional investments over the 2021-2030 period in order to achieve 30% energy savings: 110 out of the 175 billion euros overall SEN are expected to be spent in energy efficiency over the decade. This amount of resources is expected to result in a reduction in final energy consumption from active policies of around 10 Mtoe/year in 2030, equal to about 1 Mtoe of annual savings from new works in the period 2021-2030 and to be mainly focused in residential sector (3.7 Mtoe), services (2.3 Mtoe) and transport (2.6 Mtoe).

Translating the SEN 2017 into action, the fourth Italian NEEAP termed "Action Plan for the Energy Efficiency" (PAEE 2017) confirms the building sector as a key element for achieving the 2020 and further targets. The PAEE represents the official transposition of the EPBD recast into national law and regulations, including the tightening of minimum energy performance requirements for new and existing buildings and the consolidation of the tax deduction system for the energy refurbishment of the existing buildings.

Given the large cost-effective potential of the existing buildings stock, three additional instruments were annexed to the PAEE in order to strengthen the action on the residential and service sectors. The first one is the *"Strategy for Energy Refurbishment of the National Building Stock"* (STREPIN 2015). In this document, the RBS is characterised and retrofit criteria based on the cost optimization identified in order to overcome the technical, economic and financial barriers hindering the realization of energy efficiency measures in buildings. Starting from a review of policy measures put in place to overcome the barriers, some actions to improve the effectiveness of the support tools are proposed and the expected savings to 2020 estimated (4.2 and 1.5 Mtoe/yr for residential and service sectors, respectively). The "Italian Action Plan for nZEBs" (PANZEB 2015) translates and clarifies the updated definition of nZEBs completed in 2015, evaluates the performance of sample buildings, estimates the additional investment costs compared to standard renovations and proposes improvements to the existing financial instruments that would support the increase of nZEBs in Italy. The third and last instrument called "Plan for the Energy Refurbishment of the Public Administration" (PREPAC) establishes programs for the energy improvement of PA buildings at a rate of at least 3% per year between 2014-2020 (PAEE, 2017).

Narrowing down the scope to the residential sector only, the Italian strategy foresees a complete renovation of 3.5% of SFHs and 3% of MFHs built from 1946 to 2005. The plan also foresees a partial renovation of 4% of buildings constructed in the same period. The expected total annual energy savings by 2020 are 48,888 GWh/y and the estimated investments to achieve the potential savings are €13.6 billion per year for complete renovation and €10.5 billion for partial renovation (STREPIN 2015). Further expansion of works is expected under the updated National Fund for Energy Efficiency, approved in March by the 2018 Budget law to support projects that require a high initial investment, stimulating their financing by banks.

2.2 Residential Building Stock

With reference to the last Italian census of buildings by ISTAT, in 2011 there are 12.2 million residential buildings (roughly 90% of the overall building stock) hosting 31.2 million dwellings (ISTAT, 2011). The ODYSSEE database's estimate for 2016 is at 32.1 million (ADEME 2018). About 13 million dwellings are located in just 5 regions (Sicily, Lombardy, Veneto, Puglia and Piedmont) while Sicily and Lombardy alone host almost 25% of the national dwelling stock. The two regions are also representative of climatic zone B and E, the two dominant climatic areas in Italy as defined by the Presidential Decree no. 412/1993, from zone "A" to "F" according to the number of heating degree days (HDD) (**Figure 2**). Following the convention established in the TABULA project, these can be further grouped into three "macro-areas":

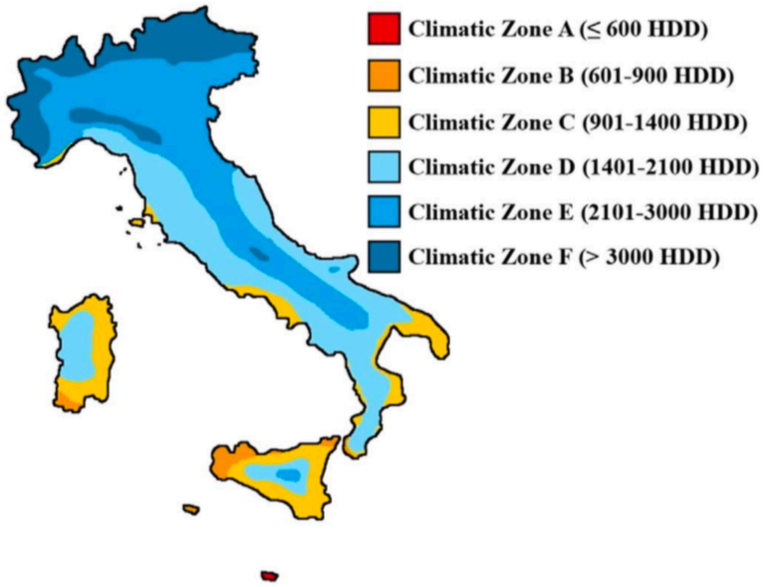


Figure 2. Map of the Italian climatic zones and HDD range Source: *Ballarini et al. (2017)*

- *Temperate Zone*, corresponding with "E zone";
- *Alpine Zone*, corresponding with "F zone";
- *Mediterranean Zone*, corresponding with "A zone", "B zone", "C zone" and "D zone".

In order to understand the relative importance of each climatic zone, **Table 4** summarizes how municipalities, population and buildings are distributed across each one of them.

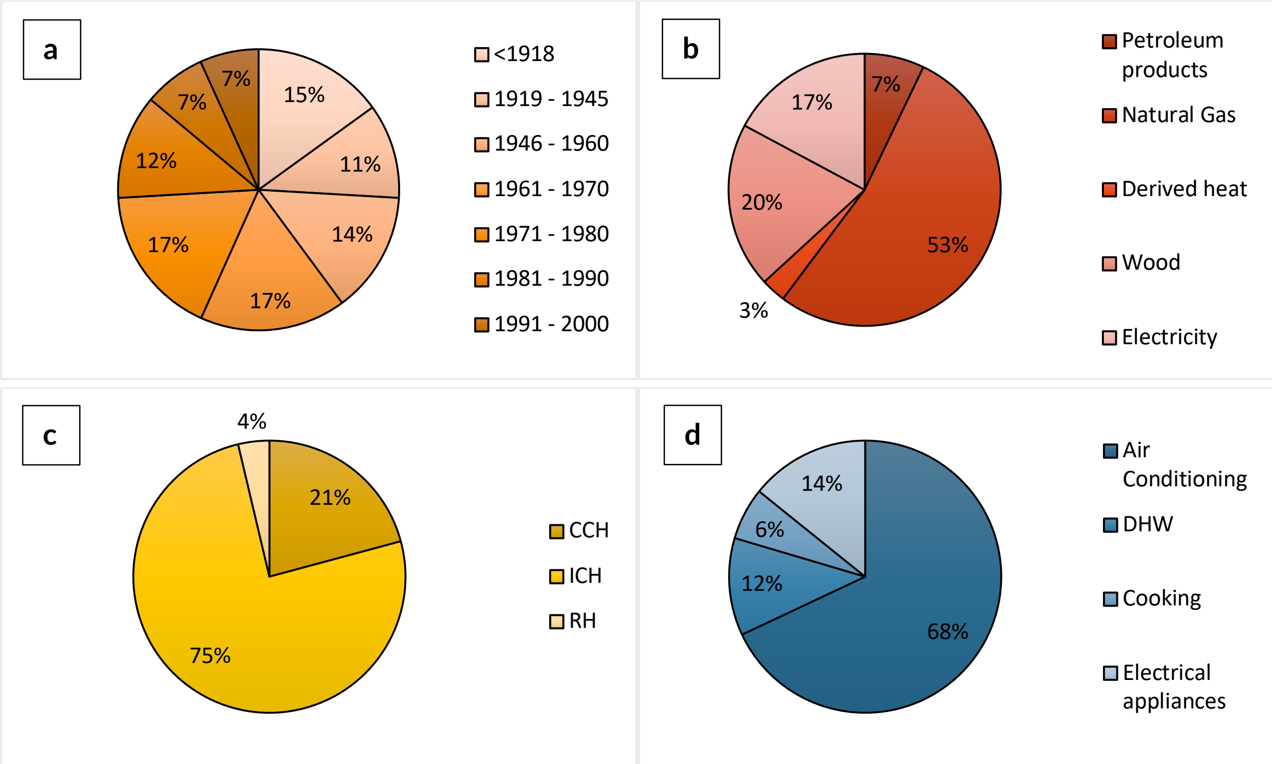
Table 4. Distribution of municipalities, inhabitants and buildings across climatic zones. *Source: STREPIN (2015)*

Climatic zone	Municipalities		Inhabitants		Buildings	
	n°	%	n°	%	n°	%
A	2	0	22.989	**0.04**	4.875	**0.04**
B	157	1.9	3.176.382	**5.33**	699.573	**5.74**
C	989	12.2	12.657.407	**21.25**	2.710.544	**22.24**
D	1.611	19.8	14.970.952	**25.13**	2.858.016	**23.45**
E	4.271	52.8	27.123.848	**45.53**	5.191.960	**42.63**
F	1.071	13.3	1.619.003	**2.72**	722.730	**5.93**

More than 60% of the dwelling stock is older than 45 years and thus built before the first national law of 1976 on energy savings (**Figure 3a**): of this building segment more than 25% has a very high specific unit consumption ranging between 160 kWh/m^2 and above 220 kWh/m^2.

Figure 3. Overview of significant statistical data on Italian residential buildings in 2016: a) Frequency of buildings by age cohort, b) fuel mix, c) technical building system typology and energy consumption by end-

use. Sources: ISTAT (2011), ODYSSEE-MURE DATABASE, EUROSTAT database, European Building Stock Observatory



NOTES: CCH – Collective Central Heating; ICH – Individual Central Heating; RH – Room Heating; Air conditioning also includes cooling demand (<1%)

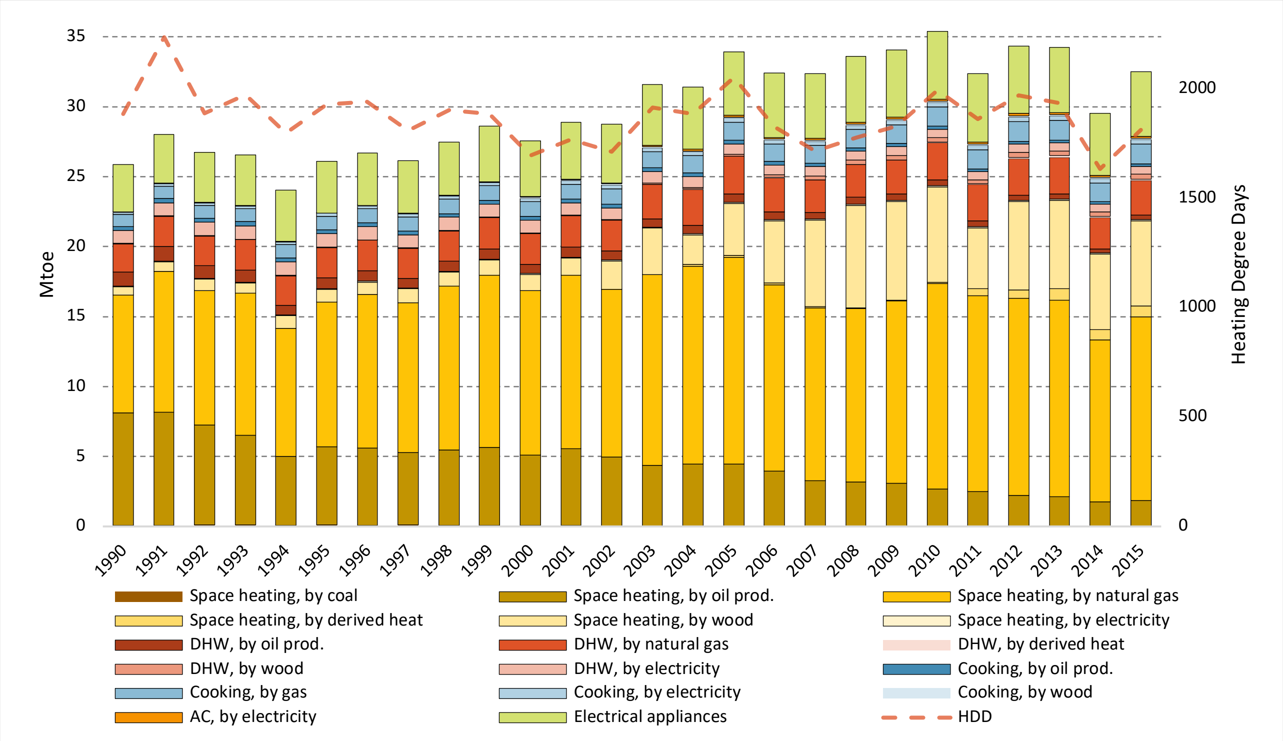
The main energy carrier in the residential fuel mix is gas (over 50%), followed by biomass (20%) and electricity (17%) which together provide 90% of the energy need in dwellings. The most remarkable change in the fuel mix has been experienced by natural gas, which consumption grew by 14.2% over the 2000-2016 period, mostly due to the substitution of oil products (15% and 62% reduction in share and overall consumption in the 2000-2016 period, respectively) (**Figure 3b**). As far as TBSs are concerned, individual central heating[2] is the dominant one representing three quarters of the space heating systems in use. Over the 2000-2016 period, this type of collective heating experienced a 13% increase in share at expenses of room heating, which is gradually being phased out. The share of collective central heating has remained rather stable loosing 2 points compared to 2000 levels (**Figure 3c**). Air conditioning is the largest end-use category, making up 68% of total consumption almost exclusively for space heating. It is followed by electricity use by lighting and electrical appliances (14%), DHW (12%) and cooking (6%). The end-uses shares have remained substantially unchanged compared to 2000, with only a 2% shift from DHW to space heating consumption (**Figure 3d**).

Figure 4 offers a more detailed look into the evolution of total consumption by end-use broken down by energy carrier. As of 2016, total residential energy consumption amounted at 32.2 Mtoe, down by 0.9% from 2015 (32.5 Mtoe). As it can be seen, gas consumption for space heating takes the lion's share at 40.4% of total consumption (+7.8% compared to 1990), followed by wood at 18.7% (+16.4% compared to 1990), electricity for cooling, lighting and appliances at 14.2% (+1.2% compared to 1990), natural gas for DHW purposes at 7.5% (-0.3% compared to 1990) and oil products for space heating at 5.7% (-25.4%). All the remaining uses take an individual share below 5% and, altogether,

[2] Central heating includes district heating, block heating, individual boiler heating and electric heating. Compared to room heating, where a stove provides heat to the main room only, the thermal comfort greatly improves at expenses of an increase in consumption, estimated at about +25% on average.

they make up the remaining 13.4%. With space heating being the predominant energy end-use, the overall consumption trend shows good fit the HDDs trend.

Figure 4. Trend in Italian residential energy consumption by end-use and supplying energy carrier (left axis) and correlation with HDDs (right axis), 1990-2015. *Source: ODYSSEE-MURE database*



In the light of this, it appears logical that Italian energy policies are prioritizing the substitution of obsolete space heating systems in energy inefficient dwellings like the ones constructed before 1975. However, when looking at the concrete actions taken as they appear from the statistical trends, the Italian effort seem short-sighted and less ambitious than what it could be. The increasing penetration rate of natural gas in all end-uses categories can be interpreted as a tendency to prefer business-as-usual solutions that, if on the one hand do deliver energy (more efficient condensing boilers) and carbon savings (cleaner fuel), on the other remain a suboptimal choice compared, for instance, to a larger implementation of RES. Another influencing factor is represented by the shift from room to central heating, which is known to bring comfort benefit at the expenses of increased heating demand. Italy's trend in this regard seems to prefer individual rather than collective heating systems. While this is not an arguable choice per sè, it still shows that substitution occurs within the range of business-as-usual options and does not lead to the avoidance of traditional heating systems as foreseen by nZEBs ambitions.

2.3 Construction and energy Markets

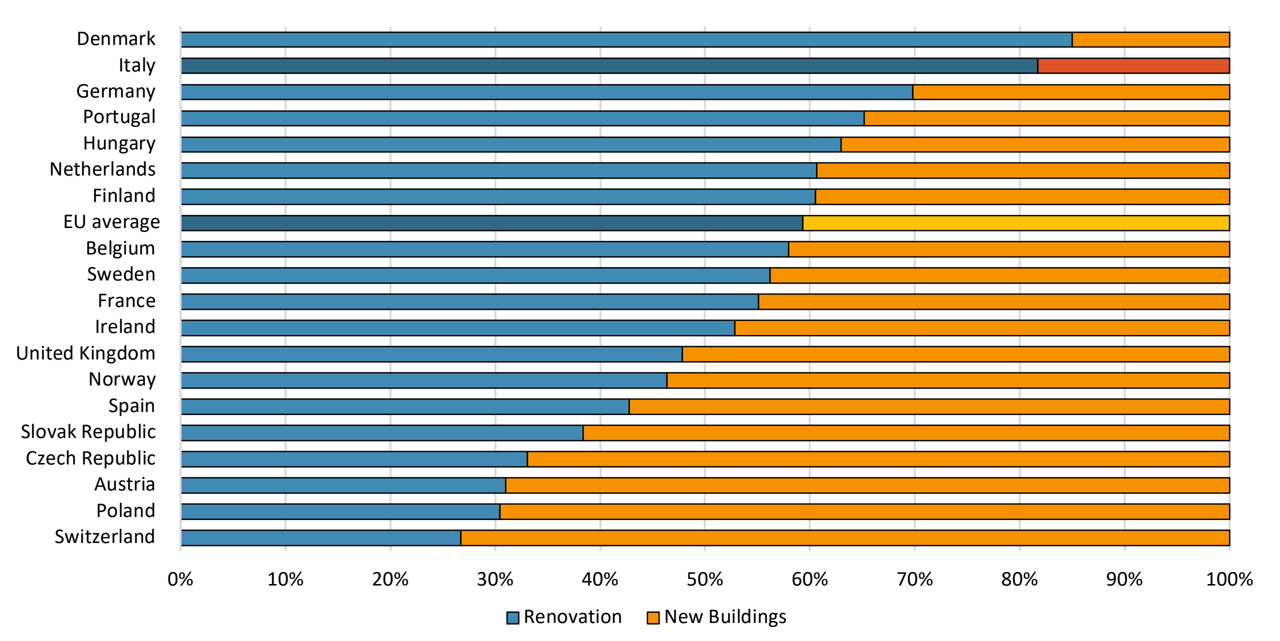
The Italian construction sector is vital element of the national economy, with a contribution to the gross value added of 18.7% of GDP. Between 2010-2016, the country experienced a 8.9% drop in the number of construction companies with severe repercussions on production, which fell by 32.2% over the same period. Profitability and employment in the sector have also declined and the turnover and gross operating surplus dropped in 2016 by 17.3 and 17.2%, respectively, compared to 2010. The number of workers has also been declining over the same period of time by 22.4% reaching 2.2 million employees in 2016. The causes of this drop have been identified in a particularly unfavourable access to finance, delays in payments from Public Administrations and, as a result, an historical high in the number of failures in construction companies (ECSO 2018).

After a bad convergence, in the next period the Italian construction sector is expected to slowly recover, also thanks to Budget Law 2017 which introduces important measures to stimulate public and private infrastructural investment in energy efficiency. However, the employees in the construction industry will continue to decrease, and the suboptimal efficiency of the PAs may discourage private foreign investment in the future (ECSO 2018). This is a particularly bad news for Italy, which in 2017 was the MS with the lowest share of active population (70%) and an unemployment rate just below EU average (8.4% against 8.6%). Furthermore, the ESCO reported that: *"GHG emissions (CO, CO_2, CH_4 and PM) from activities in the construction and real estate sub-sectors amounted to 5.250 and 263 kton in 2014, respectively. The former has experienced a 17% decrease since 2010 (6.326 kton) while the latter declined by 20.7% (331.5 kton in 2010)".*

As also recognized at the EUROCONSTRUCT conference, the old age of European buildings impacts on the share of expenditure for interventions on the existing stock. In 2015, an estimated 371 billion euro refers to works of refurbishment, repair, maintenance and energy efficiency upgrade of the RBS. It means that the recent renovation activity absorbs about 60% of the total residential output, while in 2007 it was worth only 43%. In Italy, the residential output as a share of construction is the third highest at around 45%, of which 82% is due to renovations activities (**Figure 5**). In fact, Italy is after Denmark the country with the highest share of renovation in total residential construction output and the first one in the non-residential sector (69%) (EUROCONSTRUCT 2015). However, it should also be noticed that in this case the term renovation refers not just to energy-efficiency upgrades, but also general restorations, modernisations, extensions, conversions, repairs and maintenance of dwellings.

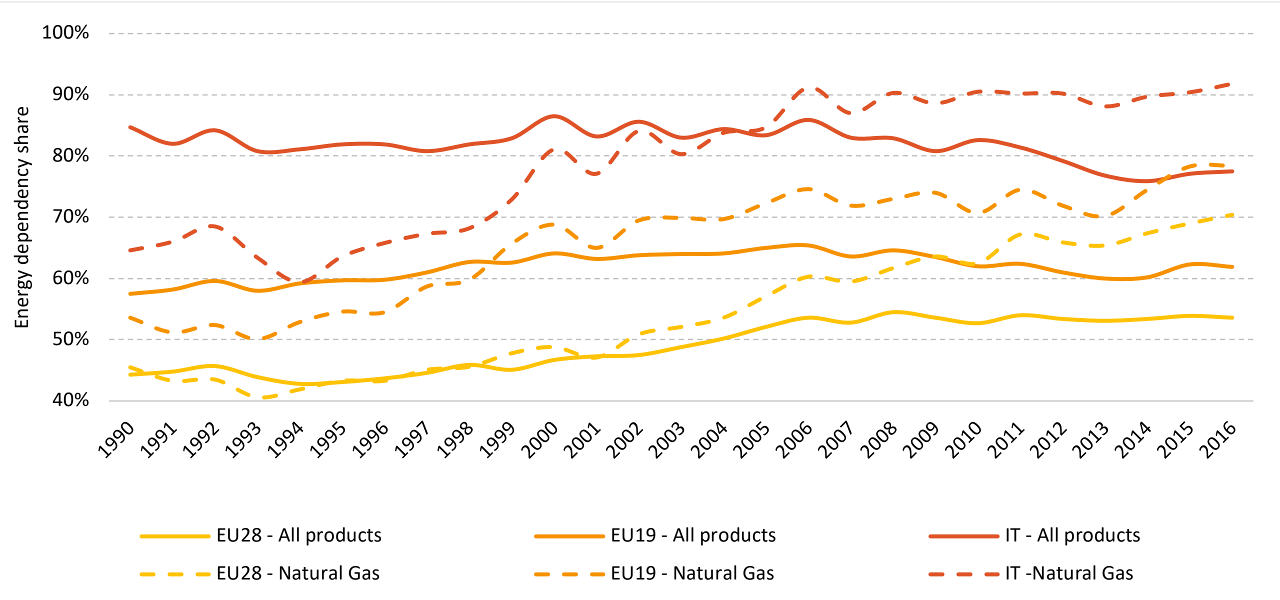
Since the '90s, regulations in the Italian energy market have been resting upon two principles: decentralization of power generation from the former monopolist Enel and liberalization of the energy market through unbundling of generation, transmission and retail. Today, the Italian power market is fairly dispersed, yet it has not been able to fully address the "energy hotspots" of the country (Deloitte 2015).

Figure 5. New buildings and renovation share in residential construction market output, 2015 (at m€2014 prices). *Source: EUROCONSTRUCT report 2015*



Energy dependency is probably the most relevant, especially from the point of view of residential energy consumption. Energy dependency defines the extent to which a country relies on imports in order to meet its energy needs. **Figure 6** shows that, between 1990-2016, Italy has been steadily relying for 80-85% on energy imports in order to meet its energy need. This is on average 20% more than the MSs in the Euro-area and about 35% more than the EU28 average. In the long-term, Italy is slowly bridging its energy dependency gap, moving from a +40% difference in 1990 to +25% in 2016. The same is not true when looking at the energy dependency from natural gas, the main energy carrier in the residential fuel mix. Between 1990-2016, the dependency on this energy carrier increased at an average 1.5% yearly rate from almost 65% to over 90% against a European average of 70%. This means that in 2016, Italy imported about 17.5 Mtoe of natural gas just for residential purposes (including the natural gas share in electricity use), corresponding to a €13.6 billion expenditure assuming a price of 0.72 €/Sm^3 (ARERA 2018).

Figure 6. Comparison of energy dependency rates between Italy, EU19 and EU28 for all energy products and natural gas only, 1990-2016. *Source: EUROSTAT database*



3 METHODOLOGY AND METHODS

This Chapter starts with a general description of the methodologies and the underlying techniques available for modelling the residential sector. It is followed by review of the main scientific papers where the NTNU dwelling stock and energy model was developed and a more detailed, yet not exhaustive, explanation of the model's working. Afterwards, the new environmentally-extended economic model is presented by its two main components: Standard Economic Evaluation (SEE) and Input-Output Analysis (IOA). Finally, the conceptual outline of the scenarios is laid out together with the underlying assumptions regarding the rate of renovation, the ambition level of technical building standards and the market penetration rates of RES technologies.

The literature distinguishes between two general modelling approaches to the analysis of the residential sector: top-down and bottom-up. The top-down modelling approach works at an aggregated level and tends to be used to investigate the inter-relationships between the energy sector and the economy at large. They could be broadly categorised as econometric and technological top-down models. The econometric top-down models are primarily based on energy use in relationship to variables such as income, fuel prices, and gross domestic product to express the connection between the energy sector and economic output. The technological top-down models include a range of other factors that influence energy use (i.e. saturation effects, technological progress, and structural change), although they are described not explicitly within the models. On the other hand, bottom-up methods are built up from data on a hierarchy of disaggregated components, that are then combined according to some estimate for their individual impact on energy usage. This implies that they may be useful for estimating how various individual energy efficiency measures impact on CO2 emission reduction, such as by replacing one type of heating systems with another. Often these models are seen as a way to identify the most cost-effective options to achieve given carbon reduction targets based on the best available technologies and processes. The bottom-up models work at a disaggregated level, and thus need extensive databases of empirical data to support the description of each component (Kavgic et al. 2010).

For bottom-up models, the approach to energy analysis can be either statistical or engineering-based. The formers rely on measured consumption data when available and apply techniques such as regression or conditional demand analysis to estimate the energy demand of buildings. The engineering-based approach starts instead from data on buildings' geometry, technological and thermophysical properties to estimate the energy demand through energy performance calculations. Depending on the scope and application of the model, the time-steps for the energy performance calculation can range from hourly to annual. For this reason, they require quantitative input data on the efficiency of technical building systems, heated floor area, areas of different dwelling elements (walls, windows, doors, roof, floors), external conditions and user behaviour. In combination with assumptions on the development of the internal and external factors such as climate, demography or policies, the allow modellers to estimate the energy demand of dwellings for the past, present and future (Mastrucci et al. 2017). Time is in fact a further element of distinction between models classifying them further into either static or accounting, quasi-stationary or dynamic.

Accounting models are mainly aimed at quantifying the size and composition of stocks and associated physical flows. This type of models are not intended to analyse the drivers of stock expansion nor its energy performance but rather just at estimating or measuring it. Conversely, the other two model approaches explain the size, composition, and energy consumption of the stock by means of driving factors. Quasi-stationary models commonly focus on a single year, while dynamic models analyse longer time periods. There are different ways in which the driving factors can be factored in, which separates the models between activity-driven or inflow-driven and stock-driven (Vásquez et al. 2016). Activity-driven models generally use external construction, demolition and renovation rates, most of the times based on past trends. When the stock is the driving factor, this is usually depends on a service demand/provision concept (Müller 2005) linking the change in stock to time-depending factors such as population and preference in building typology or size. Stock-driven models use the buildings' lifetime for explaining and estimating construction and demolition activities which requires to cover a longer time-span due to the long lifetime of buildings. Renovation is often modelled by defining renovation cycles. Those of inflow- and stock-driven models are recognized concepts in the field of industrial ecology which have been first applied to the dwelling stock analysis by Müller (2005), Bergsdal et al. (2007) and Sartori et al. (2008).

To perform the energy analysis at the stock level, two aggregation principles are generally used: building-by-building or archetype approach. The former is the most time consuming because involves the modelling of individual buildings and thus is mainly suitable for applications of limited scope such as at the neighbourhood or district level, or by making use of GIS databases (Pasetti 2016). The archetype approach instead relies on a representative sample of building described by detailed physical and technological data from different sources. In some cases, like for instance the IEE-TABULA project, energy performance calculations for each archetype have been already performed under standard conditions (Loga et al. 2014, 2016). Stock segmenting factors typically include housing type, size or age of construction. Results from the representative sample of buildings are eventually extrapolated to the entire stock based on the number of dwellings or floor area in each segment. Therefore, while in the archetype approach a subset of the system is analysed and the results upscaled, in the building-by-building approach the total performance is obtained by summing up single results. ***Within this methodological framework, the NTNU dwelling stock energy model positions itself as a state-of-the-art bottom up, dynamic and stock-driven model based on a type-cohort-archetype segmentation.***

3.1 THE NTNU DWELLING STOCK ENERGY MODEL

This study builds on a long-lasting research conducted at NTNU with contributions from a range of researchers within different institutions. Among the contributors to the model's development there are senior researcher Igor Sartori at SINTEF Buildings and Infrastructure, postdoc Nina Holck Sandberg, PhD candidates Magnus Inderberg Vestrum and Jan Sandstad Næss and professor Helge Brattebø at NTNU. The dwelling stock energy model is a mixed Matlab-Excel model intended for long-term analysis of aggregate effects of changes in RBSs, at the scale of municipalities, regions or nations. The model, its mathematical formulation and applications are documented in a series of publications that are summarized below.

Sandberg et al. (2014a and 2014b) first presented a dynamic dwelling stock model based on material flow analysis (MFA) principles. Driven by population size and number of persons per dwelling, the dwelling stock demand and construction, demolition and renovation activity are estimated for each year towards 2050. The relative importance of uncertainty in input parameters is explored through sensitivity analysis and found the model's output being most sensitive to changes in population and dwellings' lifetime. The main conclusion from these two studies is that renovation rates necessary to achieve policy targets in energy and carbon savings are unrealistic when considering the dwellings' "natural" need for renovation.

Vásquez et al. (2015) investigated the influence of different national boundary conditions by comparing two quite different countries sheltered under the same European energy-reduction policies and goals: Czech Republic and Germany. They applied a slightly modified version of the model where the parameter persons per dwelling type is substituted by floor area per capita and type split of construction. For the first time, the dwelling stock analysis is complemented by a scenario-based energy analysis using energy intensities from the Intelligent Energy Europe project *"Typology Approach for Building Stock Energy Assessment"*, *2009-2012* (IEE-TABULA). The study concludes that current regulations are once again not sufficient for achieving long-term targets on GHG-emissions and that the same renovation policy applied in different national contexts leads to different energy reduction levels.

In Sartori et al. (2016), the conceptual outline and general algorithm of the model are improved and formalised. The application to the Norwegian case study is used to exemplify the model's validation against statistics and to estimate the best value for the "natural renovation flow" which is found to be a 40 years renovation cycle. The effect of shorter renovation cycles (30-20 years) is also tested and interpreted to provide recommendations on their possible meanings and modelling applications.

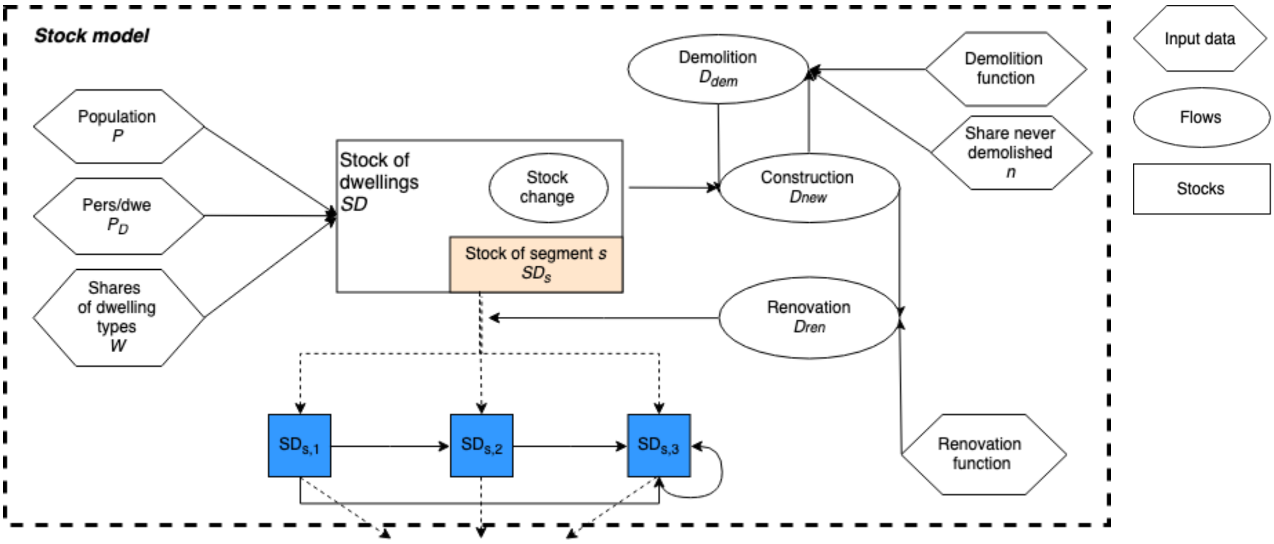
Sandberg et al. (2016a) applied the model to 11 European countries to test its suitability in simulating long-term changes in dwelling stock composition and expected annual renovation activities across diverse national contexts. Similar patterns in future trends for construction, demolition and renovation activity are observed across the case studies, all pointing to a natural need for "deep" renovations that is not in line with the renovation rates required in many decarbonisation scenarios. The proposed solutions are either leveraging the single natural opportunity for deep renovation by applying best available EEMs or stimulating more frequent renovation, thereby shortening the renovation cycles.

Sandberg et al. (2016b) further expanded the model by formalising an energy module for detailed analysis of the dwelling stock energy demand. The case study on Norway is used to investigate the past residential energy demand between 1960-2050 and to explore the phenomena and causes of historical changes. In Sandberg et al. (2017), the focus shifts from the explanation of historical trends to the estimation of future energy savings and GHG emission mitigation potentials from the housing stock. By analysing the relative and combined effect of several scenarios the authors concluded that, for the Norwegian case, increased penetration of photovoltaics (PV) and heat pumps (HP) has a much greater reduction potential than further improvement through more advanced/frequent renovation of the building's envelope.

All model variables and its main equations are presented the Nomenclature section at the beginning of the report. Further explanation of the model mathematical principles is given by Sartori et al. (2016), segmentation of the stock is introduced in Sandberg et al. (2017) while the energy layer is extensively described in Sandberg et al. (2016c).

3.1.1 Stock Model

Figure 7. Conceptual outline of the building stock model. Hexagons represent input variables, rectangles stocks and ovals flows. All inputs and output are time-dependent. *Source: Sandberg et al. (2017)*



Due to the long lifetime of dwellings, the dwelling stock system is changing slowly and the composition of the stock depends on activities far back in time. A long time-horizon is therefore needed in the dwelling stock model and the 1800-2050 period is chosen for this purpose. The core of the building stock model is the population's demand for dwellings (SD) and its distribution over various dwelling stock segments (SD_s). A segment is defined by the dwelling type and construction period (cohort). Each year t, the demand is estimated based on the trend of the underlying drivers in the system: the population size (P), the dwelling occupancy measured in number of persons per dwelling (PD) and the share of dwellings being of each dwelling type (W). The number of dwellings demolished (D_{dem}), constructed (D_{new}) and renovated (D_{ren}) each year are outputs from the model. Demolition activity is estimated by applying a demolition probability function on construction activity from all previous years whereas the construction activity is estimated using mass balance principles: what needs to be constructed to replace demolished buildings and to meet the increase in housing demand.

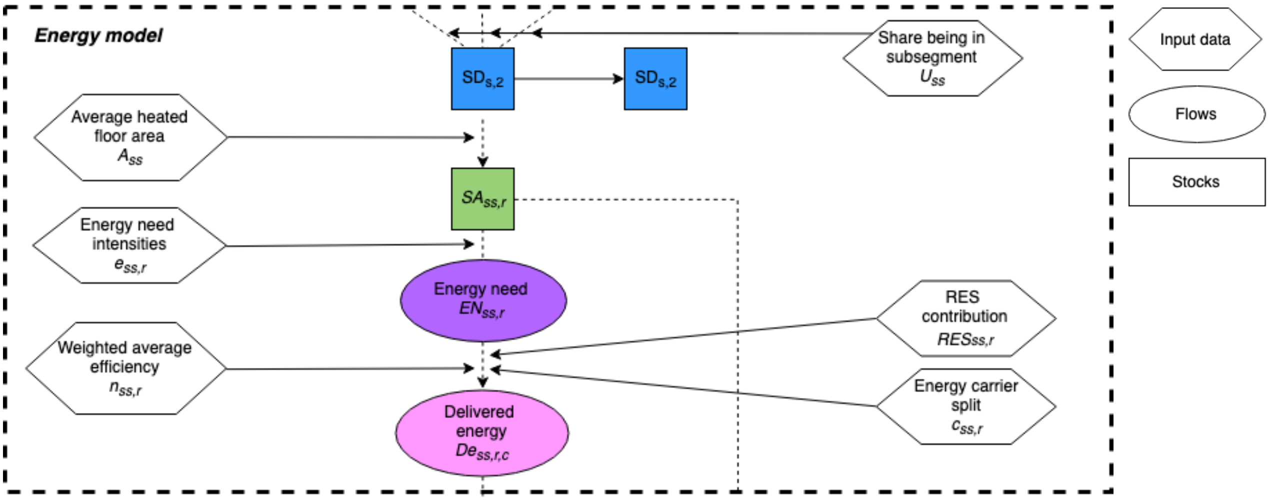
While demolition of a dwelling can happen only once, renovation can happen several times during a building's lifetime. The renovation activity in year t is estimated by applying a cyclic renovation probability function to the construction from all previous years. This is described by the renovation cycle (τ) which represents the average time between renovations of a certain dwelling. The cyclic renovation probability function is linked to the lifetime probability function, preventing a dwelling from being demolished shortly after going through renovation. The renovation activity is independent of the mass balance and does not affect the dwelling stock size or distribution to segments. The dwelling stock size and the activities are measured in number of dwellings and number of dwellings per year.

Construction typologies and cohorts define a dwelling's segment. A dwelling segment can be further classified according to its renovation stage (e.g. detached houses from the 1970s being in their original state without significant energy-renovation improvements). $SD_{s,r}$ is the archetype defined by segment (s), and renovation period (r). The principle used for the distribution to archetypes is that when a dwelling is renovated, it always moves from its archetype to the next one (e.g. from r = 1 to r = 2) within the same segment. However, it is the scenario-specific energy performance assigned to each archetype, i.e. its energy standard, that decides whether the renovation has had an energy-efficiency purpose and its level. The model allows for choosing three renovation periods and the archetype describes the ambition level of renovation within this period for each segment and scenario. This adds flexibility to the model, since energy intensities are a consequence of building codes, energy saving measures and other factors that may change over time. Archetype 1 always consists of dwellings in their original state (not yet renovated) and of dwellings that back in time have only undergone renovation that did not significantly improve their energy standard. New buildings are also by definition always in Archetype 1. Renovation period 2 begins in a given year from when energy-efficient renovation is assumed to have started and lasts until a year where the average energy-efficiency standard of renovated buildings has, or in the future possibly could, change to a different level. Then, Renovation period 3 starts.

A certain share of the dwellings constructed each year are assumed to end up as heritage buildings that are never demolished and also not altered through deep energy-renovation measures. When the remaining share of dwellings constructed in a certain year reaches this value, the demolition function is truncated and no more dwellings from that construction year will be demolished. The total construction, demolition and renovation activities in the system are not affected by the distribution of segments to archetypes. New dwellings are per definition always placed in renovation period 1. Demolition and renovation activities are allocated to dwellings of different archetypes without affecting the total number of dwellings demolished or renovated within each segment. The model gives the number of dwellings of each segment that are demolished or renovated each year. This number is distributed to the corresponding archetypes. To prevent dwellings from being demolished or re-renovated just after renovation, the demolition and renovation activity is distributed to the dwellings of different renovation periods due to their internal proportions over one renovation cycle, back in time. Mathematically, this is obtained by convolution between the demolition and construction function and between the renovation and construction functions.

3.1.2 ENERGY MODEL

Figure 8. Conceptual outline of the building stock energy model. All inputs and output are time-dependent. Source: Sandberg et al. (2017)



The analysis of the historical development in delivered energy for the Italian dwelling stock is simulated for the 1960-2050 period. The dwelling types Single-family Houses (SFH), Terraced Houses (TH), Multi-family Houses (MFH) and Apartment Blocks (AB) are used in the energy analysis. In the building stock model, SFHs are grouped together with THs, and MFH together with AB2, to form just two general typologies called “detached” and “compact” buildings, respectively (Sandberg et al. 2014a). The coarser aggregation is due to limitations in data availability and changing definitions of building types in sources like censuses and housing investigations from far back in time. However, while a “detached” versus “compact” distinction can be sufficient for modelling long-term stock dynamics, these heterogeneous building groups become a limiting factor when accounting for different levels of energy performance in dwellings.

For this reason, in the first step of the energy model, the turnover of dwellings in “detached” and “compact” buildings are split into SFHs, THs, MFHs and ABs and converted into their equivalent floor area ($SA_{ss,r}$). This is done by applying type-split coefficients (U_{ss}) and average heated floor areas per segment (A_{ss}) in the way explained in Chapter 4.1.3. Once the floor area of each building typology is known, segment- and archetype-specific energy need intensities ($e_{ss,r}$) are applied to obtain the complete dwelling stock energy performance profile. For each scenario, this is characterized by 144 segment-archetype combinations (e.g. apartment blocks from the 1980-90 period being in their original state i.e. in Archetype 1), each one with a specific energy need intensity. Together with data on weighted average system efficiency $(\eta_{ss,r})$, energy mix ($c_{ss,r}$) and use of RES $(RES_{ss,r})$, it is used to estimate the energy need, delivered energy and use of different energy carriers for all years, either for the total stock, per dwelling type, cohort, segment or archetype.

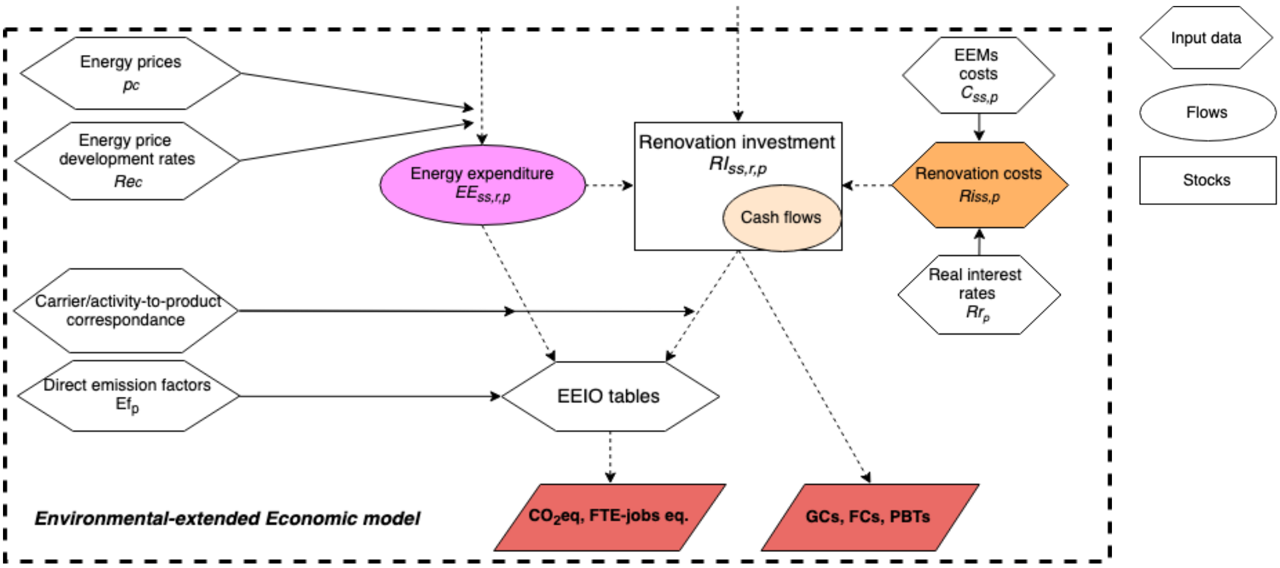
Technology changes in the building envelopes affect the energy need in the system, which depends on the technical standard of the building envelope, and represents the amount of energy needed for space heating or cooling, DHW, ventilation and electrical appliances. In this study, energy need intensity figures (in kWh/m^2/year) for each archetype are taken from TABULA (Loga et al. 2016) and reflect archetypal changes in energy-efficiency standards for the Italian dwelling stock since the XXth century. In parallel, changes in energy mix, energy efficiency and use of local RES affect the conversion from energy need to delivered energy. The delivered energy is the amount of energy that has to be delivered to the dwelling to fulfil the energy need after accounting for onsite energy generation and losses in the heating system. (see Chapter 4.1.2). Therefore, the energy need $(EN_{ss,r})$ is corrected for energy contributions from RES technologies, namely HPs, PVs and solar heat collectors and converted to delivered energy per archetype $(DE_{ss,r,c})$ using the weighted system energy efficiencies. Finally, the model is calibrated for changing electric load and outdoor climate as described in Chapters 4.2.1 and 4.2.5., respectively.

The energy results are further calibrated against statistics on total delivered energy in the system since 1960. The model also allows to account for so called "prebound" and "rebound" effects. The former occurs when, especially in dwellings with poor energy performance, the "technical estimate" is higher than the "real" demand due to smaller shares of the building being heated to the assumed temperatures. The second case is instead observed when a highly energy-efficient dwelling is heated to higher temperatures than the ones assumed due to comfort or energy expenditure factors, resulting in a lower real energy performance. To take into account these effects, a thermal adaptation factor f_A is calculated within the model based on empirical observations of measured versus calculated energy demand and used to adjust for changing user behaviour (heating habits) and uncertainty in model results. Due to time restrains, no specific f_A could be developed for Italy while the application of the one developed for Norway resulted in poor fit with statistics. Therefore, no thermal adaptation factor was applied in this study and results only presented in terms of technical and not real delivered energy.

3.2 ENVIRONMENTALLY-EXTENDED ECONOMIC MODEL

To evaluate the most effective renovation scenario and prioritize actions for enhancing residential energy efficiency, the financial feasibility and broader socioeconomic implications of each strategy should be taken into account. Hence, the aim of the environmentally-extended economic model (Figure 15) is to identify the most beneficial strategy from a macroeconomic or societal standpoint that is also financially feasible for the investor; while taking into account potential trade-offs across impact categories (i.e. carbon, energy, labour, monetary). It focuses one "use" or "operational" phase of building. The Delegated Regulation N° 244/2012 supplementing the EPBD recast requires MSs to define the minimum performance requirements of buildings based on a cost-optimal assessment (COA) (Atanasiu and Kouloumpi 2013). The optimal level of energy performance as a function of the costs is defined as "the energy performance level that brings to the lowest cost throughout the estimated building's economic life-cycle". One original contribution of this work is a first attempt at integrating a COA of renovation options in the NTNU dwelling stock energy model. Among the other things, this involves estimating the costs of renovation options and of energy, and their expected development over time. Additionally, combining the same economic data elaborated for the COA with environmentally-extended input-output analysis (EEIOA); life-cycle carbon, employment and embodied energy impacts are estimated. To this end, a robust link between the life-cycle costs categories and the IO system needs to be established. Hereafter, the two methods underlying the abovementioned tools, namely Standard Economic Evaluation (SEE) and Input-Output Analysis (IOA) are presented.

Figure 9. Conceptual outline of the building stock environmentally-extended economic model. All parameters are time-dependent. *Source: Own elaboration based on Sandberg et al. (2017)*



3.2.1 Standard Economic Evaluation

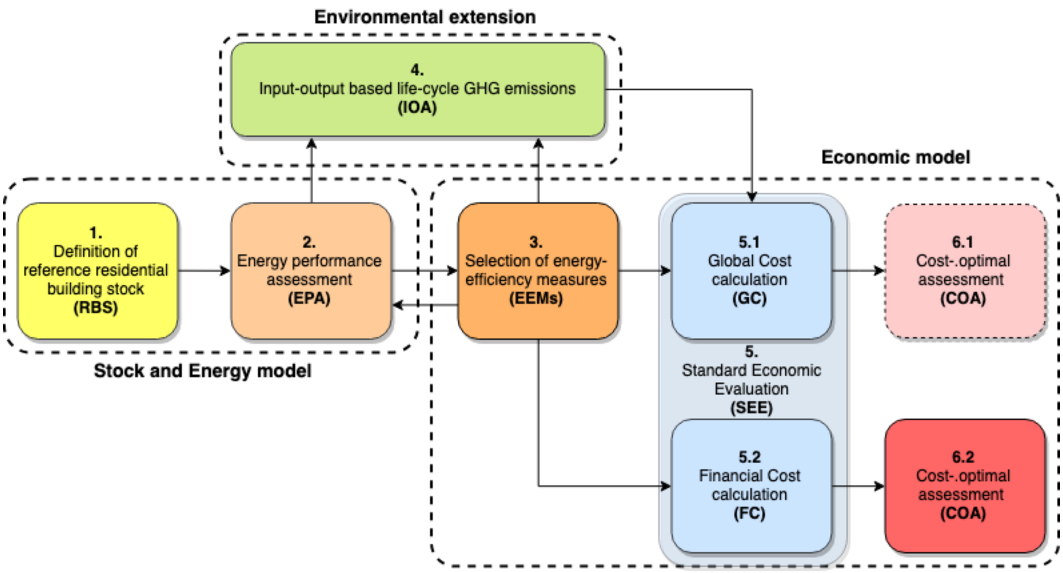
The Delegated Regulation N° 244/2012 prescribes the cost-optimal calculations to be carried out according to the UNI EN 15459 specification (European Committee for Standardization 2011). The specification illustrates a SEE method tailored for energy efficiency interventions (Corrado et al. 2014d). It distinguishes between two perspectives under which the cost calculation can be carried out: *financial and macroeconomic*. While the first reflects a microeconomic perspective linked to the feasibility of the investment from the point of view of the end-user, the latter reflects instead a broader societal standpoint. **Table 5** lists the main assumptions that characterize each perspective.

Table 5. Assumptions for private and societal perspectives. *Source: Ferrara, Monetti, & Fabrizio (2018)*

Parameter	Financial Perspective	Macroeconomic Perspective
Interest rate	Real interest rate	Societal interest rate
Subsidies and incentives	Included	Excluded
Taxes	Included	Excluded
Cost of emissions	Excluded	Included

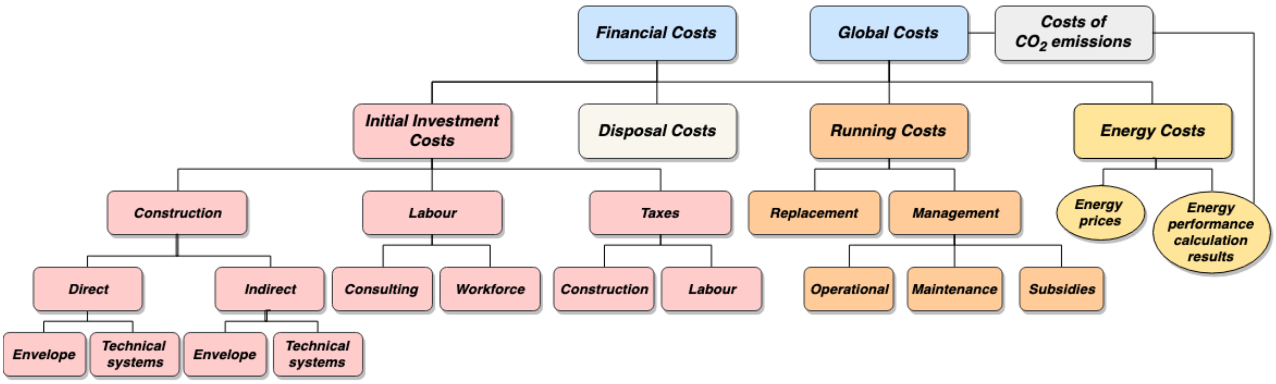
Despite the terminology used in the specification is slightly different, in order to avoid any confusion, in this report all renovation costs estimated under a financial perspective aretermed *financial costs (FC)* while all those referring to a macroeconomic standpoint are referred to as *global costs (GC)*. In the present work, the costs and benefits of renovation strategies are evaluated from both a financial and macroeconomic perspective. **Figure 10** depicts a simplified flow diagram of the model where the relationship between the stock energy model and environmentally-extended economic model is highlighted. The shaded box 6.1 is because the full COA from the macroeconomic perspective was only partially completed.

Figure 10. Simplified flow chart showing the relationship between stock energy model and the new environmentally-extended economic model.



The starting point for the determination of both financial and global costs is a renovation costs inventory, wherein basic prices for all the selected EEMs are collected by cost category in the way prescribed by the technical standard (European Committee for Standardization 2007a). As shown in **Figure 11**, renovation costs include the initial investment in its sub-components (direct and indirect construction costs, labour and taxes), the running costs divided into replacement and annual management costs (including operational, maintenance and subsidies), disposal and energy costs. The renovation costs inventory is of two parts: the first part includes the list of basic prices for each EEMs and their average lifetimes and the second part summarizes the geometrical features of each reference building and the information on each renovation variant (archetype), namely the size of opaque (façade) and transparent (windows) envelope to be insulated and the type and power load of the new technical systems to be installed (Corrado and Corgnati 2014; Corrado et al. 2014b). This information is combined to create a renovation investment matrix which describes all segment- and scenario-specific costs per square meter of useful floor area by each cost category (within A3).

Figure 11 Scheme of the cost categorizes included in the renovation costs inventory. *Source: Own elaboration based on Capozza et al (2014) and Corrado, Ballarini, Ottati, et al. (2014)*



One of the key factors that differentiate a merely financial from a macroeconomic perspective, is the inclusion of the CO_2 emission costs as the monetized value of the environmental damage caused by the energy-related emissions of the building. As such, SEE is slightly different but in its principles comparable to a life-cycle costing analysis (LCCA) as defined by the UNI EN 15686 (European Committee for Standardization 2011). It is, however, not comparable to a full life-cycle assessment (LCA) in that it does not include all environmental costs but only those related to energy consumption. The inclusion of IO-based life-cycle CO_2 emissions before carbon pricing allows to slightly improve upon this limitation. In LCA terminology, this study is almost entirely focused on the "use" or "operation" phase of buildings as in fact new construction is excluded from the economic and environmental impacts assessments (but included in the stock and energy analysis) while the end-of-life phase is only roughly considered.

Under SEE, costs represent the sum of the present value of all costs (with reference to the starting year) including initial investment and the residual value of components. Therefore, the final figure expressed in €/m^2 gives the total actualized investment value over the defined calculation period τ. In order to account for the time value of money, SEE uses the concept of Net Present Value (NPV) of the investment. The NPV is a common method for the financial evaluation of medium- to long-term projects whereby the actual value of expected incoming and outgoing cash flows are summed together after discounting them according to country-specific discount rates. By actualizing the future costs and revenues related to the alternative allocation of financial resources, the NPV allows for comparison of investments in the financial markets on the same time-horizon and accounting for interest and inflation rates (V. Corrado, Ballarini, Ottati, & Paduos, 2014). From the basic financial assessment based on the NPV, other relevant indicators for the end-users such as the payback time (PBT) can be estimated.

The indirect costs of construction are defined as those not strictly related to the EEMs, yet necessary for the completion of the energy renovation works. In this study, they are interpreted as the additional costs to be allocated to the energy renovation investment in case of missing the "window of opportunity". That is to say that the energy renovation does not take place contextually to regular maintenance works necessary for the functionality, safeness and good-state of the building. Typical values for natural rates of replacement/maintenance are; 20 years cycle for replacement of components (e.g. generation or distribution systems), 30 years for replacement of construction elements like windows and the "natural" 40 years renovation cycle for deep renovation of facades. However, for simplifying the calculations, it assumed that the window of opportunity occurs indistinctively for all building elements and stock segments if the renovation cycle of the scenario is equal to the natural renovation cycle ($\tau = 40$). For instance, it was supposed that the insulation of the buildings' envelope would occur in case there was already the necessity of refurbishing the facades. In this case, the cost-benefit evaluation is not carried out in comparison to the ex-ante situation, but compared to a basic intervention, namely the refurbishment of the facades. This entails calculating the *additional costs*, or the difference between the costs of the energy renovation and the basic intervention. **Table 6** presents the details of the cost items included in the basic intervention. No corresponding basic intervention was assumed for the installation of PVs, solar heating collectors, HPs or ventilation with heat recovery. For simplicity, the additionality concept was not extended to the energy savings. As observed by Capozza and colleagues (2014), the energy savings related to regular maintenance operations are anyways minimal.

Table 6. Cost items of the basic interventions and correspondence with energy efficiency measures. *Source: Capozza et al. (2014)*

EEM	Basic intervention	Cost items of basic interventions
Insulation of the external vertical walls	Façade refurbishment	Façade painting, adjustment deteriorated plaster, scaffolding (assembly and disassembly), replacement of descendants
Window frame substitution	Substitution of "basic" window frames (U=1.5 kWh/m^{2}K)	Supply and installation of window frames (double glazing), removal, transport and landfill of old windows.
Condensing boiler installation	Installation of "3 stars" boiler for space heating and/or DHW production	Supply and installation of generators and of any expansion vessel, possible masonry and electrical works at the thermal plant, removal, transport and landfill of old generators

Both the direct and indirect construction costs related to the envelope are dependent on the geometry (type) and the age cohort of the reference buildings and thus are segment-specific. The direct interventions on the envelope are assumed to employ the same insulation materials and techniques for all renovation variants (archetypes) while only changing the amount of insulation to be added according to the targeted U-value. Accordingly, the indirect costs are also independent from the archetype, but can change according to the renovation cycle of the scenario as a result of the renovation occurring within or outside the "window of opportunity". The direct and indirect costs related to generation and distribution systems are segment-, archetype- and scenario-specific. Ventilation systems with heat recovery were not included in the analysis because of the lack of reliable basic price data. **Table 7** compares the elements considered in this analysis with those recommended by the EN 15459 in case of comparison between existing buildings with reduction of heat demand.

Table 7. Overview of the building elements included in the energy and economic assessments. *Source: EN 15459 (2007a)*

Example of costs calcuation	Heating	DHW	Ventilation	Cooling	Lighting	Envelope
Recommended	✓	✓	✓	✓		✓
Included	✓	✓				✓
Note			Excluded for lack of reliable economic or consumption data. Minimal contribution of about 2-3% of total final energy consumption		Included separately with no modelled EEMs	

The first connection between the energy and economic models is described by the following equations:

$$RI_{s\prime,\tau,i} = \sum_{ss} SA_{ss,i} * Ri_{ss,\tau,i}$$

$$Ri_{ss,\tau,i} = C_{ss,i} + \sum_{i=1}^{\tau} (Ca_{(ss,i)} * f_{pv}(i)) - \sum_{j=1} V_{f,\tau}(j)$$

Where $RI_{ss,\tau,i}$ is the *total annualized renovation investment* at year τ for sub-segment ss, SA_{ss} is the renovated floor area for each dwelling subsegment in a specific year and $Ri_{ss,\tau,i}$ is the annualized cost per square meter of the renovation investment in year i over the accounting period τ**.** Note that in these formulas, the parameters are not dependent on the renovation period anymore since the environmentally-extended economic model only focuses on buildings renovated after 2020 ($r = 3$). The complete generalized equation set for the calculation of $Ri_{ss,\tau,i}$ according to the SEE method can be found in Section I of the **Appendices** (European Committee for Standardization 2007a).

As anticipated, there are several indicators of financial performance that can be derived from SEE, the most common of which is the financial PBT. Financial PBT stands for the number of years necessary to recoup an investment cost. However, the principle of a PBT can potentially be applied to all cases where positive and negatives flows are involved, for example in the case of (embodied) energy and carbon. These PBTs would then indicate the time period needed to offset the initial amount of embodied) energy or carbon emissions consumed/generated (positive flows) as a result of an activity through yearly energy and carbon savings (negative flows). They can be thought of as forms of environmental PBTs. The financial PBTs a very straightforward indicator, especially from the point of view of the investor and it suitable not just for comparison of different building typologies, but between investments in different sectors from energy efficient renovation. Its drawback is that it not granted that the investment with the lowest PBT is also the most convenient.

Because the dwelling stock energy model adds new renovation activity on a rolling basis and computes the aggregated energy performance each year, it is not possible to follow nor to trace back the energy savings of a specific segment as a result of renovation occurred in a specific year. As consequence, financial and environmental PBTs had to be calculated in a simplified way, assuming that the energy savings in the first year are repeated every year an only change as a function of energy prices and their development over time. Under the following assumption, PBTs are calculated for every year using the following equations and their average over the 30 years is used as final indicator:

$$PBT_i^{fin} = \frac{Ri}{\sum_i \left(\frac{\Delta Es_{c,i}}{(1 + Re_c)^i} \right)}$$

$$PBT_i^{co_2} = \frac{(b'_{en}\, L\, \Delta y)_i}{\sum_i \Delta DE_i * \delta_i}$$

$$PBT_i^{en} = \frac{\left(b'_{co_2}\, L\, \Delta y\right)_i}{\sum_i b'_{en}\,(i)}$$

Note that because these equations cannot be explicitly solved, an iterative process is applied.

3.2.2 Environmentally Extended Input-Output Analysis

In macroeconomic assessments, the renovation investment is usually evaluated at least in terms of direct and supply chain (or indirect) impacts. One of the most common approaches to do so is to treat the renovation investment as a "stimulus" of economic demand within an IO framework. In this particular case this entails assigning each of the cost categories in **Figure 11** to a corresponding sector within the IO database involved in the economic transaction. As such, the renovation investment can be interpreted as a trigger of economic activity in all those sectors directly connected to the renovation activity (for the correspondence table see Chapter 4.3.2.

EXIOBASE is a multi-regional environmentally extended input-output (mrEEIO) database that represents the global economy by means of inter-sectoral transactions within and across 48 world regions. In general terms, every sector receives inputs from other products/sectors and supplies outputs to other products/sectors. By linking the monetary flows related to the renovation investment to EXIOBASE, the model can estimate the indirect economic impacts generated by each flow on the rest of the economy. That is to say, for every million euro spent on renovation (allocated to the different products/sectors involved), how many additional € are indirectly generated in other products/sectors to satisfy the extra demand for renovation works. The environmental extensions (or accounts) are matrices of structured environmental data (e.g. carbon emissions, material inputs, land use) linked to the economic ones and that allow to estimate the environmental impacts embodied in each monetary transaction. That is to say, for every million euro spent on renovation how many additional CO_2 emissions are indirectly generated in each other sector as a result of meeting the extra demand for renovation works. This information is used to compute the direct and indirect (or macroeconomic or life-cycle) impacts of the strategies in terms of carbon, but also labour. The last year for which EXIOBASE input-output tables (IOTs) are available is 2011, however it was decided to use the 2010 data and to express all macroeconomic results in constant 2010 prices.

Estimation of the socioeconomic and environmental impacts of the energy renovation scenarios for the Italian RBS was based on input-output analysis (IOA). The study of the structural relationships among economic products/sectors through IOA finds its early origins in the work of Wassily Leontief (Leontief and Georgescu-Roegen 1952). At the base of this methodology, input-output tables (IOTs) "*allow the static representation of each sector's production process through a vector of structural coefficients that describes the relationship between the intermediate inputs consumed in the production process and the total output*" (Oliveira et al. 2014). The supply side is split into several processing industries that deliver their total production output either for intermediate consumption or final demand. These relationships can be illustrated through the following equation:

$$x_i = \sum_{j=1}^{n} x_{ij} + y_i$$

where x_i is the output of sector i, x_{ij} is the input from sector i to sector j, and y_i is the total final demand for sector i. The monetary values in the transaction matrices can then be converted into ratios called technical coefficients. This is done by dividing each cell of the domestic intermediate matrix by its column total (output at basic prices):

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_i$$

in which the coefficients a_{ij} are the amount of input delivered by sector i to sector j per unit of sector's j output, known as technical coefficients (or direct coefficients). The productive system at a national level can then be represented through the following basic IO system of equations:

$$x = Ax + y$$

where A is a matrix of technical coefficients, y is a vector of final demand, and x is a vector of the corresponding outputs. In order to finally calculate the output multipliers, one needs to derive Leontief inverse matrices by rearranging the previous equation to:

$$X = (I - A)^{-1}Y$$

where I is the identity matrix with convenient dimensions and $(I - A)^{-1}$ is also known as the Leontief inverse L. Each generic element b_{ij}, of $(I - A)^{-1}$represents the total amount directly and indirectly needed of good or service i to deliver a unit of final demand of good or service j. Let r' represent a generic intervention vector (e.g. tons of air pollutants or million workings hours) where each element r_{ij} represents for instance the amount of pollutant i released by sector j, then:

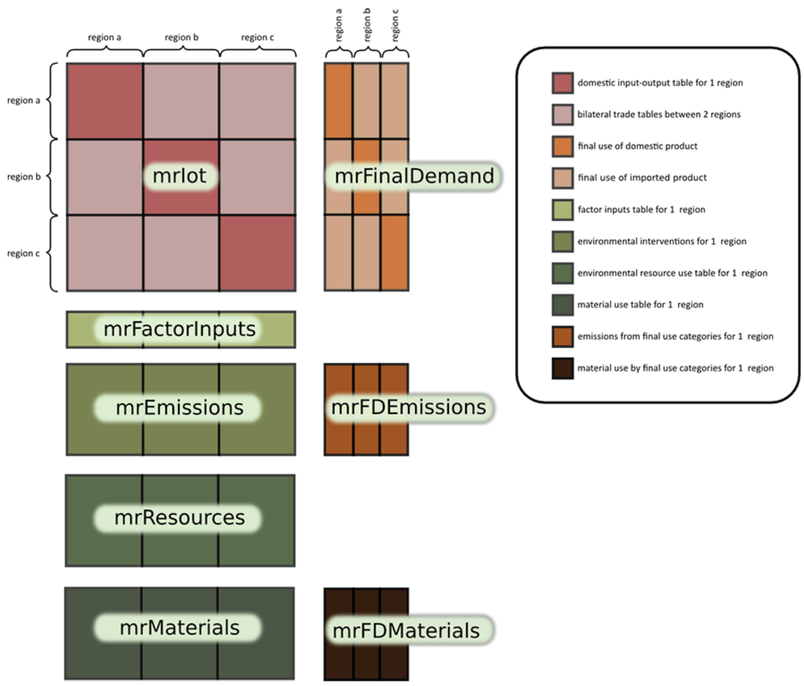
$$b' = r'\hat{x}^{-1}$$

represents the direct intensity vector, that is the amount of pollutants emitted per unit of output by each sector. Combining the previous equations, the final formula for calculating the indirect impacts for any intervention due to a change in final demand:

$$B = b'(I - A)^{-1}\Delta Y$$

The present analysis relies on EXIOBASE v3.3, a global multi-regional environmental extended supply and use/input output (mrEE SUT/IOT) database which represents the world's economy by 48 regions, 163 industries and 200 product categories (Tukker et al. 2013; Wood et al. 2015). SUTs, IOTs and environmental intervention matrices for production factors, energy and emissions, among the others, are provided therein (**Figure 12**).

Figure 12. Graphical representation of EXIOBASE multi-regional IO system. Source: EXIOBASE website (2019)



3.3 Renovation Scenarios

To facilitate the implementation of successful climate-change mitigation policies, it is crucial to better understand the dynamic and complex nature of the future building stock energy system. The energy demand of a dwelling stock depends on (i) the size and composition of the stock, (ii) the energy-efficiency state of the buildings, (iii) outdoor climate, (iv) the energy mix and efficiencies of the energy distribution and conversion technologies, (v) the use of local energy sources and (vi) the user behaviour. All these factors will change over time, and the temporal changes must be examined in scenario analyses. Of the six elements outlined above, the scenarios elaborated in this study to answer the main research question are focused on:

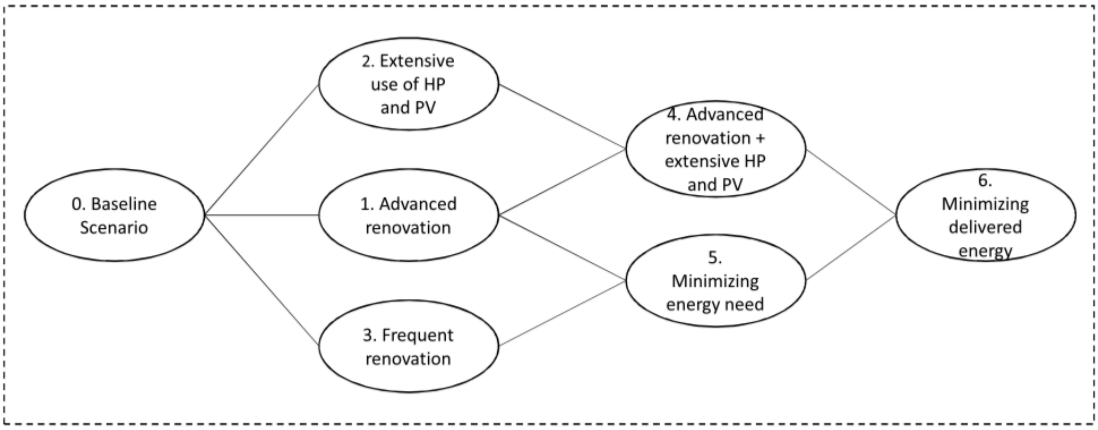
- The energy efficiency state of the buildings;
- The energy mix and efficiencies of the energy distribution and conversion technologies; and
- The use of local renewable energy sources.

In particular, since the aim of this study is: *"to evaluate and compare the effectiveness of (a) improved energy efficiency due to more ambitious and/or frequent renovation and (b) increased use of local renewable energy"*, the structure of the scenarios was developed as follow:

1. Advanced rather than standard renovation regime;
2. Extensive implementation of local RES in the form of HPs, PVs and SHCs; and
3. Frequent rather than natural renovation regime.

Hence, the baseline scenario is characterized by standard renovation of the building envelope at a natural rate (standard and natural renovation regime). It is based on the assumption that future developments in the system will follow the most likely continuation of recent trends, present common practices and known policies and regulations for the near future. **Figure 13** show the three alternative development paths listed above branch out from the Baseline case.

Figure 13. Conceptual outline of the scenario analysis. The links between the scenarios show how they build on each other. *Source: Sandberg et al. (2017)*



Therefore, while scenarios 1 to 3 evaluate the effect of basic renovation regimes – Advanced, Extensive and Frequent – scenarios 3 to 6 evaluate their combined effectiveness. The combination of advanced and more frequent renovation maximizes the ambition level and rate of renovation of the building envelope and therefore it is termed "Minimizing energy need" scenario. Conversely, scenario number 4 tests the effectiveness of high ambition levels for both envelope renovation and implementation of RES technologies at a natural renovation rate. Finally, the sixth and last scenario assumed that all three basic strategies are deployed in a single policy plan. **Table 8** compares the key characteristics and parameter values for each scenario.

Table 8. Key characteristics and parameters values for each scenario.

Scenario description	Ambition level of renovation after 2020	Use of local RES	Rate of renovation after 2020	Window of opportunity
	Archetype 3 (A3)	*Share of HPs and PVs*	*Renovation cycle (τ)*	*Indirect costs excluded*
0. Baseline	Standard	Following trends/Expected future development	40 years	✓
1. Advanced renovation	Advanced	Following trends/Expected future development	40 years	✓
2. Extensive use of local RES	Standard	Extensive use of HPs and PVs	40 years	✓
3. More frequent renovation	Standard	Following trends/Expected future development	30 years	
4. Advanced renovation and extensive use of local RES	Advanced	Extensive use of HPs and PVs	40 years	✓
5. Minimizing energy need	Advanced	Following trends/Expected future development	30 years	
6. Minimizing delivered energy	Advanced	Extensive use of HPs and PVs	30 years	

4 Model Input Data

In this chapter, all input data are presented consistently with the flow logic of the model. Where the figures presented in Chapter 2, were used only for calibration/validation, the one presented in this chapter constitute the actual input data. Table 9 provides an overview of the key model's parameter values in 2016 and 2050 together with their source and a short explanation.

Table 9. Summary table of parameters value in 2020 and 2050 with data sources and short explanation. Source: based on Sandberg et al. (2017)

Parameter	2016 value	Source/comment	2050 value	Source/comment
STOCK MODEL				
Population	60.7 million	ISTAT	58.9 million	ISTAT, Eurostat
Persons/dwelling	2.37	ISTAT	2.2	Assumption
Average lifetime of dwellings	125 years	Estimation in line with Sandberg et al. (2017)	125	Assumed continuation of trends
Renovation cycle (deep renovation of facades)	40 years	Estimation in line with Sandberg et al. (2017)	Scenario specific	Assumed continuation of trends
ENERGY MODEL				
Average heated floor area per dwelling	Segment specific	Corrado and Ballarini (2016a); Corrado et al. (2014a)	Segment specific	Assumed continuation of trends
Energy need for heating and DHW	Archetype specific	TABULA/EPISCOPE	Archetype and scenario-specific	TABULA/EPISCOPE
Energy mix	Residential stock average	IEA energy balances; ODYSSEE database	Scenario-specific	Bernante et al. (2013); Gaeta et al. (2013)
Electricity mix	Residential stock average	Lanati et al. (2016)	Residential stock average	Lanati et al. (2016)
System efficiencies	Energy carrier and segment specific	Corrado et al. (2014a)	Energy carrier and segment specific	Assumed convergence towards maximum values
Electric load	2200 kWh/dwelling	ODYSSEE database	2300 kWh/dwelling	Assumption
Share having HPs	Segment specific	GSE (2016b)	Segment specific	Bernante et al. (2013)
Average COP	2.73	Estimation in line with GSE (2016b) and EHPA (2019)	2.92	Estimated based on share of different HPs
Share of heating demand covered by HPs	20%	Estimation in line with Bernante et al. (2013)	60%	Estimation in line with Bernante et al. (2013)
Share having PVs and SHCs	Segment specific	GSE (2016c)	Segment specific	Assumption
Energy production from PVs and SHCs	Segment specific	Corrado and Corgnati (2014)	Segment specific	Corrado and Corgnati (2014)
Outdoor climate (HDD factor / relative difference in heating need from 1961-1990 average)	0.66 / 0.88	ISPRA (2017); ISTAT	0.66 / 0.80	ISTAT; RCP 4.5
ENVIRONMENTALLY-EXTENDED ECONOMIC MODEL				
Basic EEMs prices	Segment specific	DEI (2011, 2012)	Segment specific	Estimated constant growth
Other costs and lifetimes of EEMs	Segment specific	European Committee for Standardization (2007e); Capozza et al. (2014)	Segment specific	Estimated constant growth
Subsidies	65% - 55%	ENEA (2018)	65% - 55%	Assumed continuation of trends
Interest rates	4% – 3.5%	Corrado et al. (2014b); Ferrara et al. (2018)	4% – 3.5%	Assumed continuation of trends
Energy prices	Energy carrier specific	Virdis et al. (2017); ARERA (2018)	Energy carrier specific	Estimated by prices development rates
Energy prices development rates	Energy carrier specific	Capozza et al. (2014); Gaeta et al. (2013)	Energy carrier specific	Assumed continuation of trends
Energy emission factors	Energy carrier specific	Romano et al. (2018); Caputo (2017)	Energy carrier specific	No change assumed
End-use coefficients	Product specific	ODYSSEE database and assumptions	Product specific	ODYSSEE database and assumptions

4.1 Stock Model

4.1.1 Demography and Occupancy

The main source of demographic data are the Italian censuses of population and dwellings which are being hold every decade since 1861, year of the constitution of the Italian Kingdom. A few other sources such as cadasters and construction bulletins were also consulted. Population statistics (P) are available since 1770, although in a scattered way. For the pre-unitary period (1800-1861), data collections from the various counties on Italian soil are used to estimate the population living within the borders of the future Kingdom of Italy. Time-series based on censuses data elaborated by the Italian Statistical Office (ISTAT) are used to cover the 1891-2019 period. The "medium variant" population scenario by Eurostat, roughly corresponding to the "median" scenario by ISTAT, was instead used to cover the 2019-2050 period. Average dwelling occupancy (PD) data are mostly available in each census, whereas the construction type split (W) was only available from 1981 to 2011 and therefore had to be either estimated or assumed for the remaining periods. **Table 10** summarizes the statistics and assumptions used to build the input time series. Gaps between raw data points were linearly interpolated. An extensive explanation of the data used to build the full time-series with references has been added to the **Appendices**.

Table 10. Key statistics (**bold**), assumptions and references for P and PD input time-series. *Source: own elaboration*

Year	Share of P living in SFH	Assumptions	SFH + TH		MFH + AB		TOT	
			P (Mpp)	PD (pp/dwe)	P (Mpp)	PD (pp/dwe)	P (Mpp)	PD (pp/dwe)
1800	96%	Sandberg et al. (2016)	16,55	7,00	0,69	7,00	**17,23**	7,00
1861	90%		22,49	6,61	2,52	6,23	**25,01**	**6,57**
1901	86%		28,90	4,67	4,70	4,22	**33,60**	**4,60**
1921	80%	(Niceforo 1931) (RSE 2015)	29,99	4,50	7,49	4,17	**37,49**	**4,53**
1945	68%		30,83	4,36	14,51	4,12	**45,34**	**4,38**
1961	47%		23,72	3,87	26,65	3,66	**50,37**	**3,76**
1981	26%		**14,82**	**3,31**	**41,65**	**3,12**	**56,48**	**3,19**
1991	26%	-	**14,67**	**2,94**	**42,07**	**2,81**	**56,74**	**2,84**
2001	25%	-	**14,51**	**2,84**	**42,44**	**2,54**	**56,96**	**2,60**
2011	22%	-	**13,00**	**2,58**	**46,36**	**2,42**	**59,36**	**2,39**
2050	22%	Own assumption	12,86	2,32	46,10	2,1	58,96	2,20

Figure 14 shows the entire time-series for both input parameters: After growing by a factor 3.5 between 1800 and 2018, the Italian population has started to decline in the present year and it is projected to reach just below the 59 million persons in 2050. Dwelling occupancy in 1865 amounted at 6.57 pp/dwelling and it was assumed to start at 7 pp/dwe in 1800 and to end 2.2 pp/dwe in 2050 (**Figure 15**). Overall, the Italian dwelling stock started, like in most countries in the XIX century, as mainly of typical low-rise, rural and densely populated detached or semi-detached houses and underwent a massive transformation throughout the whole XX century. In the first stage (1900-1945) and particularly in the first post- war period (1918-1945), the demographic boom together with improved construction techniques, allowed for the first big expansion of compact dwellings, although also the share living in detached houses continued to increase. In the second phase (1945-1980), the second post-war economic boom, enabled the middle class to emerge and reshape the urban landscape (RSE 2015). Within 35 years, the share of population living in SFH dropped from 68% to 26% and it is expected to level-off at around 22% of the total population by 2050.

Figure 14. Development in total population and in persons living "detached" (SFH+TH) and "compact" (MFH+AB) dwellings (left axis). Share of the population living in detached houses (right axis). *Source: own elaboration based on census data from ISTAT and Sandberg et al. (2017)*

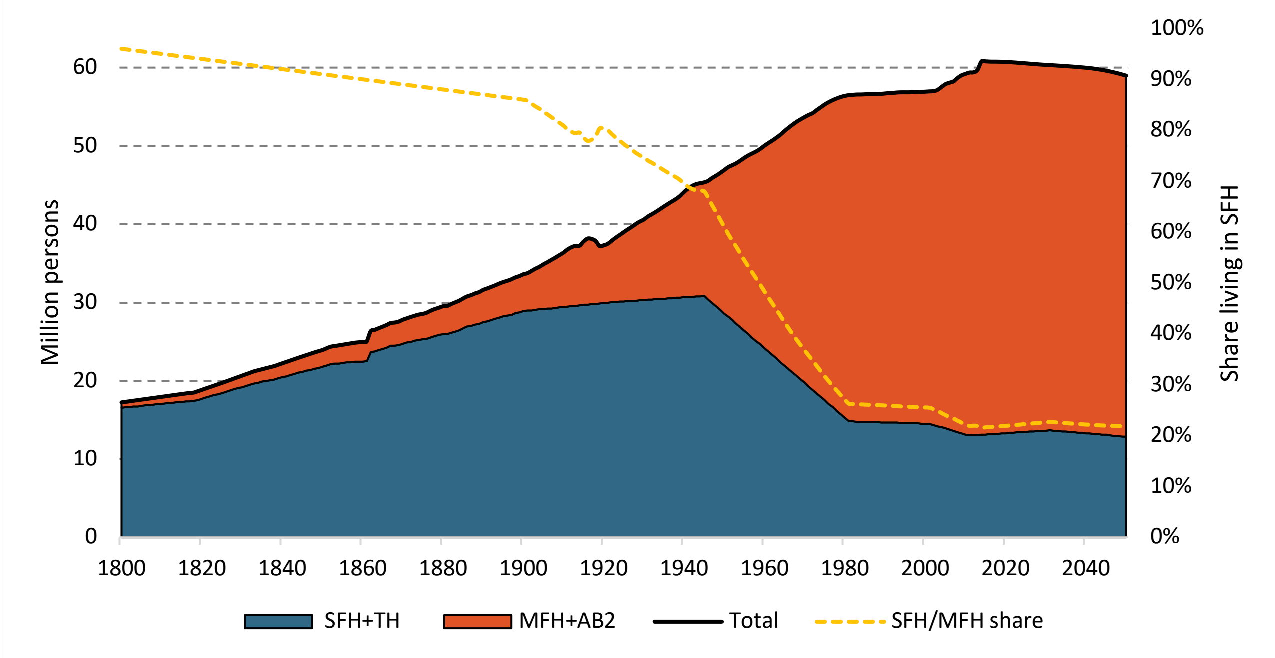
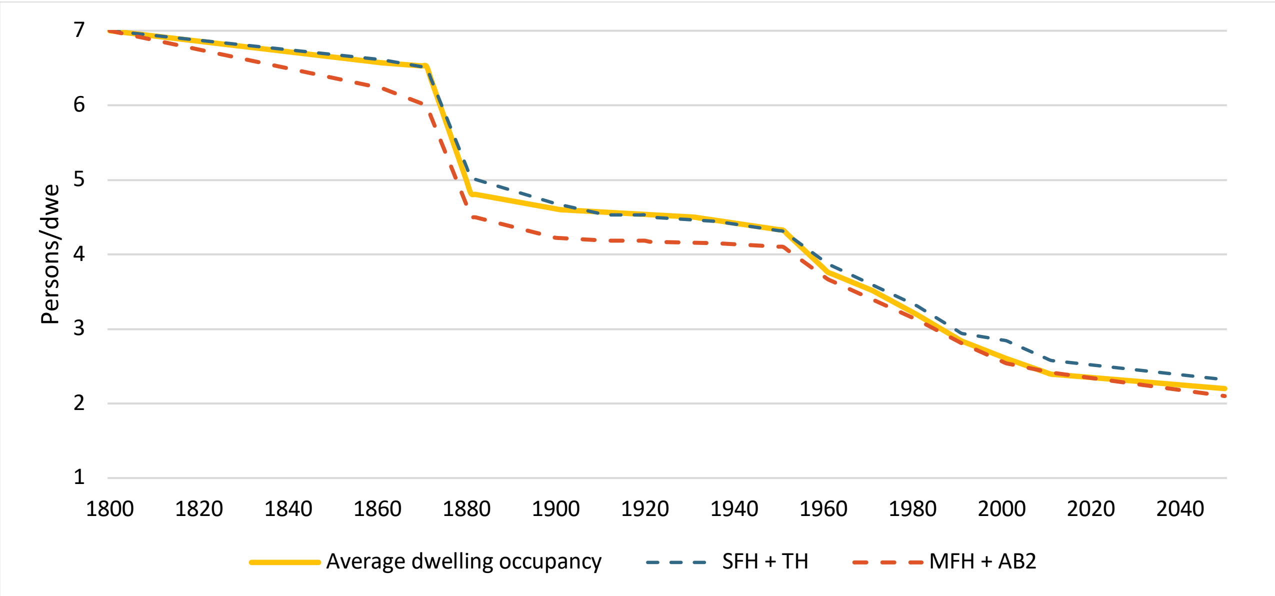


Figure 15. Development in persons per dwelling for the total stock and for each dwelling type. *Source: Own elaboration based on census data from ISTAT*



4.1.2 Construction, Demolition and Renovation

The construction activity depends in the first place on the lifetime of buildings. The lifetime probability function is assumed to follow a Weibull distribution defined by the parameters average lifetime per dwelling and the initial period after construction where the probability of demolition is zero, according to the recommendations in Sereda & Litvan (1978). The initial period after construction with no demolition, which corresponds to the Weibull location parameter, is assumed to be equal to one natural renovation cycle (R_c), or 40 years (Sandberg et al. 2017; Sartori et al. 2016). The average lifetime of dwellings is estimated at 125 years based on the several case studies presented in Sandberg and colleagues (2016) and model calibration; although values from literature where found to be significantly smaller. For instance, in a life-cycle assessment based on the real case study of an apartment block built in 1965, Blengini (2009) used the reported real life-time of only 40 years. In a more recent case, Vitale and colleagues (2017) assess the life-cycle performance of a typical residential MFH in South Italy to which they apply a life-time of 60 years. The model calibration was carried out by comparing the resulting shares of different age cohorts with those from available statistical data (2001-2011)The definition of the renovation activity in the model is case-specific. This study is based on the interpretation elaborated by Sandberg et al. (2014) where two renovation cycles with average time between renovation of 30 and 40 years were explored. In line with the estimation by Uihlein & Eder (2010), the 30 year cycle year cycle was identified with the replacement of construction elements such as windows or roofs while the 40 year cycle with the deep renovation of facades. Since only deep renovations are modelled in this study (all renovation options include interventions on windows, facades and technical systems), it follows that scenarios with a 30 years renovation cycle imply an anticipation of the natural cycle for deep renovations. As it was explained in **Chapter 3.1.2**, this will come with the economic backlash of operating outside a so called "window of opportunity". The model allows for flexibility on the choice for the starting of the different renovation periods. After calibration, in this study the beginning of the first and second renovation cycles were set to 1980 and 2020, respectively.

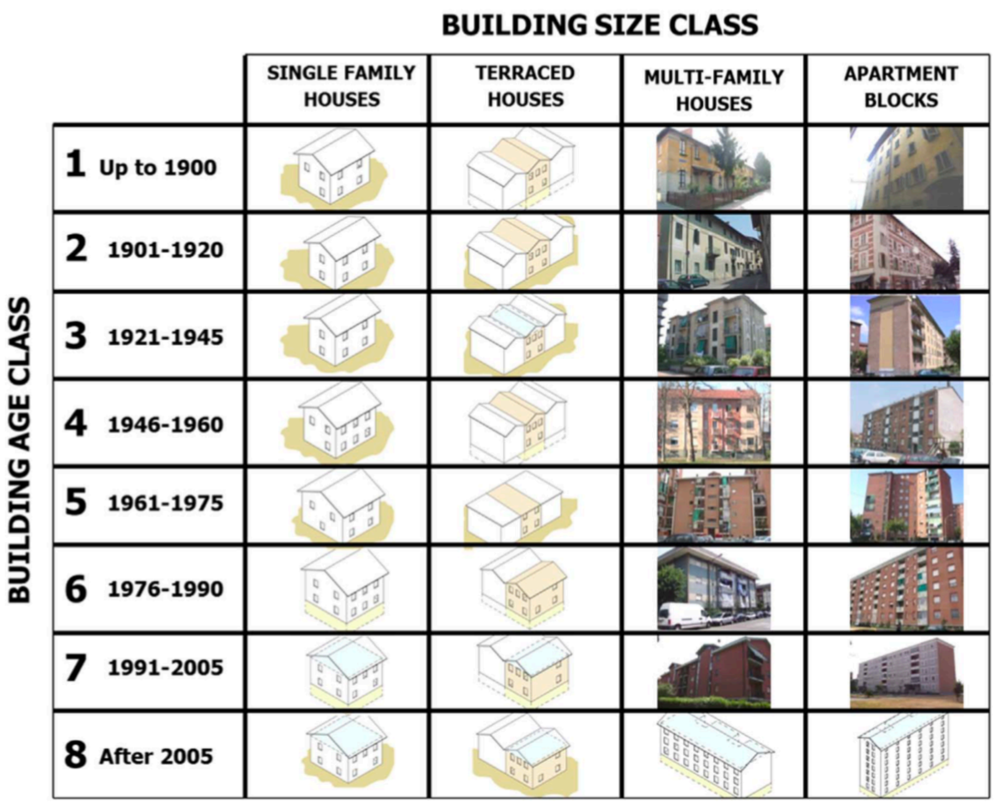
As reported in the UNESCO World Heritage List, Italy hosts 4.7% of the world architectural heritage, occupying 46% of the entire country. More specifically in terms of building heritage, over 4 of the 5,36 million worldwide monuments are located in Italy and there are many buildings built before 1919 that have public or residential use. As a result, existing historical buildings having residential function make up a non-negligible part of the Italian building stock and generally characterized by poor energy performance (Galatioto et al. 2017). Furthermore, the Italian legislation does not prescribe minimum performance requirements for historical buildings due to their "*historical protected status*". Based on the research by Galatioto and colleagues (2017) and by Ciulla and colleagues (2016), there are 1.2 million residential historical buildings, mostly identifiable with Terraced Houses (TH) and to a minor extend with Multi Family Houses (MFH). As of 2011, this represents 55% of the buildings constructed before 1919 and 9.8% of the whole RBS. Based on data from the MiBAC (Ministry of Cultural Patrimony Activity and Conservation), the estimated share of dwellings within these buildings that is never demolished is 3% for SFH and 9,5% for MFH (MiBAC, last accessed 22/01/19).

4.1.3 Dwelling Segments and Archetypes

The so-called "building typology" or "archetype" approach is a widespread concept and method at the basis of many building stock energy assessments. Its main application is for the evaluation of energy refurbishment strategies on existing buildings. In the IEE-TABULA project (Loga et al. 2014, 2016), an harmonized structure for National Building Typologies was established, presenting a set of model buildings (named "building types" or "average buildings") with characteristic energy-related properties forming a National Building Typology Matrix. This country-specific matrix has been used as a showcase for demonstrating the energy performance and the energy saving potentials which can be obtained by local, regional or national renovation programs focusing on the thermal envelope and the supply system. Two ambitions levels of renovation have been considered, *standard* and *advanced*, The demonstration calculations have been performed according to national technical specifications (UNI/TS 11300 series) reflecting the European technical standard EN 15316 series (European Committee for Standardization 2007b) and by showing the pre- and post-renovation energy performance (Ente Nazionale Italiano di Unificazione 2014a, 2014b, 2010, 2016a, 2016b).

In the original Italian Building Typology Matrix (**Figure 16**), the dwelling stock was segmented according to 4 size classes (types), 8 age classes (cohorts) and the most representative of the climate areas "E". Building types for the other Italian climatic areas are not directly available on TABULA, but were developed by Madonna & Vincenzo (2014) and by Capozza and colleagues (2014) as part of more in-depth studies. The decision of not incorporating specific typologies for each climate area is addressed in the model's imitation section (**Chapter 6.4**).

Figure 16. Italian "building typology matrix" for the middle climatic zone "E" with illustration of building types. "*ReEx*" approach illustrated with real image and "*SyAv*" approach illustrated with simplified volumetric Chapter. *Source: (Corrado, Ballarini, & Corgnati, 2014)*



Three different approaches to define the geometrical and the technical characteristics of each building type were devised ("*Real Example*", "*Real Average*" and "*Theoretical*"), resulting in 8 plausible combinations. When no statistical data is available, building types are prevalently chosen from a real building based on experience ("Real Example Buildings" or "*ReEx*") and are shown in the matrix by their actual picture. Building types entirely constructed from statistics ("Theoretical Buildings" or "*SyAv*") are instead illustrated through a simplified volumetric Chapter. A more detailed explanation of each approach and their application to build the Italian Typology matrix can be found in Ballarini, Corgnati, Corrado, & Talà (2011) and Corrado, Ballarini, & Corgnati (2014). Each of these segments consists of dwellings mainly having the same type of geometrical features, construction and supply technology and ownership. Similar renovation strategies or policy measures are therefore assumed to fit dwellings within each segment.

However, in order to fit the segmentation to the time horizon of this study, the age bands were slightly modified as follow:

- Class 1, from 1800 to 1920, representative of the XIX century;
- Class 2 from 1921 to 1945, between the two World Wars;
- Class 3, from 1946 to 1960, characterized by the Post-war and Reconstruction periods;

- Class 4, from 1961 to 1975, identified with the oil crisis period;
- Class 5, from 1976 to 1990, distinguished by the first building codes and laws concerning the energy performance of buildings (Decree 373/76);
- Class 6, from 1991 to 2005, characterized by more recent regulations concerning the energy performance of buildings (Decree 10/91);
- Class 7, from 2006 to 2020, represented by more stringent minimum performance requirements set out in the EPBD (Decree 192/05 and recast);
- Class 8, from 2021 to 2050, representative of the application of the EPBD recast requirements for new nZEB construction.

Cohort 1 spans over a long time period (1800-1920), yet large part of its dwellings is constructed between 1900 and 1920, with minor changes in either the thermal envelope or energy supply systems and thus resulting in rather homogeneous energy intensities. Moreover, as argued by Sandberg et al., 2017, energy use statistics are available only since 1960 and thus the long timespan of Cohort 1 is expected to not really affect the overall conclusions from the study. Each of the age cohorts is characterized by construction size classes, i.e. buildings with specific geometric and dimensional features:

- Single Family House (SFH), characterized by a single housing unit (dwelling), on 1 or 2 floors, detached or semi-detached and with a compactness ratio between 0.7-0.8;
- Terraced House (TH), characterized by a single housing unit (dwelling), on one or two floors, attached to other units on both sides except for the bordering units and with a compactness ratio between 0.5-0.6;
- Multi Family House (MFH), small-sized buildings characterized by a limited number of housing units (between 2-5 floors and 15 dwellings or 2-4 floors and 2-16 dwellings) and with a compactness ratio between 0.4-0.5;
- Apartment Blocks (AB), big-sized building characterized by an elevated number of housing units (>16 dwellings) and with a compactness ratio between 0.3-0.4.

For the analysis of development in heated floor area and energy demand, the aggregated "detached" and "compact" dwelling types are split into their subsegments based on statistics about their shares in each cohort in the 2011 stock. This was done by following the correspondence outlined above and using the number of apartments to differentiate MFH from AB and the contiguity to other buildings for distinguishing SFH from TH (Corrado and Ballarini 2016b). Using the compactness ratio to distinguish between building types would have provided more accurate results, however this would have only been possible using a cartographic layer or, alternatively, a regional EPC database (Pasetti 2016). These shares differ between the cohorts, but they are assumed to be constant within each cohort during the time period of the energy analysis. Average heated floor area per dwelling for each segment is presented in **Table 11** together with the other statistics. Data for cohort 1-7 are taken from TABULA and, according to the UNI/TS 11300-1 specification, the common reference floor area (conditioned floor area based on internal dimensions) was considered equal to the heated floor area (Corrado et al., 2014). The average heated floor area of cohort 0 is assumed to be equal to the values for cohort 1 for each dwelling type.

Table 11. Cohort definition, construction typology split (statistical values in bold) and average heated floor area per dwelling in each segment. *Source: own elaboration based on data from Corrado and Ballarini (2016) and Corrado et al. (2014)*

COHORT			**TYPE SPLIT**		**AVERAGE HEATED FLOOR AREA (m^2)**			
Cohort	**Start year**	**End year**	**Share of "detached" being SFH**	**Share of "compact" being MFH**	**SFH**	**TH**	**MFH**	**AB**
0	1800	1800	0.55	0.97	**139**	**123**	**110**	**56**
1	1801	1920	**0.55**	**0.87**	**115**	**112**	**69**	**61**
2	1921	1945	**0.62**	**0.78**	**116**	**113**	**49**	**64**
3	1946	1960	**0.73**	**0.70**	**162**	**111**	**68**	**62**
4	1961	1975	**0.81**	**0.65**	**156**	**89**	**79**	**61**
5	1976	1990	**0.86**	**0.71**	**199**	**125**	**86**	**64**
6	1991	2005	**0.89**	**0.75**	**172**	**111**	**63**	**77**
7	2006	2020	**0.85**	**0.74**	**174**	**127**	**64**	**68**
8	2021	2050	0.85	0.75	174	127	64	68

4.2 Energy Model

4.2.1 Energy Need Intensities

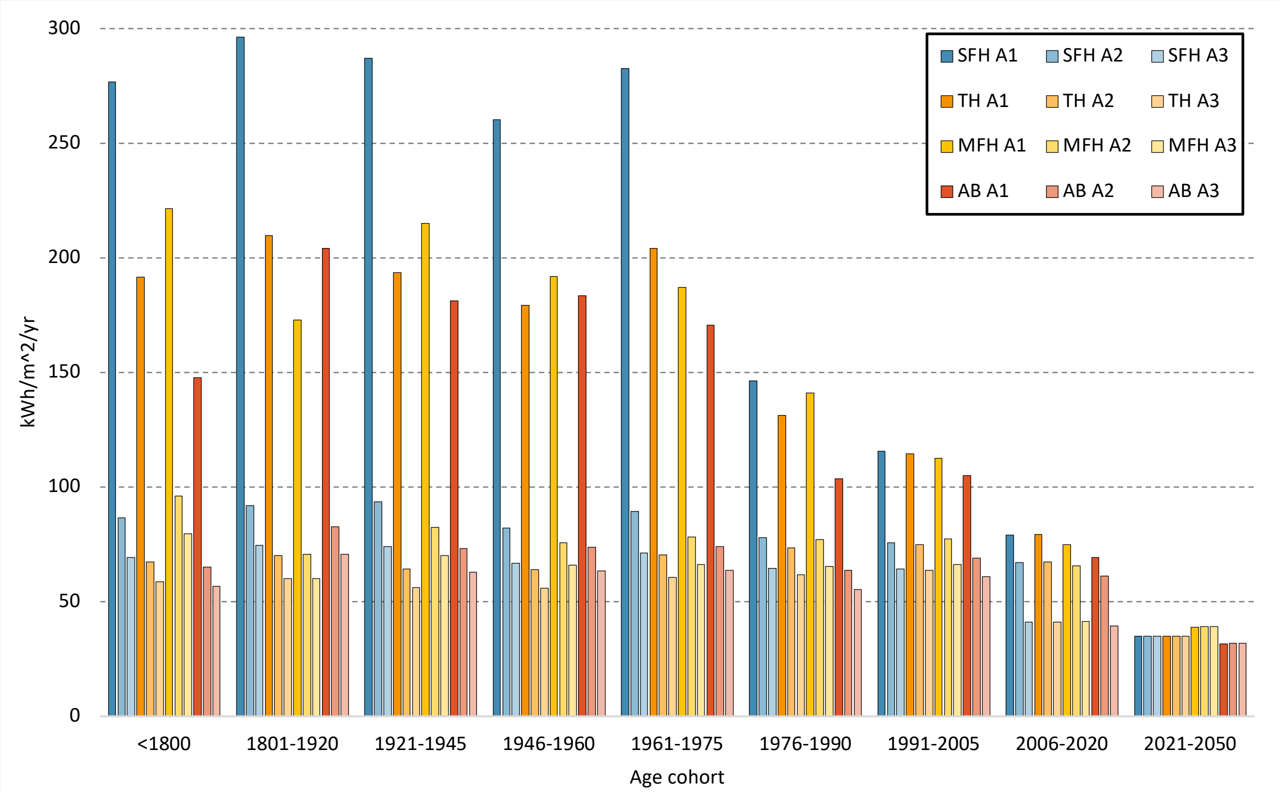
The segments defined by dwelling type and cohort are further distributed to archetypes by their renovation period, τ. The renovation period defines if and when a dwelling has gone through its most recent renovation. After the calibration process carried out by the authors of the model in previous publications, the start year of renovation is set to 1980. Dwellings in their original state and dwellings exposed to renovation prior to 1980 are in Renovation period 1, since the common renovation measures until then included EEMs only to a little degree. Further, it is assumed that since 1980 technology has been available so that inclusion of EEMs was possible whenever a dwelling was renovated. Dwellings renovated since 1980 are therefore placed in Renovation period 2. The baseline assumption - used in model calibration and in most of the scenarios - is that renovations in period 2 correspond to standard renovation, as defined in TABULA. Future renovation, characterized by state-of-art EEMs, makes dwellings move to archetype 3. For each "real building" or "theoretical building", the energy need, delivered energy and primary energy have been described in detail for each type/cohort/renovation variant combination and calculated according to the UNI/TS 11300 series and connected specifications (European Committee for Standardization 2007c, 2007d, 2007e, 2008; Ente Nazionale Italiano di Unificazione 2016c) (**Figure 17**).

The technical standard for new buildings constructed after 2020 (Cohort 8) was specified according to the updated cost-optimal levels for the building envelope of nZEBs as estimated by Corrado and colleagues (2014). No further improvements in the building envelope are assumed possible, and the energy need intensity of cohort 8 is therefore equal for all renovation variants. In the Italian typology, the energy need intensities range from up to 296kWh/m^2 in original state for single-family dwellings constructed between 1801-1920 (mostly between 1900-1920) to 32kWh/m^2 in future apartment dwellings constructed after 2020. The energy need intensity also changes from original state to standard or advanced renovation decreasing by up to 70% and 75%, respectively. Especially for older cohorts, the cost-optimal improvement between standard and deep renovation only marginally enhances the energy need of the building. This correctly suggests that, as a building moves towards a "nearly zero energy" state, the relevance of TBSs in improving the final energy performance compared to envelope insulation increases.

The TABULA model estimates the energy demand for space heating and DHW only and so too does the NTNU model. This requires accounting separately for the electricity-specific ("el-specific") energy demand, which is not always distributed across the different purposes in the historical statistics. Therefore, the el-specific demand has to be estimated based on the current data and trend extrapolation.

Based on the ODYSSEE database, in 2015 the average el-specific energy demand including Air Conditioning is estimated at 2204 kWh/dwelling and upwards from the 2001 kWh/dwelling of 1990 (ADEME 2018). Before that, based on an elaboration of the IEA energy balances, there was an estimated increase from 1088 kWh/dwelling in 1973 due to a strong penetration of electrical appliances (IEA 2017d). In lack of previous and future data, linear extrapolation of the trendline from 1973-2010 backwards gives a starting value of about 840 kWh. This was deemed more realistic than 360 kWh/dwelling obtained by extrapolating backwards only the 1990-1973 trend. Despite a considerable drop between 2012 and 2015, el-specific electricity demand is assumed to level-off at 2300 kWh/dwelling in 2050.

Figure 17. Energy need intensities per dwelling type, cohort and renovation variant (archetype-specific). *Source: own elaboration based on TABULA/EPISCOPE*

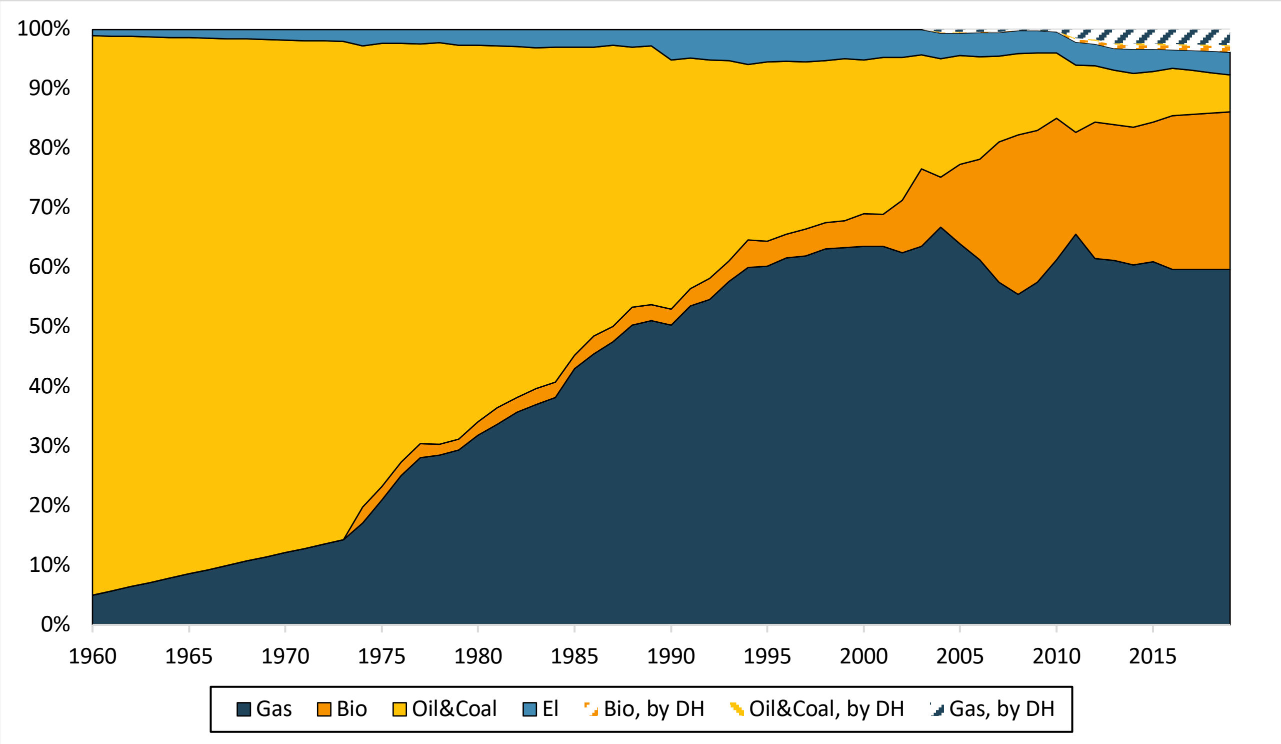


4.2.2 Energy Mix

Changes in the energy performance of buildings are not only due to technology changes in the thermal envelopes but can also result from shifts in the mix and increased use of local energy sources, which affect the conversion from energy need to delivered energy. Archetype-specific and time-dependent assumptions on energy mix as well as on use of local energy sources are used in the analysis. Unfortunately, the NTNU model currently allows to include only four energy carriers in the residential energy mix. Therefore, in order to still be able to account for all the fuels, consumption "by coal products" was aggregated with consumption by "oil products" (because of their similar historical downward trend and the fossil origin). The "oil products" category includes liquified petroleum gas (LPG) and diesel fuel, the shares of which are determined later in the report for estimation of an average CO_2 emission. Coal consumption for space heating, DHW and cooking accounted for only about 3% in 1973 and was completely phased out in 2012. Additionally, consumption "by derived heat" - which includes district heating and co-generation - was re-allocated into their primary energy carriers based on their fuel mixes during the 2004-2013 period. The use of secondary heat for residential purposes is also still very limited in Italy, contributing only 3.3% of the total energy mix in 2016. Almost the entire demand is supplied by district heating, of which 70% of the network capacity is concentrated in just three regions located in climate zone "E". In 2013, the network supplied an estimated 11,38 TWh, of which 64% for residential purposes and almost exclusively for DHW production (95%). The predominant fuel in the district heating energy mix is natural gas with more than 70% while RESs only account for 20% of the total (GSE 2016c).

Figure 18 shows the input time-series of the average energy mix for space heating, DHW and cooking in Italian dwellings from 1960 to 2016. This is the net energy mix used to cover the energy need for space heating and hot water that is not supplied by local RESs. The current energy mix is based on recent trends from statistics where the el-specific load is subtracted from the total to estimate the residual use of electricity for heating and hot water purposes. The historical development is known from the IEA energy balances and the ODYSSEE database for the 1974-1989 and 1990-2016 period, respectively (ADEME 2018; IEA 2017d). Due to the lack of detail in the time series published by ISTAT between 1960-1974, the residential energy mix was assumed to linearly converge to 1% of electricity, 5% natural gas and 94% oil products and coal in 1960 from the 1974 levels. The future development is partially based on the baseline scenario for the "civil sector" (including residential, service and agriculture sectors) by Gaeta et al. (2013), where the shares were modified to reflect only the evolution of the residential fuel mix.

Figure 18. Evolution of the residential energy mix for space heating, DHW and cooking, 1960-2019. *Source: IEA and ODYSSEE database.*



The energy mix is assumed to be constant across segments and archetypes. Segment-specific figures are only available as a result of statistical elaboration of regional EPC registers, the "Informative System for the Energy Certification of Buildings" (SICEE) and the "building cadastre register" (CENED) for Piedmont and Lombardy, respectively. Despite the two regions are the most representative of climate zone "E", it was decided to minimize the use of these two databases in that they are not representative of the average Italian context. For instance, the energy mix of the representative sample of buildings extracted from SICEE, showed that in Piedmont the use of natural gas is much more widespread compared to the reported national average.

4.2.3 System efficiency

System energy efficiency (η_{sys}) is defined as the weighted sum of all energy carrier-specific generation (η_{pr}) and distribution (η_{dis}) efficiencies. Therefore, it depends on both the efficiency of the heating/cooling technologies and the fuel their run on, but also the way there are distributed across the segments and whether they are combined with RES technologies. Altogether they determine the conversion from energy need to delivered energy according to the following equation:

$$DE_{ss,r} = \frac{EN_{ss,r} - HP_{ss,r}}{\eta_{pr_{ss,r,c}} * \eta_{dis_{ss,r,c}}} - PV_{ss,r}$$

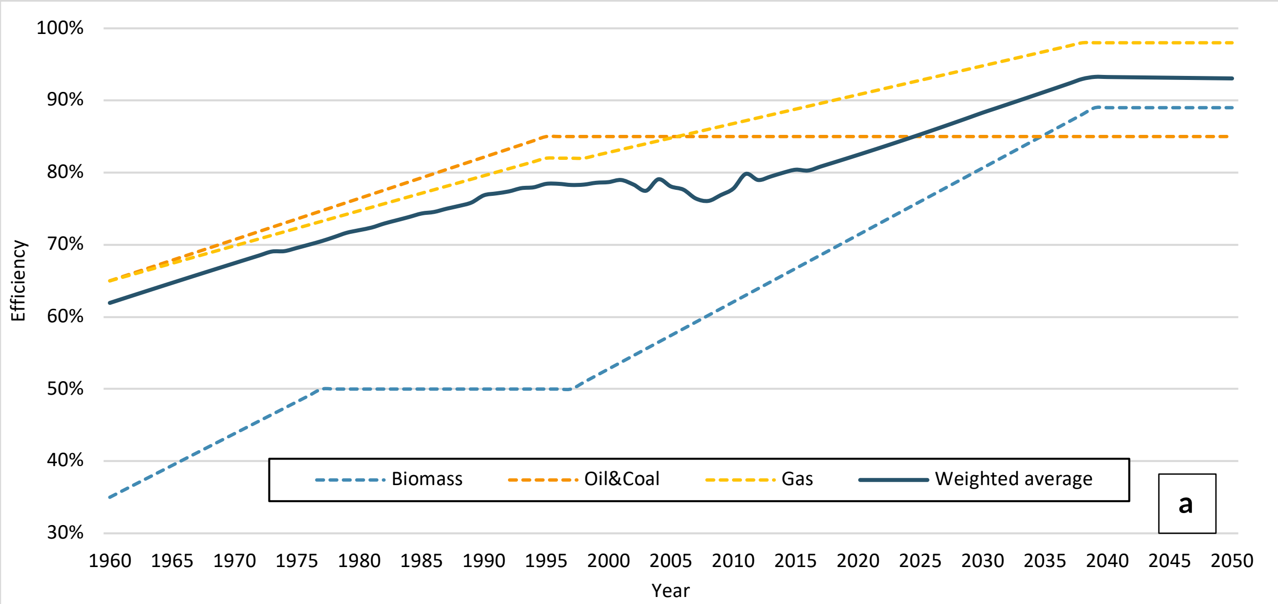
System efficiencies are estimated for each energy carrier, combined for space heating and DHW and based on the factors specified in the UNI/TS 11300-2 for oil and gas boilers and in the UNI/TS 11300-4 for biomass boilers (Corrado et al. 2014a). Production and internal distribution efficiencies are presented separately for SFH+TH and MFH+AB. Based on **Figure 3c**, apartment blocks were assumed to be heated for 75% by ICH and 25% by CCH. The room efficiency (η_{nem}) is not included as it would be improper to apply this factor when we also include DHW and cooking. Because segment-specific efficiencies are only reported since 1960, cohort 1 to 3 were grouped together under the assumption that they present similar production and distribution systems. **Table 12** summarises how $\eta_{sys_{int}}$ developed over time across dwelling types and segments.

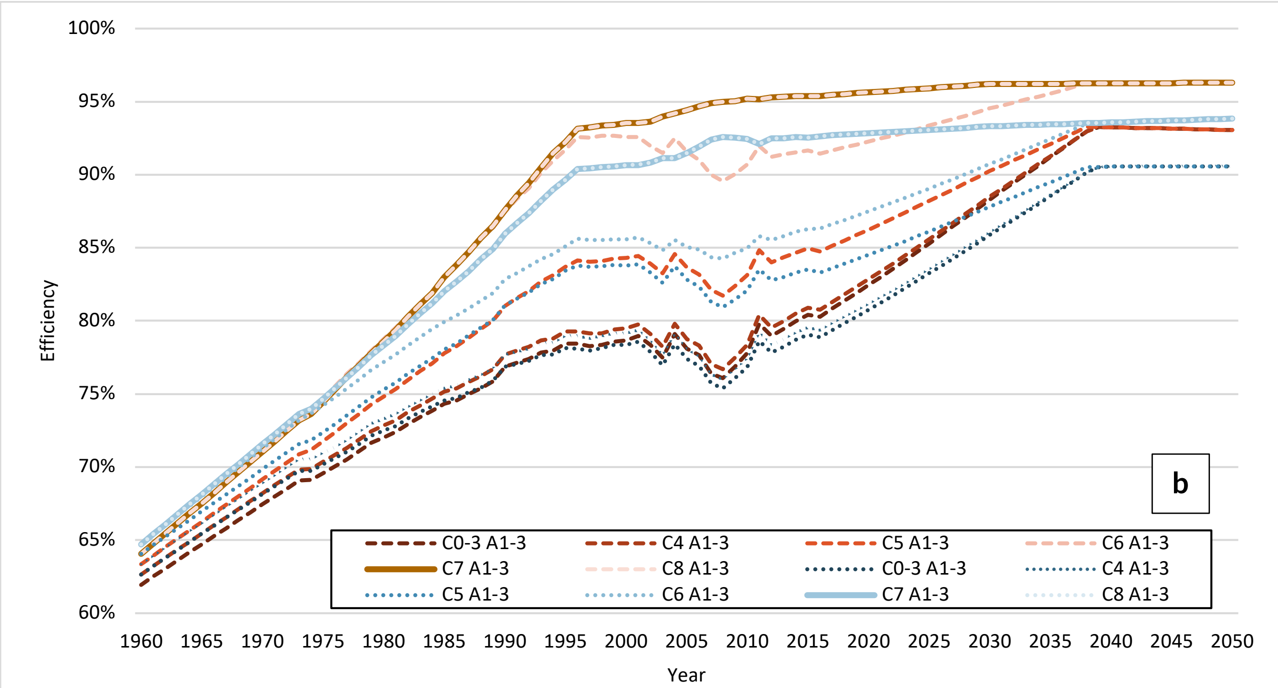
Table 12. Trend in weighted average system efficiency η_{sys} by dwelling type, segment and archetype, 1960-2050. *Source: Own elaboration*

Dwelling type		SFH + TH					MFH + AB				
Year	Segment	C0-3	C4	C5	C6	C7-8	C0-3	C4	C5	C6	C7-8
	Archetype	A1-3	A1-3	A1-3	A1-3	A1-3	A1-3	A1-3	A1-3	A1-3	A1-3
1960		0,619	0,626	0,634	0,641	0,641	0,626	0,634	0,641	0,647	0,647
1976		0,700	0,708	0,724	0,755	0,753	0,706	0,714	0,730	0,747	0,754
1995		0,780	0,788	0,833	0,914	0,921	0,777	0,785	0,831	0,848	0,895
1998		0,779	0,787	0,837	0,924	0,932	0,777	0,785	0,834	0,852	0,904
2006		0,773	0,780	0,829	0,908	0,946	0,766	0,773	0,821	0,847	0,919
2020		0,831	0,835	0,868	0,926	0,954	0,813	0,818	0,849	0,876	0,924
2038		0,928	0,928	0,929	0,954	0,954	0,897	0,898	0,900	0,924	0,924
2050		0,930	0,930	0,930	0,954	0,954	0,900	0,900	0,900	0,924	0,924

For electricity $\eta_{pr} = \eta_{dis_{int}} = 1$ for all years. For biomass, $\eta_{pr} = 0.35$ in 1960 for all types and cohorts and $\eta_{dis_{int}}$ ranging from 0.947 to 0.99 depending on dwelling type and cohort. For all distribution technologies, $\eta_{dis_{int}}$ is assumed to converge to its maximum for the dwelling type and cohort of reference within 2050. For traditional biomass boilers, $\eta_{pr} = 0.5$ for cohorts until 1977, $\eta_{pr} = 0.6$ for cohorts between 1979-1994 and $\eta_{pr} = 0.7$ for cohorts after 1995. Starting from 1998, the introduction of more efficient pellets stoves is assumed. After 1 renovation cycle, τ=40, in 2038, stoves in all dwelling type are assumed to have $\eta_{pr} = 0.88$ for cohorts 0-5 and $\eta_{pr} = 0.98$ for cohorts 6-8. For Oil&Coal, $\eta_{pr} = 0.65$ for all types and cohorts. Standard boilers for oil products are estimated to have an $\eta_{pr} = 0.85$ for cohorts until 1995 and $\eta_{pr} = 0.89$ after 1995 for both dwelling types. Finally, for natural gas $\eta_{pr} = 0.65$ in 1960 for all types. For standard gas-fired boilers in SFHs, $\eta_{pr} = 0.82$ for cohorts until 1995 and $\eta_{pr} = 0.88$ after 1995. For MFHs, $\eta_{pr} = 0.8$ and $\eta_{pr} = 0.86$. Starting from 1998, the introduction of condensing boiler is assumed so that, within 2038, boilers in SFHs all have $\eta_{pr} = 0.98$, while in MFHs, $\eta_{pr} = 0.88$ for cohorts 0-5 and $\eta_{pr} = 0.92$ for cohorts 6-8. Illustrative trends in weighted system efficiency are graphically represented in **Figure 19a and 19b**.

Figure 19. Example of development in η_{pr} for the different energy carriers and η_{sys} in segment C0-3 A1-3 (a). Comparison of development in weighted average system efficiencies η_{sys} for all segments (b). *Source: Own elaboration*





4.2.4 HP and PV Contributions

Energy supply from local RES is deemed key in all energy renovation strategies and thus is modelled separately for the two most promising technologies in the Italian context: Heat pumps (HPs) photovoltaics panels (PVs) (including solar heat collectors).

With HPs, it is intended any system that, by means of a compression cycle activated through an endothermic or electric motor, delivers heat for space heating or, if reversible, fresh air for cooling. The efficiency of an HP is given by its Coefficient of Performance (COP), which also defines whether the net energy produced can be considered renewable as prescribed by Directive 2009/28/CE. The net renewable contribution from HPs is obtained by subtracting the electricity needed to run the engine from the heat supplied. The net renewable contribution is defined by the dwelling type-specific weighted average COP minus 1. The net contribution from the surroundings is subtracted from the simulated energy need before the remaining energy need is converted to delivered energy by using the segment and time specific weighted system efficiency.

Exclusively heating and not cooling demands met by HPs can be considered as an effective renewable contribution to the energy needs of dwellings (GSE 2016a). The market diffusion tool developed within the ODYSSEE-MURE project shows that the share of Italian dwellings having HPs increased from 62% in 2011 to 75% in 2015. However, almost the entirety of this increase was due to sales of aerothermal or air-air HPs which are mostly used for cooling purposes and thus not classifiable as a RES contribution. According to the European Heat Pumps Association (EHPA), in 2016 the installed stock of HPs amounted to 1,5 million units (+13,3% compared to 2015) corresponding to a 6% ownership share for Italian households and roughly also dwellings (β_{fhp}). Of this stock, 86% are reversible air-air models with (potential) heating function (γ_{awh}) while the remaining 14% are other reversible models (γ_{ohp}). To account only for HPs having a primary space heating and/or DHW purpose, only a fraction of air-air HPs models is considered. An estimation by the EHPA (2010) on the basis of data from CRESME quantified the share of air-air HPs used as a part of an hybrid set-up (e.g. HP plus condensing boiler) at 23,4% and the share of HPs as primary device for heating at 9,5% of all air-air installations (β_{aph}). Combining these factors, in 2016 the final share of households using an HP primarily for space heating and/or DHW purposes amounts to 2,54%.

Put in simpler terms: "With about 25 million occupied dwellings and a 6% ownership share, roughly 1.5 million dwellings are equipped with a heat pump device. 210 thousand (1.5*0.14) can be considered as renewable models. Of the other 1.29 million, only 362 thousand (1.29*0.86*(0.23+0.095)) are not air conditioners and thus accounting as RES technologies. Therefore, total number of dwellings equipped with an HP considerable as renewable is 572 thousand, corresponding to 2,54% of the whole dwelling stock".

The penetration of HPs has been close to linear from 0% in 2003 to the reported share in 2016 (EHPA, 2019) but a faster uptake is expected during the 2020-2050 period (see **Chapters 4.4.3 and 4.4.4** for projections). The average COPs for air-air and for the other reversible models are 2.6 and 3, respectively (GSE 2016a). The increase in the share of households having HPs installed by dwelling type is estimated from the scenarios by Bernante et al. (2013) on the energy saving potential of HPs in Italy, yet differently no technological efficiency improvement is applied. Finally, in absence of reported data for Italy, the share of space heating demand covered by HPs is assumed to linearly increase from 20% to 60%. The equations below describe how the net share of energy need covered by HPs was calculated starting from the estimated share of dwellings having HPs (γ_{dwhp}), the share of energy need covered by HP (β_{hhp}) and the weighted average COP_{hp}:

$$\gamma_{dwhp_{ss,r}} = ((\gamma_{awh} * \beta_{aph}) + \gamma_{ohp}) * \beta_{fhp_{ss,r}}$$

$$COP_{hp} = \frac{(COP_{hp} * \alpha_{hp})}{\sum_{hp} COP_{hp}}$$

$$HP_{ss,r} = {(EN_{ss,r} * \gamma_{dwhp_{ss,r}} * \beta_{hhp} * (1 - COP_{hp}))}\Big/{EN_{ss,r}}$$

Table 13 summarizes the key parameters used for the estimation of the share of HPs and their assumed development towards 2050.

Table 13. Evolution of key parameters for the estimation of the share of dwellings equipped with HPs and the share of the energy need intensity covered by HPs, baseline scenario. *Source: Own elaboration*

Year / Parameter	γ_{awh}	β_{aph}	γ_{ohp}	$\beta_{fhp_{SFH}}$	$\beta_{fhp_{MFH}}$	$\gamma_{dwhp_{SFH}}$	$\gamma_{dwhp_{MFH}}$	β_{hhp}	COP_{hp}	HP_{SFH}	HP_{MFH}
2000	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.2**	**2.75**	**0.0**	**0.0**
2016	0.84	0.33	0.16	0.06	0.06	**0.025**	**0.025**	**0.2**	**2.75**	**0.009**	**0.009**
2030	0.75	0.40	0.25	0.195	0.15	**0.107**	**0.082**	**0.29**	**2.78**	**0.054**	**0.042**
2040	0.68	0.44	0.32	0.292	0.214	**0.183**	**0.134**	**0.34**	**2.80**	**0.114**	**0.083**
2050	0.6	0.5	0.4	0.389	0.278	**0.272**	**0.194**	**0.4**	**2.82**	**0.199**	**0.142**

Solar power in residential applications can either be in the form of photovoltaics (PV) panels for electricity generation or, alternatively, solar heat collectors for DHW production. The figures presented below incudes both these technologies. Differently from HPs, not data could be found on the number of PV installs per household requiring another estimation method. The only reported information available on the frequency of residential PV installations comes from regional EPC databases (SICEE and CENED databases): 0.5% of dwellings in the Piedmont sample and 8.3% in Lombardy (Corrado and Ballarini 2016b; CENED 2018). This discrepancy between the shares of two similar climatic regions (E) may indicate that the EPC samples are not representative enough of the average regional situation and hence cannot be used to estimate the share of dwellings having PVs. Moreover, taking two Northern regions as representative of the national situation would probably result in an overestimation of the installed power since small residential applications (<3 kW and 3kW-20kW) are generally more diffused in the Northern regions, despite the much lower solar irradiation (GSE 2016b). As of 2016, the GSE estimates the number of installations rated >3kW and 3kW-20kW at 245.000 and 422.000 units, respectively. The formers are usually found in SFHs and THs, while the latter are typical of larger MFHs and ABs. The equation used to estimate the share of dwelling in a specific year having PVs installs is the following:

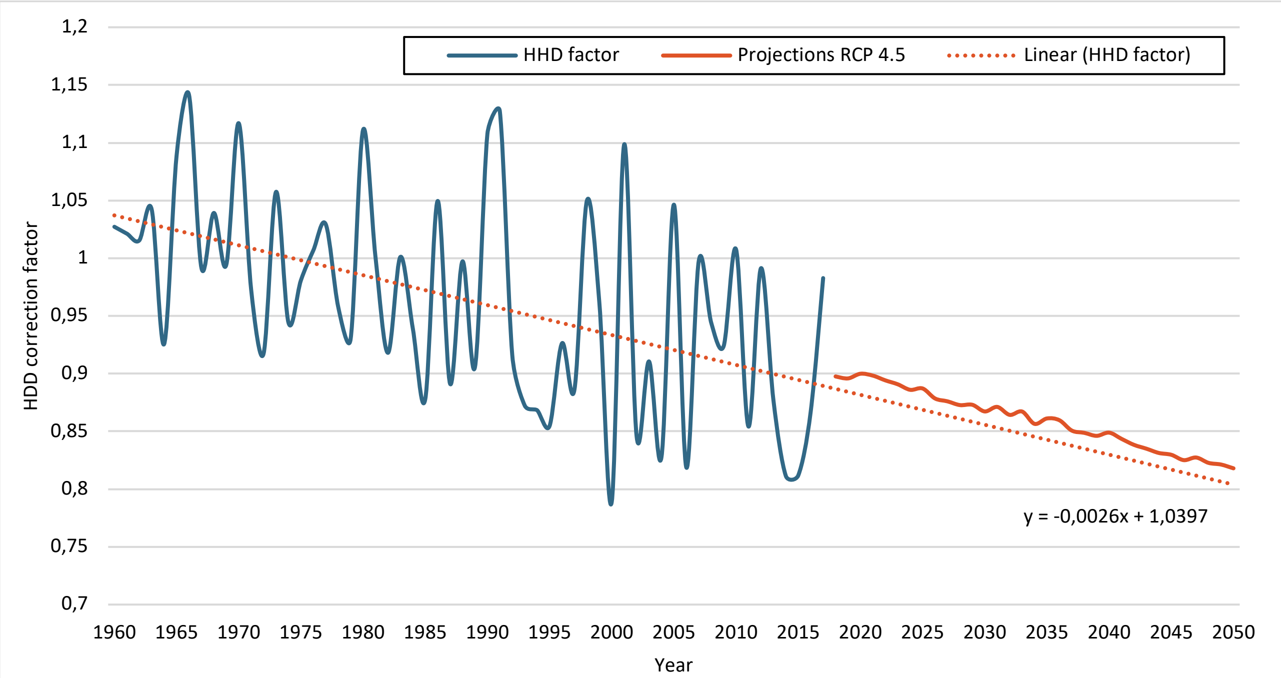
$$PV_{ss,r} = \frac{\gamma_{kw,s\prime}}{\left(\frac{SD_{s\prime}}{\alpha_{s\prime}}\right)}$$

Where $\gamma_{kw,ss,r}$ is the number of installations by power rate, $SD_{s\prime}$ is the number of dwellings by building type and $\alpha_{s\prime}$ the average number of dwellings per building served by the PVs and assuming an average conservative numbers of 1 dwelling per building for SFH and TH, 5 dwellings per MFH and 30 dwellings per AB ($\alpha_{ss,r}$). The estimated share of dwellings in SFH+TH and MFH+AB having PV installs in 2016 amounts to 4.7% and 14.3%, respectively. The 2008-2017 reports by GSE on the state of PV installations in Italy were used to develop the input time-series by assuming an S-shaped growth (**Chapters 3.4.2 and 3.4.3** for projections) towards 2050 in both the baseline and extensive use assumptions. Finally, the segment-specific average generation intensities are taken from the TABULA renovation variants by Corrado & Corgnati (2014) and no efficiency improvement over time is assumed. The underlying assumption in TABULA is that 40% of the footprint area of the building is covered by PV. Cohort 0 and 8 values for each dwelling type are assumed to be equal to the cohort 1 and 7 values, respectively.

4.2.5 Climate factors

The simulated delivered energy for heating needs to be corrected for historical and inter-regional climate effects. The first refers to corrections for year-to-year fluctuations in outdoor temperatures which can introduce errors in the comparison of historical trends. The Heating Degree Days (HDD) method is then used to normalize the delivered energy to the so-called “normal climate”, allowing for better comparison with statistical values. The yearly HDD values for Italy are taken from Eurostat for the 1973-2017 and calculated for each year based on monthly temperature data from ISTAT for the 1960-1973 period (Eurostat 2017; ISTAT 2017). The yearly HDD is divided by the average from the reference period assumed in the calculation of the energy intensities (e.g. 1961-1990). **Figure 20** displays the time-series for the final HDD correction factor, including the projections based on the RCP 4.5 degrees scenario by the IPCC.

Figure 20. HHD correction factor development with linear trendline. T_base = 18 degrees. Normal year: average 1961-1990. *Source: own elaboration based on EUROSTAT, ISTAT and RCP 4.5 data*



Italy is divided into 5 climate zones and the region of reference for this analysis is climate zone “E”, characterized by yearly HDDs in the 2101-3001 range. This is considerably more than the national average. Because, as explained in **Chapter 4.1.3**, it was preferred not to model each climate area individually, it becomes extremely important to develop a second climate adaptation factor that corrects for inter-regional differences in temperature. Based on a study from the Italian Institute for Environmental Protection and Research (ISPRA 2017), a population-weighted average HDD time series by climate zone for the 2003-2015 period was used to observation period establish the correction factor for zone “E”. The weighted average of the HDDs for all climatic zones over the was found to be 56.3% lower than for the area “E” climate. After model calibration, the value changed to 66.3% Assuming that the yearly variations in the “E” climate are representative for the whole country, the yearly delivered energy for heating based on climate area “E” is multiplied by 0.6631 to correct for the climatic differences within the country.

4.3 Environmentally-extended Economic Model

4.3.1 Renovation and Energy Costs

The main sources used to build the determine the cost of EEMs are regional price lists (DEI 2012, 2011), Annex A of the EN 15459 (European Committee for Standardization 2007a) and detailed national reports such as the ones by Capozza et al. (2014) and Corrado, Ballarini, Ottati, et al. (2014) for data integration and validation. The financial evaluation was carried out for both the cases of access to support schemes or not. To keep the estimates on the conservative side, of the available national support schemes (e.g. white certificates or Conto Termico) only the EcoBonus was considered. Since 2014 this incentive offers up to 65% tax relief (55% between 2011-2014) on some eligible buildings-related EEMs. EEMs included in the scenarios were modelled for the largest part as to fulfill the eligibility criteria and thus, for simplification, they are all assumed to be eligible for the tax reduction. Additionally, a 50% tax relief on basic renovation interventions (non-energy related) also applies, in this case to the indirect costs.

Because of the complexity of estimating indirect costs from individual items in the price lists, the population-weighted average of the basic intervention costs estimated by Capozza and colleagues (2014) for 5 Italian climatic areas are used instead. The labor costs related to workforce are expressed as a percentage of the basic price for the direct interventions. For the indirect costs related to workforce, a fixed percentage of 30% over the total was assumed. It should be noted that, while in case of a "window of opportunity" the indirect costs are neglected from the financial perspective, from the macroeconomic standpoint they are still accountable regardless of the final cost for the investor. The labor costs related to consulting activities are expressed as a percentage on the initial investment and specified for SFH+TH and for MFH+AB. Taxes on construction works, workforce and consulting services are fixed at 10%, 22% and 4% of the initial investment, respectively. Disposal and annual costs are all expressed as percentages of the initial investment costs as specified in Annex A of the EN 15459 (European Committee for Standardization 2011). Similarly to Ballarini et al. (2017a), no price development rate in real terms has been assumed for any other prices rather than the energy ones. **Table 14** presents an overview of all cost categories with related sources.

Table 14. Summary table of the cost items/performances with sources. *Source: own elaboration*

Cost Category	Item/Performance	Cost/Factor	Lifetime	Note	Source
Construction (direct)	Opaque envelope	Item-specific	50	of basic price and % of workforce	DEI (2012, 2011) for **prices** EN 15459 (2007e) for **lifetime**
	Transparent envelope	Item-specific	30		
	Condensing boiler	Item-specific	20		
	Heat pump	Item-specific	15-20		
	Solar heat collectors	Item-specific	20		
	Photovoltaics panels	Item-specific	20		
Construction (indirect)	Envelope and technical systems	Segment-specific	–	Reported value with assumed 30% share of workforce	(Capozza et al. 2014)
Labor	Workforce	Item-specific	–	Expressed as % on basic prices	DEI (2012, 2011)
	Consulting	SFH+TFH 16% MFH+AB 13%	–	Expressed as % on total initial investment (taxes excl.)	(Capozza et al. 2014)

Taxes	Construction	10%		–	Expressed as % on construction costs	
	Labor	Workforce 22%	Consulting 4%	–	Expressed as % on labour costs	
Disposal	Envelope	30%		Expressed as % of initial investment (taxes excl.). Discounted in case of lifetime > accounting period		
	Technical systems	15%				
Replacement	Envelope and technical systems	Item-specific		Depend on average lifetime of EEM. Determinant of residual value if lifetime > accounting period		(Atanasiu et al. 2013; EN 15459 2007e)
Maintenance and Operation	Condensing boiler	15%		Annual preventive maintenance including operation, repair and servicing costs in % of the initial investment		
	Heat pump	30%				
	Solar heat collectors and photovoltaics panels	1%				
Subsidies	On direct construction costs	2010-2014 55%	2014-2050 65%	–	All EEMs assumed to be eligible at same level	(ENEA 2018)
	On indirect construction costs	2010-2050 50%		–	Applicable also outside "window of opportunity"	

Together with the costs of EEMs, energy prices determine the financial and global costs of single EEMs and renovation packages. The main expected benefit from EEMs adoption in the residential context is a reduction in energy consumption and, consequently, some saving on households' energy expenditure compared to a Baseline case or compared to not taking action at all. The energy bill of a dwelling depends on the energy consumption pre- and post-intervention which is estimated by the energy model as well as on the fuel prices and their development over time and therefore is segment and scenario specific. For the sake of simplicity, only prices for the four most widespread energy carriers were considered, namely natural gas, biomass, petroleum products and electricity. **Table 15** summarizes the average price per kWh for all the considered energy carriers plus the estimated cost of CO_2. The procedure for the estimation of building typology specific prices for electricity and natural gas can be found in the **Appendices.**

Table 15. Overview of average energy prices in €2010 per unit and kWh. *Source: own elaboration based on data from ARERA (2018) for electricity and natural gas and Virdis et al. (2017) for oil products and biomass*

Energy carrier		UM	Average price per unit: 2010 share	Basic price SFH	Basic price MFH	Taxes SFH	Taxes MFH	LHV (kWh/unit)	Average price per kWh SFH+TH	Average price per kWh MFH+AB	Source
Natural gas		€/Sm³	–	0.527	0.489	0.339	0.276	9.58	**0.09**	**0.08**	Own elaboration based on ARERA (2018)
Oil products	LPG	€/kg	41%*	1.83		0.517		12.8	**0.154**		(Virdis et al. 2017)
	Diesel Fuel	€/lt	59%*	0.488		0.811		9.88			
Biomass	Wood	€/kg	50%**	0.229		0.0638		4.02	**0.05**		(Virdis et al. 2017)
	Pellet	€/kg	50%**	0.112		0.0246		4.80			
Electricity		€/kWh	–	0.191	0.12	0.021	0.014	–	**0.213**	**0.134**	Own elaboration based on ARERA (2018)

CO_2	€/ton	–	10.7	–	–	(Gaeta et al. 2013)

NOTE: *Based on 2010 IEA energy balance
**Based on s2010 tock of appliances

Energy prices are initially taken in €2010 prices, estimated to 2020 using the price development rates in **Table 16**. For the financial and global cost calculations, costs were first discounted over the 30 years accounting period using real price development rates and then expressed in constant 2020€. **Table 16** summarizes the key financial parameters of price development rates which constitutes an important, yet very uncertain part especially beyond 2050.

Table 16. Summary of key financial assumptions. *Source: Own elaboration*

Parameter	Financial perspective		Macroeconomic perspective		Source
Real interest rate (R_R)	4%		3.5%		(Corrado et al. 2014b; Ferrara et al. 2018)
Cost development for electricity (R_{E_e})	2010-2020	2020-2030	2030-2050	2050-2080	(Capozza et al. 2014; Gaeta et al. 2013)
	+2,71%	0%	-0,09%	Assumed continuation of trends	
Cost development for natural gas (R_{E_g})	+6,23%	+0.49%	-0,58%		
Cost development for oil products (R_{E_oc})	+4,75%	+0.52%	+0,91%		
Cost development for biomass (R_{E_b})	Constant ($R_{E\_b} = R_i$)				
Cost development of CO_2 (R_{Ca})	+6,26%	+7,70%	+3,50	Assumed continuation of trends	(Gaeta et al. 2013)
Cost development for other cost categories (R_P)	Price of products constant ($R_P = R_i$). For renovation costs constant growth between estimated values for 2020 and 2050 (Figure 27)				–
Time horizon (τ)	30 years				(Ferrara et al. 2018)

Another important step in the calculation of energy savings is the conversion of technical delivered energy into primary energy by means of primary energy conversion factors. While technical delivered energy defines the energy efficiency within a building's boundaries at the net of contributions from RES, primary energy takes into account also the efficiency of the electricity generation and distribution infrastructure. This is particularly important to account for generation and distribution losses in the electricity system. **Table 17** summarizes the latest official primary energy conversions factor for Italy 2016 taken from the national report for the Concerted Action EPBD initiative (Costanzo et al. 2016). ***Note that all model's results and the figures in the indicators dashboard are expressed in terms of delivered energy while primary energy factors are only applied for the estimation of the life-cycle impacts through IOA.***

Table 17. Primary energy conversion factors for the Italian energy mix in 2016, by energy carrier. *Source: Costanzo et al. (2016)*

Energy Carrier	$f_{P,\,nren}$	$f_{P,\,ren}$	$f_{P,\,tot}$
Natural Gas	1.05	0	1.05
LPG	1.05	0	1.05
Solid biofuels	0.3	0.7	1
Diesel fuel and fuel oil	1.07	0	1.07
Coal	1.1	0	1.1
Electricity*	1.95	0.47	2.42
Thermal energy from solar collectors	0	1	1
Electricity from PVs	0	1	1
Geo-, aero-, hydrothermal energy	0	1	1

District heating	1.5	0	1.5

* Because the electricity mix is known by individual energy carrier, a 1.95 factor is applied to electricity by non-renewable sources, 0.3 to electricity by biomass and 0 for electricity by other RES.

In mathematical terms, the unit energy expenditure represents one of the annual cost items contained in the $(Ca_{(i)} * f_{pv_{(i)}})$ expression and it is estimated by the following set of equations:

$$Ce_{ss,c,i} = De_{ss,c,i} * \ Pef_c * \rho_{ss,c} * \ f_{pv_{(i)}}$$

$$Ce_{s',i} = \sum_c \sum_{ss} Ce_{ss,c,i}$$

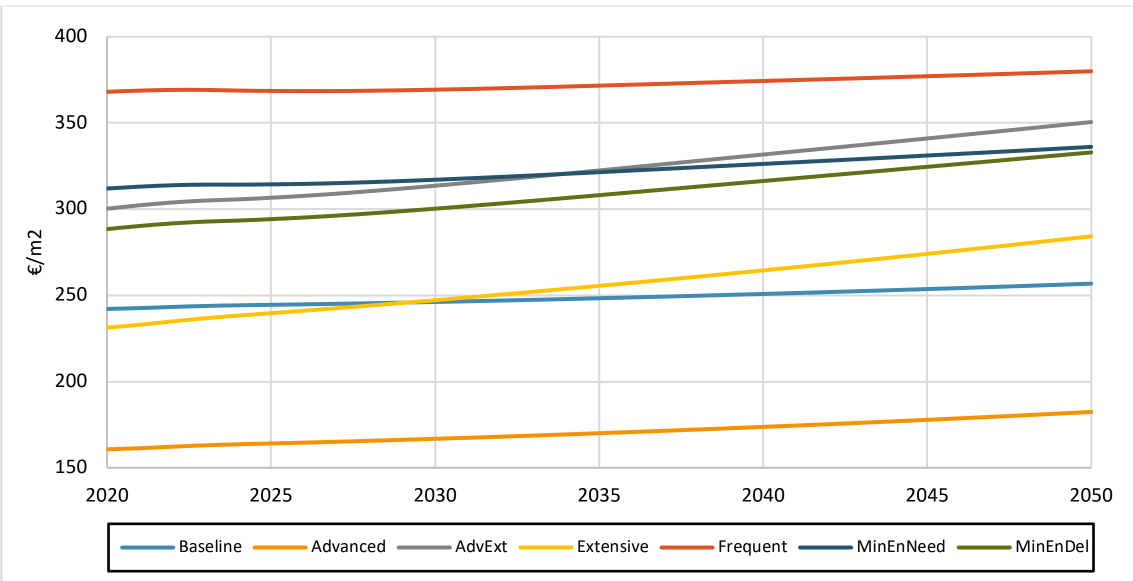
Where Pef_c is the primary energy conversion factor for energy carrier c and assumed to be constant, $De_{i,ss,c}$ is the delivered unit energy consumption (kWh/m[2]/year) of subsegment ss by energy carrier c in year i, $\rho_{i,ss,c}$ is the price (€/kWh) of energy carrier c for subsegment ss and $f_{pv_{(i)}}$ is the present value factor in year i (for more information refer to section C in the **Appendices**). The unit energy savings compared to the Baseline scenario can then be simply calculated as:

$$\Delta Ce_{s',i} = Ce_{s',i}^{scenario} - Ce_{s',i}^{baseline}$$

$$\Delta Ce_i = \sum_{s'} Ce_{s',i}$$

The development of renovation costs (both financial and global) is based on constant growth between estimated values for 2020 and 2050 for each segment. The estimation procedure used: (i) the energy mix and energy efficiencies of each segment, (ii) the share of dwellings having HPs or PVs installed and (iii) the shares of renovated segment (e.g. C3-A3) within the renovated stock after 2020 (A3) as constraints to manually allocate the technologies across different segments. This way, the technological mixes that - for each scenario - best match the 2020 and 2050 model's inputs/outputs are defined, and their costs estimated. Due to the lack of time for developing an automated procedure to repeat this for every year, constant growth is assumed for the data points in between, resulting in the weighted average unit cost development shown in **Figure 21.**

Figure 21. Weighted average financial costs of renovation for each scenario (at the net of subsidies and residual value), 2020-2050 period. *Source: Own elaboration*



4.3.2 Input-Output Framework

In this study, a simplified 2 regions system distinguishing between Italy (IT) and the Rest of the World (RoW) is employed. The aggregation procedure follows the same mathematical formulation as the one proposed by Donati (2017) and it is not reported here for conciseness. The selected system is represented in the form of a *symmetrical product-by-product table given in 2010 current prices*. Because the focus of this analysis is not on quantifying emissions embodied in trade, all economic transactions and impacts related to the renovation investment are assumed to take place in Italy.

In order to estimate the impacts associated with the renovation investments, a correspondence between the cost categories in **Table 14** and the EXIOBASE products needs to be established. This represents the connection between the renovation investment matrix and the IOT and allows to identify the economic products directly involved in:

- The production and installation of EEMs components;
- The reduction in energy generation;
- Al of the ancillary activities such as consulting and disposal activities.

The correspondence table is based on the work by Oliveira and colleagues (2014), Henriques and colleagues (2015) and Cellura and colleagues (2013) and it is complemented by own assumptions based consultation of the PRODCOM product classification. **Table 18** lists the activity-to-product allocation factors (not considering the expected weight of each renovation investment on the overall level of household final demand input).

Table 18. Action-sector correspondence tables with specification of allocation factors. *Source: own elaboration*

Activity	Allocation factor	Product	Product code
Production of walls insulation (assumed to be entirely XPS, no rockwool)	90%	Chemicals nec	p24.d
	4%	Wholesale trade services	p51
	6%	Retail trade services	p52
Production of window (glaze+ frame) (argon-filled double/triple glazed windows with PVC or aluminum frames)	45%	Rubber and plastic products	p25
	45%	Fabricated metal products	p28
	5%	Chemicals nec	p24.d
	2%	Wholesale trade services	p51
	3%	Retail trade services	p52
Production of condensing boilers	90%	Machinery and equipment n.e.c.	p29
	4%	Wholesale trade services	p51
	6%	Retail trade services	p52
Production of heat pumps, solar heat collectors and PV panels	90%	Electrical machinery and apparatus	p31
	4%	Wholesale trade services	p51
	6%	Retail trade services	p52
Installation of wall insulation and technical building systems	100%	Construction work	p45
Procedure to obtain tax reduction and general architectural/engineering consultancy	100%	Real Estate services	p70
Disposal of building envelope elements	50%	Incineration of waste: Metals and Inert materials	p90.1.d
	50%	Landfill of waste: Inert/metal/hazardous	p90.5.d
Disposal of technical building systems	25%	Incineration of waste: Metals and Inert materials	p90.1.d
	75%	Landfill of waste: Inert/metal/hazardous	p90.5.d
Energy expenditure on natural gas	100%	Distribution services of gaseous fuels through mains	p40.2.1
Energy expenditure on oil products	40%	Gas/Diesel Oil	p23.20.f

	60%	Liquefied Petroleum Gases (LPG)	p23.20.i
Energy expenditure on electricity (dependent on evolution of electricity mix)	100%	Electricity by various carriers	p40.11.a-l
Energy expenditure on biomass	100%	Wood and products of wood	p20

Once the cost categories are mapped to the EXIOBASE products, the expected weight of each renovation investment on the overall level of household expenditure on that sector needs to be estimated. This is quite a hard task in that it requires to determine how much of the household expenditure on, for instance fabricated metal products, was spent on renovation activities and it done by applying end-use coefficients. Therefore, end-use coefficients are used to isolate the portion of household final demand for a product that is related to a specific use being investigated, in this case renovation activity and purchases of energy products. **Table 19** lists the end-use coefficients applied in this study together with a short explanation of how they were derived.

Table 19. Renovation and energy end-use coefficients for household final demand. *Source: Own elaboration*

EXIOBASE product code	Product name	Corresponded product/activity	End-use coefficient	Estimation method
p20	Wood and products of wood (excl. forniture	Biomass for residential combustion	0.96 * 0.5 = **0.48**	Share of use in residential excluding cooking (from statistics) * share of use in residential over total use (assumption)
p23.20.f and p23.20.i	Gas Oil/Diesel/LPG	Petroleum products for residential combustion	0.79 * 0.1 = **0.079**	
p24.d	Chemical nec	Product used in renovation activity (insulation, window frames, TBSs,..)	**0.5**	Assumed values
p25	Rubber and plastic products			
p28	Fabricated metal products			
p30	Machinery and equipment			
p31	Electrical machinery and equipment			
p40.11.a-l	Electricity by different carriers	Electricity for residential uses	0.8 * 0.085 = **0.065**	Share of use in residential excluding cooking (from statistics) * share of use in residential over total electricity use (from statistics)
p40.2.1	Distribution services of Gas	Natural gas for residential uses	0.92 * 1 = **0.92**	Share of use in residential excluding cooking (from statistics) * share of use in residential over total use (assumption)
p45	Construction works	Labour part of renovation activity	**0.82**	Share of renovation in total construction output (EUROCONSTRUCT, 2015)
p51	Wholesale trade	Wholesale trade	**0.5**	Assumed value
p52	Retail trade	Retail trade	**0.05**	Assumed value after investment/final demand check
p90.1.d	Inert, metal, hazardous waste: incineration	EOL of renovation products	**0.5**	Assumed values
p90.5.d	Inert, metal, hazardous waste: landfill			

Applying the generalized equations of **Chapter 3.2.2**, the change in final demand for a specific year can be calculated by the following equations:

$$\alpha_{s',c,i} = \frac{(DE_{s',c,i}^{scenario} - DE_{s',c,i}^{baseline})}{DE_{s',c,i}^{baseline}}$$

$$\Delta y_{en}(s',c,i) = \alpha_{s',c,i} * Pef_c * \delta_c * y_c$$

$$\Delta y_{en}(c,i) = \sum_{s'} \Delta y_{en}(s',c,i)$$

$$\Delta y_{ren}(c,i) = \sum_{s'} (RI_{s,',ci}^{scenario} - RI_{c,i}^{baseline}) * \delta_c$$

Where $\alpha_{\tau,i}$ is the coefficient of relative impact, Pef_i is the primary energy factor for energy product i, δ_i is the end-use coefficient for product i, and y_i is the vector of final demand from household. In the renovation equation, $(RI_{\tau,i}^{scenario} - RI_{\tau,i}^{baseline})$ represent the scenario-specific marginal investment for renovation. Therefore, the change in final demand for the energy and renovation activities are calculated in slightly different ways: For energy, it is based on physical energy quantities (GWh/yr) rather than monetary. These are used to determine, for each year, a coefficient of relative impact $\alpha_{\tau,i}$ under the assumption that the impacts of the Baseline scenario are null. The difference between the Baseline impacts and those of other scenarios represents the impact of that scenario. The primary energy conversion factors Pef_i and end-use coefficients vectors δ_i ensure that the right energy quantities are applied to the right portion of household final demand. Finally, the resulting coefficient is multiplied by the household final demand vector y_i to determine the value in monetary units. For renovation, a simpler approach based on just the marginal investment compared to the Baseline and the vector of end-use coefficients is used. The impacts resulting from the change in final demand – whether they are in terms of GHG emissions, employment or embodied energy - can then be quantified by the following set of equations.

$$b'_{hh}(i) = \sum_{i} DE_{i,c} * Pef_c * \partial_c$$

$$\Delta r_{en}(i) = b' \, L \, \Delta y_{en}(i) + b_{hh}(i)$$

$$\Delta r_{ren}(i) = b' \, L \, \Delta y_{ren}(i)$$

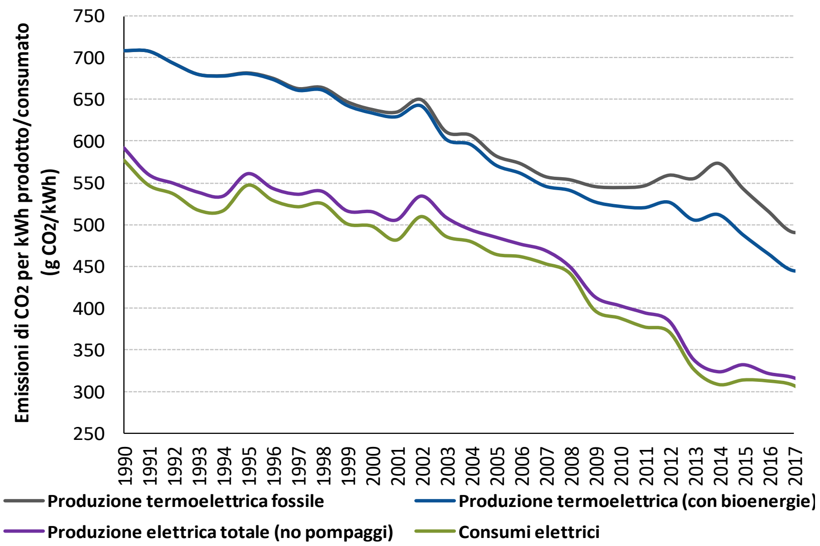
Where b'_{en} is a custom-made direct impact vector of which the i-th element shows the total direct impact by household for category i. *Note that the direct impact vector is used only for the estimation of GHG emissions from direct combustion of fossil fuels and electricity consumption and it is estimated by applying energy carrier specific characterized emissions factors to the scenario specific primary energy demands*. The terminology introduced by the GHG protocol is used to classifiy the different emission "*Scopes*", namely: direct combustion of fuels (*Scope 1*) and purchase and consumption of electricity (*Scope 2*) both included in b'_{en}; and upstream and downstream economy-wide emissions related to the purchase of all energy products (*Scope 3*) estimated by the following expression $b' \, L \, \Delta y_{en}$ (Pankaj et al. 2011). For the renovation activity, the terminology *direct* and *upstream* emissions is used instead where direct emissions correspond, in technical terms, to *"first layer"* emissions. Direct impacts related to on-site fuel combustion during the renovation activity are deemed negligible and thus neglected. The characterization of emission factors is based on the life-cycle impact assessment method called Baseline Problem Oriented Approach developed by CML (CML, 1999). **Table 20** lists the emission factors for each energy carrier included in the analysis.

Table 20. Average emission factors (∂_i) for the Italian residential sector, reference year 2014. *Source: Virdis et al. (2017) for residential fuels and Caputo (2017) for electricity generation.*

Energy carrier		Product code	Aggregate emission factors (ton/GWh)						Aggregate emission factors (kg/GWh)	
			CO_2	CH_4	NO_x	CO	NMVOC	SO_x	PM_{10}	$PM_{2.5}$
Solid biofuels (wood)		p20	331.1	1.14	0.21	19.25	2.28	0.05	1442.5	1429.29
Petroleum products	Gas Oil	p23.20.f	263.2	0.03	0.18	0.07	0.01	0.17	16.43	12.86
	LPG	p23.20.i	231.9	0.00	0.18	0.04	0.01	0	7.14	7.14
Natural Gas		p40.2.1	202.6	0.01	0.11	0.11	0.02	0	0.71	0.71
Electricity by coal		p40.11.a	876.7	3.45	1.19	0.44	0.37	3.4	-	-
Electricity by natural gas		p40.11.b	372.8	1.31	0.45	0.17	0.14	1.29	-	-
Electricity by petroleum products		p40.11.f	585.3	0.62	0.21	0.08	0.07	0.61	-	-
Electricity by biomass and waste		p40.11.g	146.3	0.44	0.15	0.06	0.05	0.44	-	-

Due to time constraints, no development of emission intensity factors for electricity generation by energy carrier could be implemented. However, as shown in **Figure 22** the average emissions factor for electricity generation/consumption have seen great improvements between 1990 and 2012, but seems to have levelled-off in the last years at around 300 ton/GWh.

Figure 22. Evolution of average emission factors for electric and thermoelectric generation/consumption. *Source: Caputo (2017).*

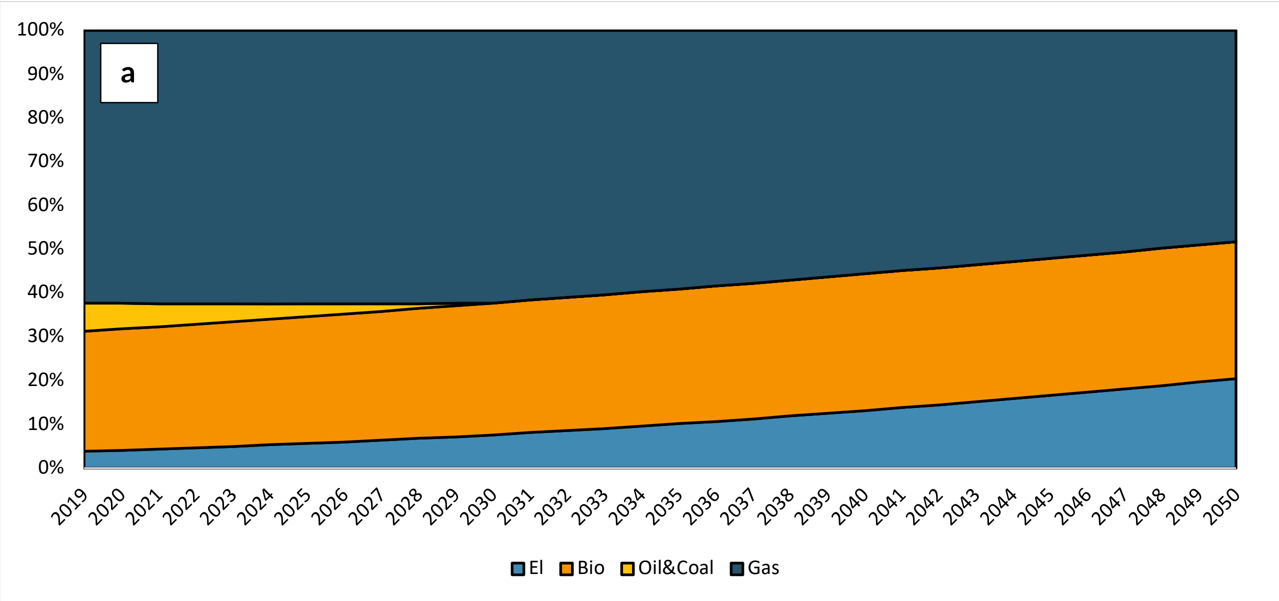


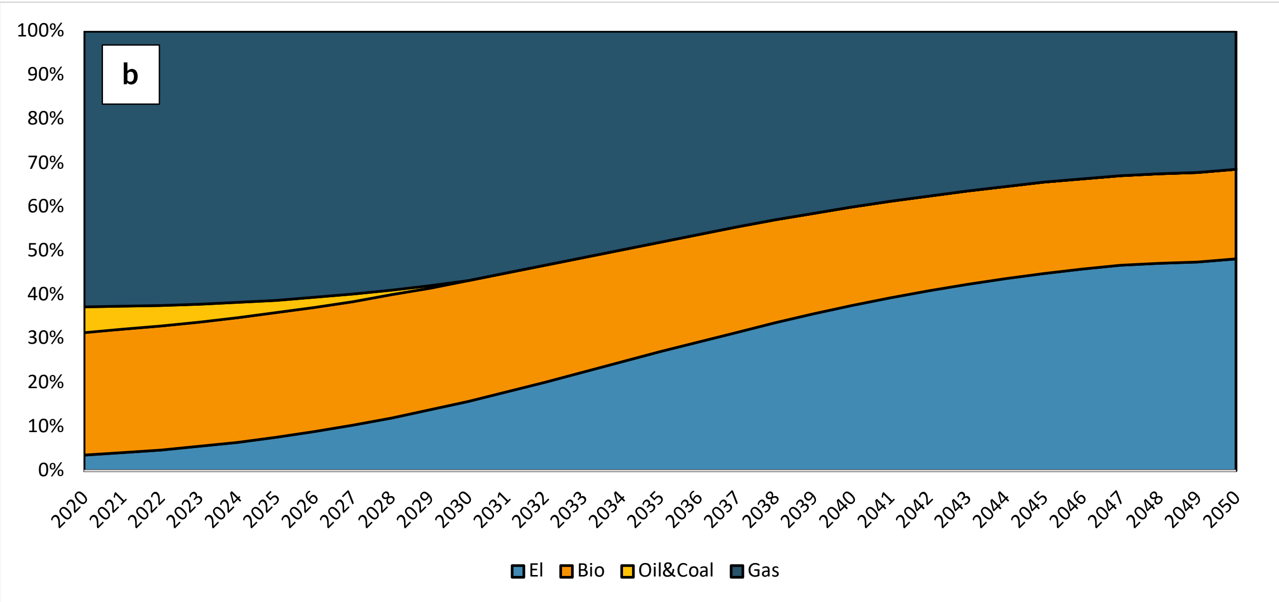
4.4 Future Developments

4.4.1 Heating Energy and Electricity Mixes

Due to the important role that the energy mix plays in determining future consumption, cost and emissions levels, a dedicated chapter was reserved to its development towards 2050. **Figure 23a and 23b** depict the 2019-2050 development of the residential energy mix for the *standard renovation regime* and the *extensive HPs and PVs implementation regime*, respectively. Their development was based on identical assumptions expect for those underlying the share of electricity. In both cases, “Oil&Coal” products are assumed to be phased out by 2030 (SEN 2017).

Figure 23. Evolution of the residential energy mix for space heating and DHW under normal (a) and extensive (b) use of heat pumps and photovoltaics. *Source: Own elaboration based on Bernante et al. (2013) and Gaeta et al. (2013)*





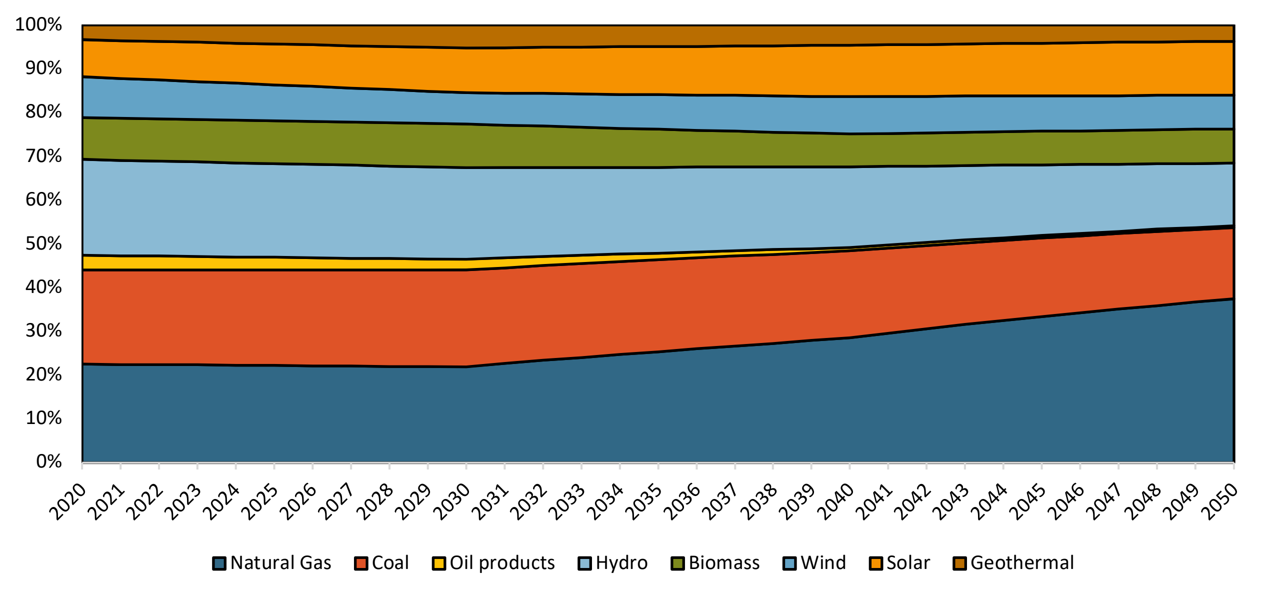
Similarly, the ratio of biomass to natural gas is assumed to move from 30% to 33% between 2016-2030 and from 33% to 40% between 2030-2050 while the share of district heating in expected to linearly reach 7,5% by 2050 (DH energy mix is assumed to linearly converge to 50% biomass including waste and 50% natural gas).

As far as electricity is concerned, the share consumed by HPs in the residential energy mix is not reported in Italian statistics because at present still very limited. Therefore, the average COP (model's input) and the share of delivered energy by heat pumps (model's output) were used to derive the technical delivered energy consumed by HPs according to the equation below and then to recalibrate the energy mix accordingly:

$$El_{hp}(\tau) = DE_{hp}(\tau)/COP_{\tau}$$

Figure 24 shows the evolution in the electricity fuel mix according to the projections in Lanati et al. (2016). Remarkably, between 2020-2050 the renewable share in the Italian electricity mix decreases from 52.6% to 45.8% at the advantage of a much higher penetration of natural gas.

Figure 24. Evolution of the Italian electricity energy mix, 2020-2050. *Source: Lanati et al. (2016)*

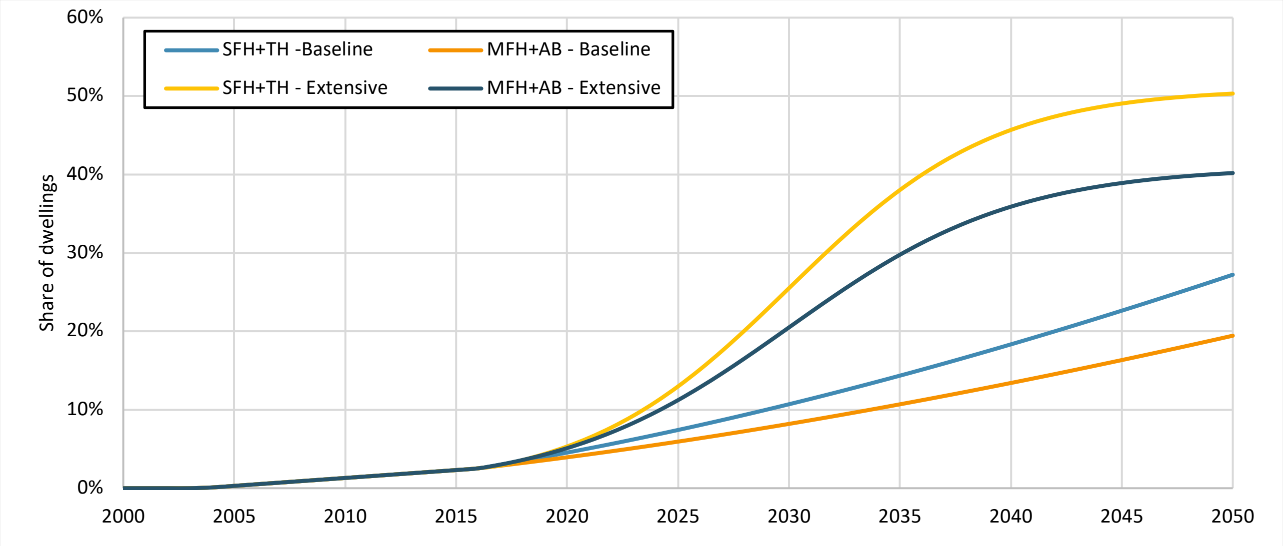


4.4.2 Renewable Energy Technologies

The penetration of RES technologies, namely HPs and PVs+SHCs follows two different regimes: "baseline" for scenarios 1,3 and 5 and "extensive" for scenarios 2, 4 and 6. In the first case, the market penetration is based on a continuation of the current trends. This is implemented as an extrapolation of the trendlines observed in the past for the two aggregated building types resulting in final shares of 27% for SFH+TH and 19.5% for MFH+SFH. As illustrated in **Figure 25**, under the "extensive" use" assumption, the market penetration of HPs follows and S-shaped curve to reflect the natural tendency of technologies for market saturation.

The saturation point is assumed at a share of 65% for SFH+TH and 60% for MFH+AB by 2050. This is the result of a much larger share of families having an HP installed, which amounts to 78% for SFH+TH and 72% for MFH+AB (against 39% and 28% of the baseline), but also a change in the stock composition of HPs.

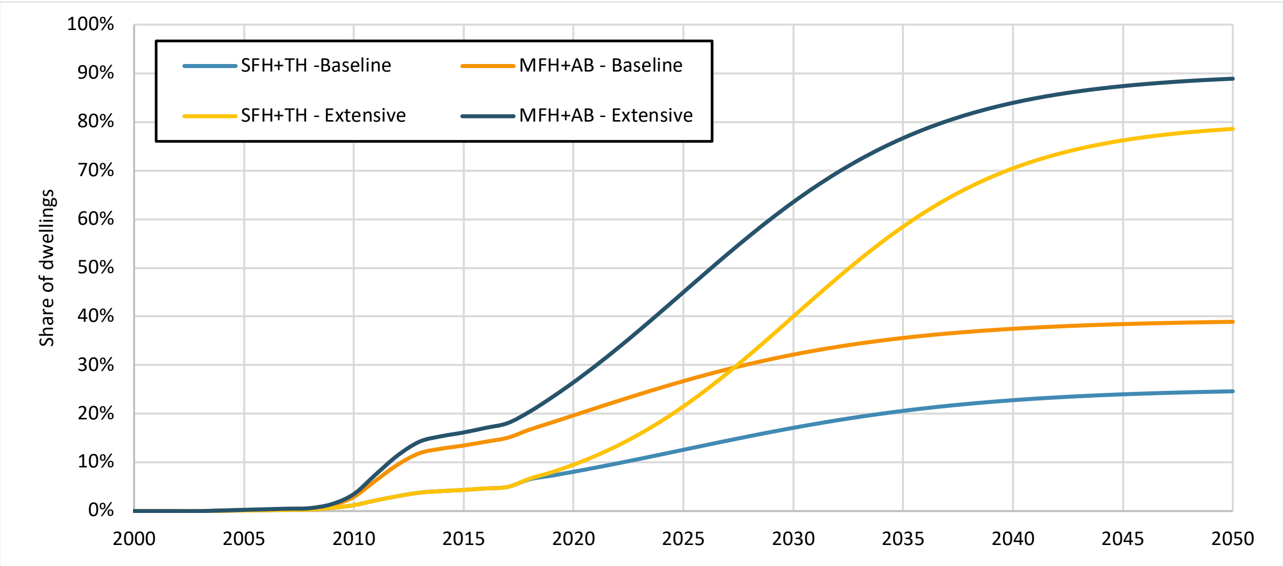
Figure 25 Evolution in the share of dwellings in SFH+TH and MFH+AB having HPs installed under "baseline" and "extensive" assumptions. *Source: own elaboration*



In fact, as anticipated in **Chapter 4.2.4,** the share of air-air compared to that of other HP types (e.g. waterborne and geothermal) is assumed to shift over the 30 years with a larger share of waterborne and geothermal devices under the "extensive" assumption. This development leads to a slightly higher weighted average COP of 2.9 against 2.8 under the baseline assumption. Changes are assumed also in the average share of energy need covered by HPs which linearly increases from 20% in 2015 to 40% in 2050 in the baseline and to 60% in the extensive scenario for all segments (for the development of the other HP-related parameters see **Table 13**).

The assumed development in the share of dwellings having PV installed is shown in **Figure 26**. In this case, the baseline assumption is that from the last known shares of 5% for SFH+TH and 15.1% for MFH+AB in 2017, the evolution follows an S-shaped trend. This results in a final share of 25% and 39% for SFH+TH and MFH+AB, respectively. A similar trend is assumed under the "extensive" assumption: for SFH and TH, the peak in growth is expected in 2030, levelling off thereafter to reach a share of 79% by 2050. For MFH and AB, the peak is instead expected to occur slightly before in 2025 and to reach a final share of 89% in 2050. In the extensive use assumption, applied in Scenario 2, 4 and 6, all new dwellings after 2020 (cohort 8) have PV installed.

Figure 26. Baseline and extensive assumptions for share of dwellings in SFH+TH and MFH+AB having PVs installed. *Source: own elaboration*



5 RESULTS

In this section, the model results are extensively presented in the following logic: First, the evolution of the dwelling stock is analysed, and its composition broken down by segments and archetypes, highlighting the differences between renovation strategies under the natural renovation and more frequent cycle. Secondly, using the development of energy need intensities (buildings' technical standards) as the linking element between the physical and energetic state of stocks, the energy results are presented. The technical "theoretical" delivered energy demand of the dwelling stock is described under its different components, namely stock segments, end-uses and energy mix. In the third section, the results from the renovation cost calculations, namely financial and global costs are analysed. For the financial costs, the full results from the cost-optimal assessment are also shown. In the fourth section life-cycle GHG and employment impacts are addressed.

A large number of results was produced by the model, asking for careful consideration into how they should be presented. For each section, an exemplary scenario is selected, and its results presented through different analytical angles, e.g. segments, end-uses, energy carriers and combinations thereof. This allows for appreciating the level of depth of the analysis, particularly throughout the stock and energy results, and to underpin interesting behaviours happening at different levels within the model. These behaviours can then be compared against other scenarios and generalized for later discussion. The insights gained from the single scenario deep-dive should help the reader throughout the second part of each section, where the scenarios are compared against each other.

Throughout the next chapters, abbreviations in the name of some scenarios will be used to ease readability. The abbreviations are listed in **Table 21**.

Table 21. Summary table of abbreviations and specific terminology

Full scenario name	Abbreviations	Groups
Baseline	"Baseline"	-
Advanced renovation	"Advanced"	"Basic"
Extensive Use of HPs and PVs	"Extensive"	
Frequent renovation	"Frequent"	
Advanced renovation and Extensive use of HPs and PVs	"Adv&Ext"	"Composite"
Minimizing Energy Need	"MinEnNeed"	
Minimizing Delivered Energy	"MinEnDel"	

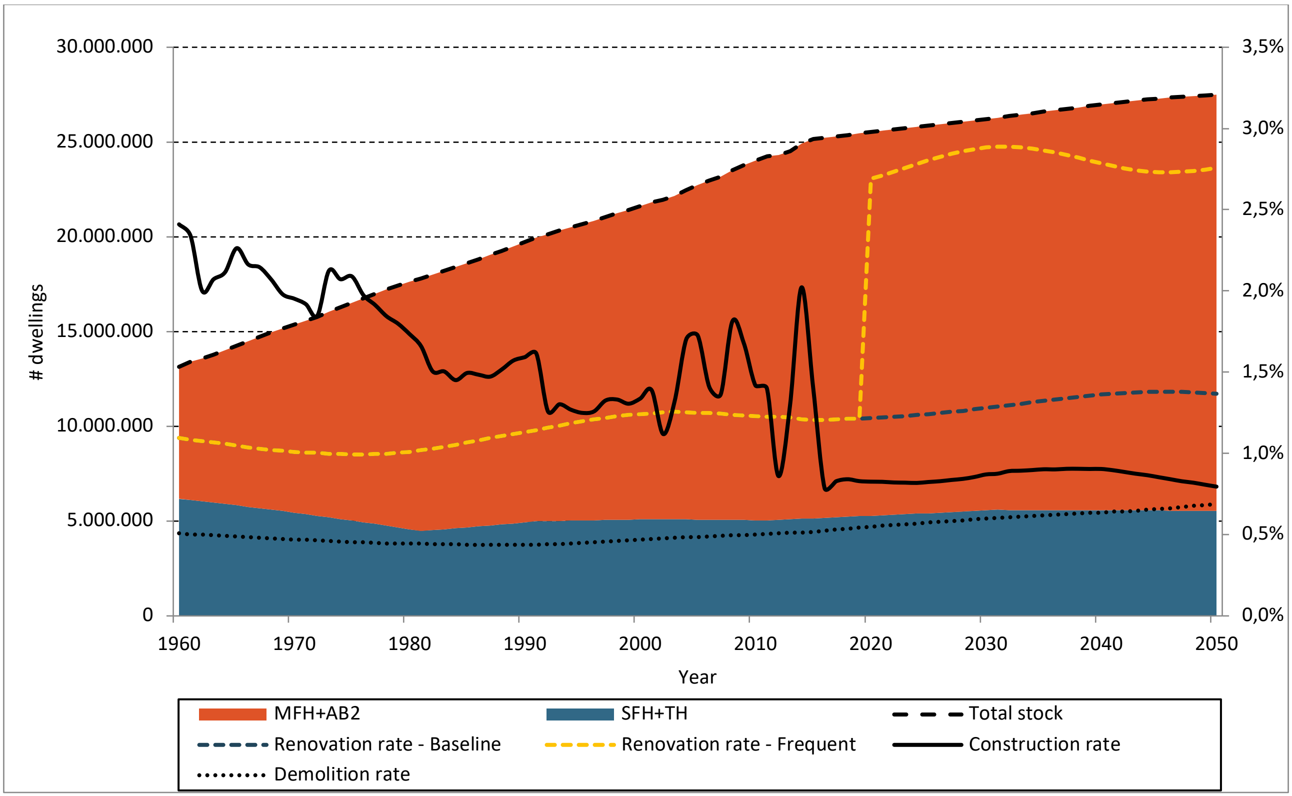
5.1 Dwelling Stock Composition

Typology and age of construction of buildings have a strong influence on their energy consumption and therefore represent an easy indication of priority areas for a renovation strategy. In this section, the segmented stock dynamics are illustrated for the two renovation regimes that differ in terms of renovation rates, namely: "Baseline", "Advanced", "Extensive" and "Advanced and Extensive" scenarios with a natural renovation cycle of 40 years - and "Frequent", Minimizing Energy Need" and " Minimizing Energy Delivered" with a shortened renovation cycle of 30 years. "Baseline" and "Frequent" used as the exemplary scenarios for this section. Although all equally relevant, the focus is put on the renovation rather than the construction and demolition activity, as the amount of renovated floor area in each cohort will be a key input to the original contribution of this work, the environmentally-extended economic model.

5.1.1 Segmented Stock Dynamics

Stock-related results are presented from the start of the energy analysis in year 1960 and up to 2050. The evolution of the Italian stock from 1960 to 2050 is presented In **Figure 27**. The number of occupied dwellings has almost doubled between 1960 and 2015, when it reached the 25 million units. This growth was driven by the demographic boom following World War II, along with a slow but steady decrease in the average number of occupants. 2015 was a tipping point in the stock growth as the number of persons per dwelling reached a plateau while population started to decline. Nevertheless, even after 2015 the construction activity experiences some slow growth due to the need for compensating demolition of older cohorts. The fact that total size of the stock does not decrease within the timeframe of the analysis is quite important because the NTNU model is not yet able to account for vacant stock in the energy analysis in that case would leadto overestimated results.

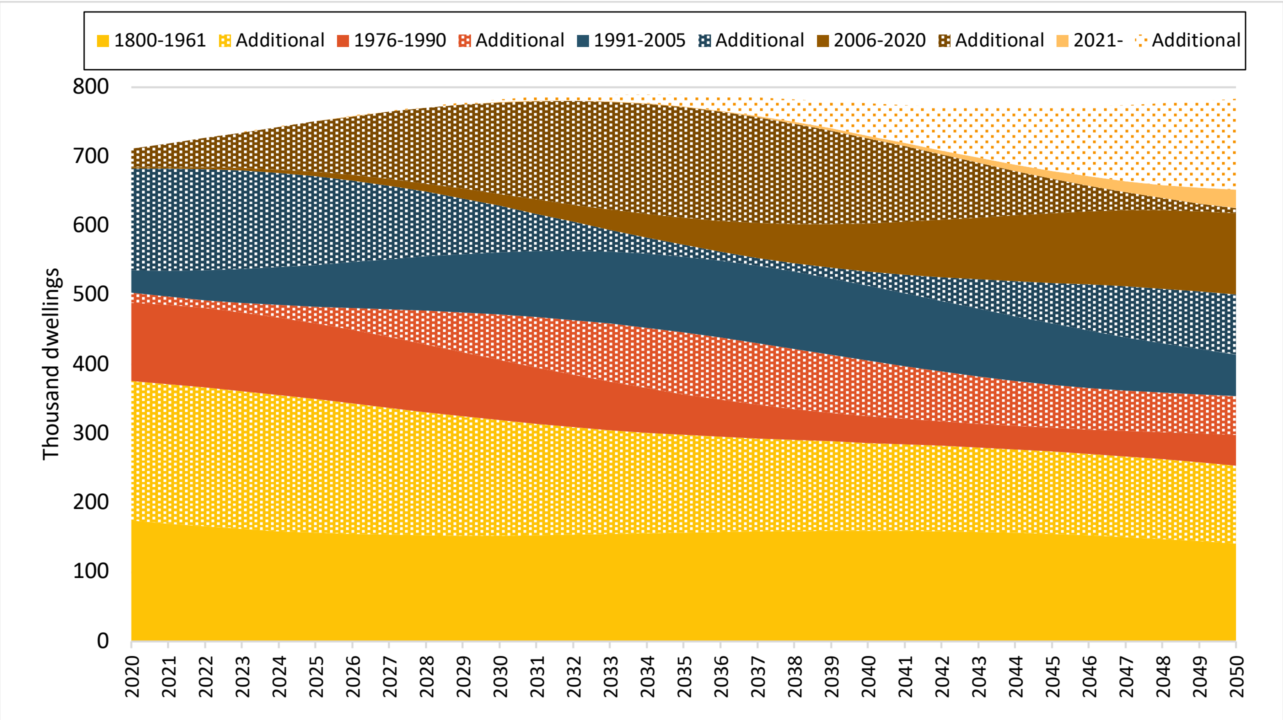
Figure 27. Evolution of the number of dwelling in the Italian stock by type building type (left-axis). Comparison between renovation rate of the two reference scenarios as shares of the total stock (right-axis).



Total stock size and composition of the stock are the same in all scenarios, but the future energy state of dwellings in the various segments varies. One of the variables that influences the future energy state is the rate of renovation, also shown in **Figure 33**. The rates for the two scenarios follow exactly the same oscillating trend until 2020 when the change in renovation cycle makes the rate for frequent renovation jump from 1,2% to 2,7%. This also means that according to the underlying cyclic renovation function, shortening the renovation cycle from by 10 years equals an increase in renovation rate of 1,5% at the stock development rate of 2020. This is an interesting information for discussion when considering that some bodies call for a rate of renovation of the stock between 4-5% per year (Babiker et al. 2018).

Figure 28 compares "Baseline" and "Frequent" renovation in terms of number of renovated dwellings in the 2020-2050 period and their distribution across cohorts. Solid fillings represent the number of dwellings renovated under the normal renovation cycle while patterned fillings represents the share of additional dwellings in scenarios with more frequent renovation. The upper dotted pattern represents newly constructed buildings. Under an increased renovation rate, the cohorts that are majorly invested by new renovation activity are cohort the ones going from 1961-1975 to 2006-2020. The cohort most invested is the one of buildings constructed in the most recent period (2006-2020) rather than the older ones, which generally have worse energy performances. This implies that in frequent renovation scenarios, interventions are not always prioritized to dwellings in more need of energy renovation thus not tapping into the full energy saving potential of the strategy. Overall, the number of additional dwellings renovated between 2020-2050 amounts to 6,7 million, corresponding to a floor area of roughly 600 Mm^2.

Figure 28. Comparison between the number of dwellings renovated under normal and frequent renovation rates across different age cohorts, 2020-2050.

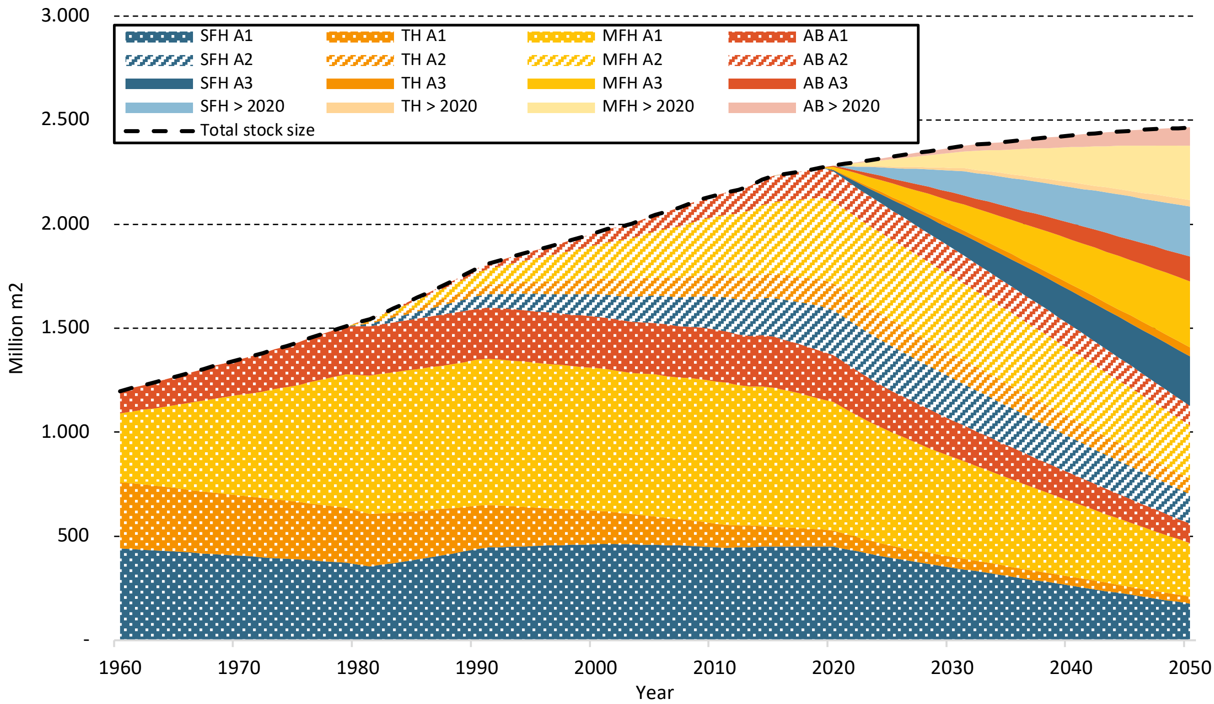


5.1.2 Archetypes Distribution

So far, the stock has been broken down into its segments and some preliminary analysis on the renovation activity was made, yet without any consideration about the renovation stages that define the archetypes. The inclusion of this element allows to relate each strategy to its time development, and this is particularly important given that the analysis extends over a long timeframe. Perhaps even more importantly, it helps in framing and properly account for the portion of stock which is the focus of the later analysis, namely buildings renovated after 2020.

Figure 29 illustrates the changing stock composition of heated floor area in dwellings of various renovation states according to the "Baseline" scenario. The dotted areas represent dwellings constructed prior to 1980 and remaining in their original state or being renovated before 1980 (without a significant energy-saving effect). Striped areas represent past constructions that has been subject to historical renovation in the period 1980–2020 and with an energy-saving effect corresponding to segment-specific standard renovations. The dark-filled bands represent buildings subject to future renovation after 2020 and filled light-filled bands represents future new construction after 2020 (according to nZEBs energy standards). Therefore, pattern-filled bands represent the share of the stock that is not expected to change in respect to its energy state in the period 2020–2050, if following the "natural" renovation cycle. The actual potential for improved energy efficiency in the stock is hence limited to the filled areas. It follows that about 50% of the 2020 stock is expected to remain unchanged until 2050, either staying in its original state or in the state of a historical renovation. To improve the energy efficiency of the stock, it is therefore highly important that the opportunity is taken to introduce energy-efficiency measures when dwellings are renovated after 2020 (dark filling), and that new construction (light filling) are as energy-efficient as possible. If the renovation cycle is reduced to 30 years from 2020 onwards, as in the "Frequent" renovation scenarios the share of the stock renovated will increase to about 65%, yet 35% of the 2020 stock will still be unchanged by 2050. Finally, it should be reminded that the environmental and economic assessments only concerned buildings renovated after 2020, hence it is limited to the dark-filled share of the stock which represents about 25% of the total.

Figure 29. Evolution of dwelling stock heated floor area between 2020-2050



5.2 Energy Performance

In this section are presented the main results of the energy analysis. Differently from the previous stock dynamics, all scenarios differ in terms of how their energy performance has developed over time and distributed across segments. Another element of distinction is given by the point at which energy performance is measured, namely energy need and delivered energy as well as in the way it is supplied by different energy carriers. The exemplary scenarios considered here are the "Baseline" and "Extensive", although stronger emphasis is put on the scenario comparison in order to highlight the effects of combining basic strategies.

5.2.1 Energy Need Intensities

Linking stock and energy results, **Figure 30** shows how the energy need efficiency evolved over time according to the Baseline scenario. An important improvement in the energy efficiency has already taken place and is expected to continue towards 2050. The solid and dotted blue bands represents old buildings of poor energy efficiency, with energy need intensities higher than 150 kWh/m^2 in their original state or renovated according historical efficiency standard, respectively. After 1980, this share of the stock decreases in number as it is either upgraded through renovation or phased out through demolition. The solid red wedge band represents the floor area of the stock being in its original state with an energy need intensity in the range 101–150 kWh/m^2, whereas the patterned red is the share that has reached this level through renovation. The same is valid for the yellow bands representing buildings in the range of 51–100 kWh/m^2 while in grey are the newest and most efficient buildings at less than 51 kWh/m^2. The share of dwellings with an energy need intensity lower than 51 kWh/m^2 being renovated is negligible.

Figure 30 shares of stock being by energy need intensity levels and state. Period 2020-2050, baseline scenario.

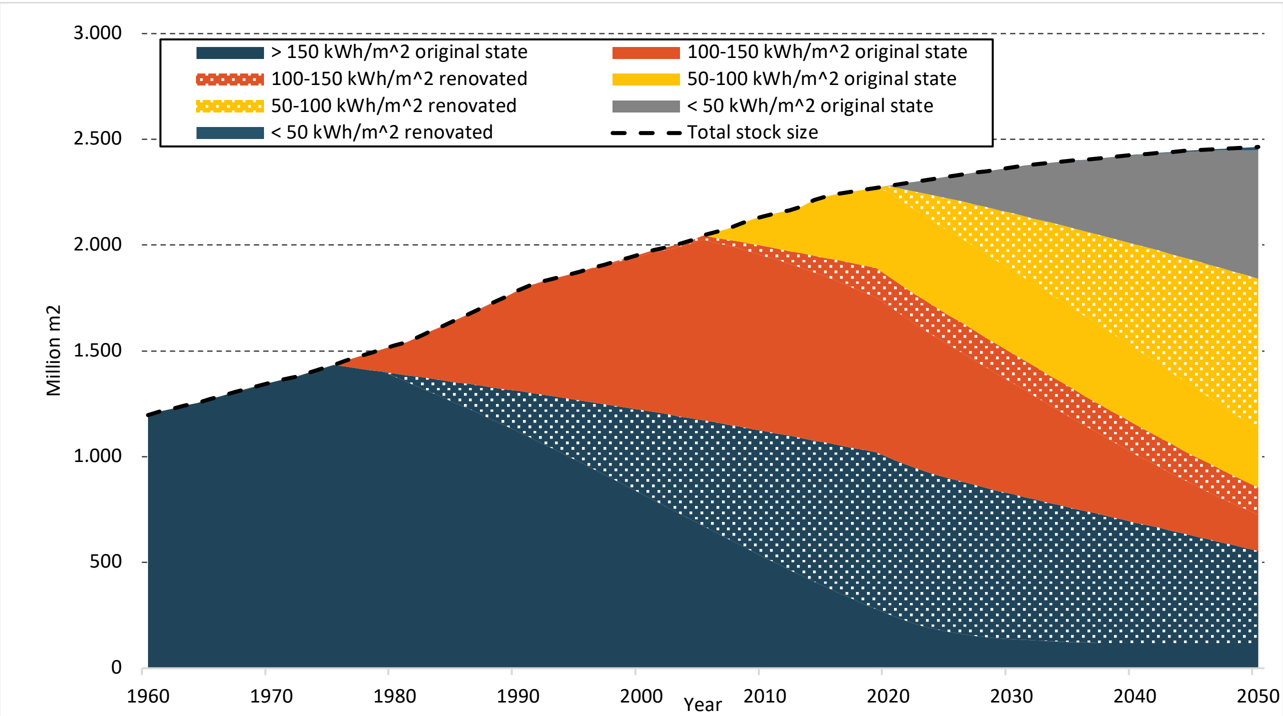


Figure 30 is an effective way of visualizing the shares of the dwelling stock that represent various energy-efficiency levels, for any year between 1960 and 2050. As an example, in 1960 all dwellings performed worse than 150 kWh/m^2 while in 2000 roughly one third already performed in the range

101–150 kWh/m^2. According to the Baseline scenario, after 2020 still a consistent part of the dwelling stock will have an energy need intensity larger than 150kWh/m^2 despite the majority have already undergone a renovation in the 1980-2020 period. Further, a considerable share of the future stock will be in the range of 101–150kWh/m^2 but rapidly decreasing to 51–100 kWh/m^2. Finally, the share having an energy need intensity less than 51 kWh/m^2 is will steadily increase to reach roughly the share of stock of the occupied by range >150 kWh/m^2. If the energy efficiency after renovation or the frequency of the renovation differs from the assumptions in the Baseline scenario, the wedge bands in **Figure 30** would evolve differently. In **Table 22**, snapshots of the stock composition in 2020, 2030 and 2050 are presented for the scenarios that involve different renovation regimes ("Advanced", "Frequent" and "Minimizing Energy Need").

Table 22. Shares of the stock in various energy need intensities level in 2020, 2030 and 2050, according to scenarios with different renovation regimes.

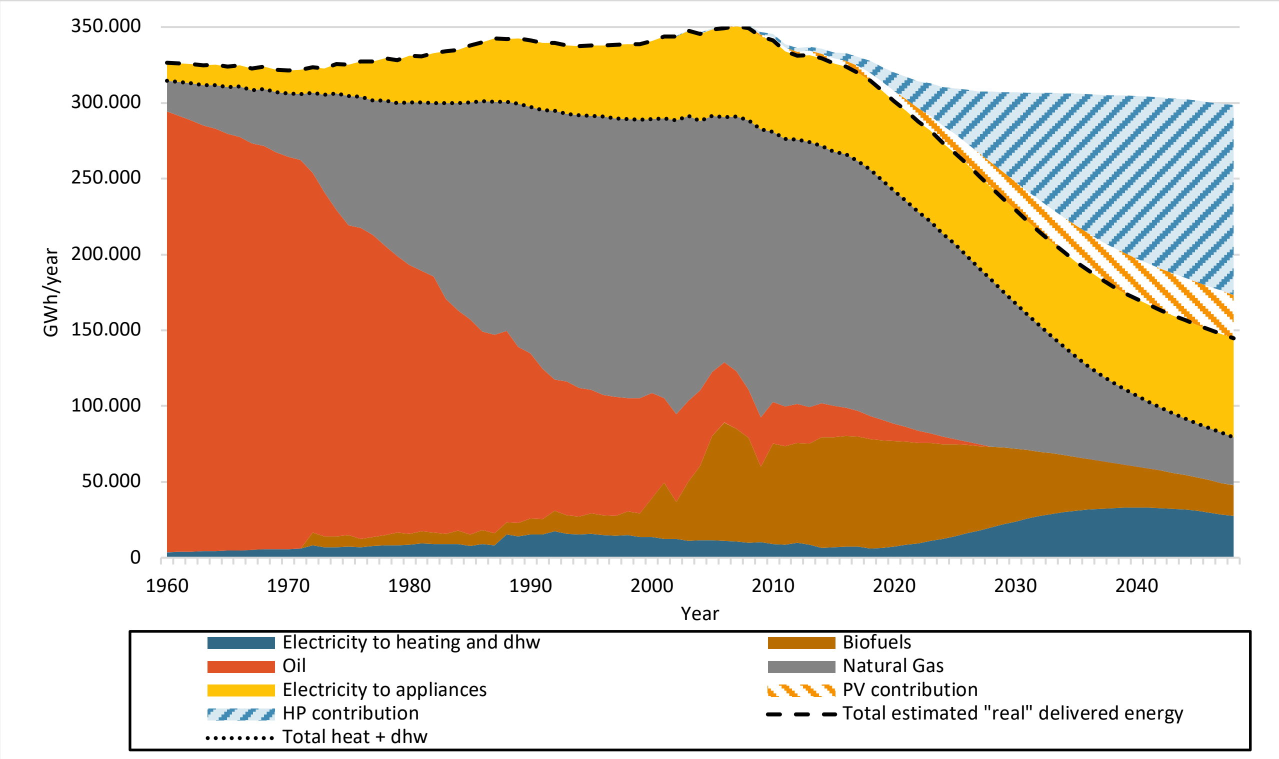
		<51 kWh/m^2		51-100 kWh/m^2		101-150 kWh/m^2		>150 kWh/m^2		Total	
		Mm^2	Shares %	Mm^2	Shares %	Mm^2	Shares %	Mm^2	Shares %	Mm^2	Shares %
2020	**Baseline**	-	0	427	18.7	857	37.6	997	43.7	2281	100
	Advanced	0	0	1309	57.4	716	32.4	256	11.2	2281	100
	Frequent	-	0	457	20.0	842	36.9	842	43.0	2281	100
	MinEnNeed	2	0.1	1336	58.6	701	30.8	1336	10.6	2281	100
2030	**Baseline**	216	9.1	660	27.9	668	28.2	660	34.8	2386	100
	Advanced	223	9.4	1481	35.8	527	22.3	1481	5.8	2386	100
	Frequent	216	9.1	848	62.5	529	22.4	848	32.7	2386	100
	MinEnNeed	290	12.2	1570	66.3	389	16.4	1570	5.0	2386	100
2050	**Baseline**	622	25.2	988	40.1	299	12.1	988	22.5	2464	100
	Advanced	746	30.3	1429	58.0	170	6.9	1429	4.8	2464	100
	Frequent	622	25.2	1252	50.8	136	5.5	1252	18.4	2464	100
	MinEnNeed	969	39.3	1315	53.4	61	2.5	1315	4.8	2464	100

Table 22 demonstrates that the share of very inefficient dwellings with energy need intensities higher than 150 kWh/m2 in 2020 has two very different starting points: around 43% for scenarios with standard renovation and around 10-11% for those with advanced renovation. For the latter, this is the result of more stringent standards being already implemented in between the 1980 and 2020 while for the former this energy savings potential is still to be exploited in the period under examination. Even without advanced or more frequent renovation, standard renovation of 'normal' cycles is expected to reduce this share to below 25%. Scenarios with advanced renovation instead are expected to bring dwellings with this energy need intensity to just those that remain in the original state for heritage reasons. Furthermore, the future share of very energy efficient dwellings does not differ much between the scenarios. This is because only cohort 7 and 8 can reach an energy need intensity below 51kWh/m^2. In cohort 7, this is an effect from either standard or advanced renovation, and in cohort 8 even in original state. Hence, only a more frequent renovation of cohort 7 ("Frequent" and "MinEnNeed") will increase the share of very energy efficient dwellings. However, there are significant differences between the scenarios regarding future shares of the stock in the range of 51–100 kWh/m2 rather than >150 kWh/m^2. Advanced renovation ("Advanced", "MinEnNeed", "AdvExt" and "MinEnDel") will strongly increase this share while the share being in the range of 101–150kWh/m2 will remain unchanged if just more frequent standard renovation is applied ("Frequent").

5.2.2 TECHNICAL "THEORETICAL" DELIVERED ENERGY

Where the energy need mostly reflects the thermophysical properties of a building's envelope, technical delivered energy includes the efficiency of the generation and distribution systems. In this context, the total technical energy can be observed from two at least perspectives: the underlying energy mix and the end-uses. **Figure 31** shows the development in technical delivered energy for the "Extensive" scenario, differentiating between energy for space heating and DHW and for electrical appliances.

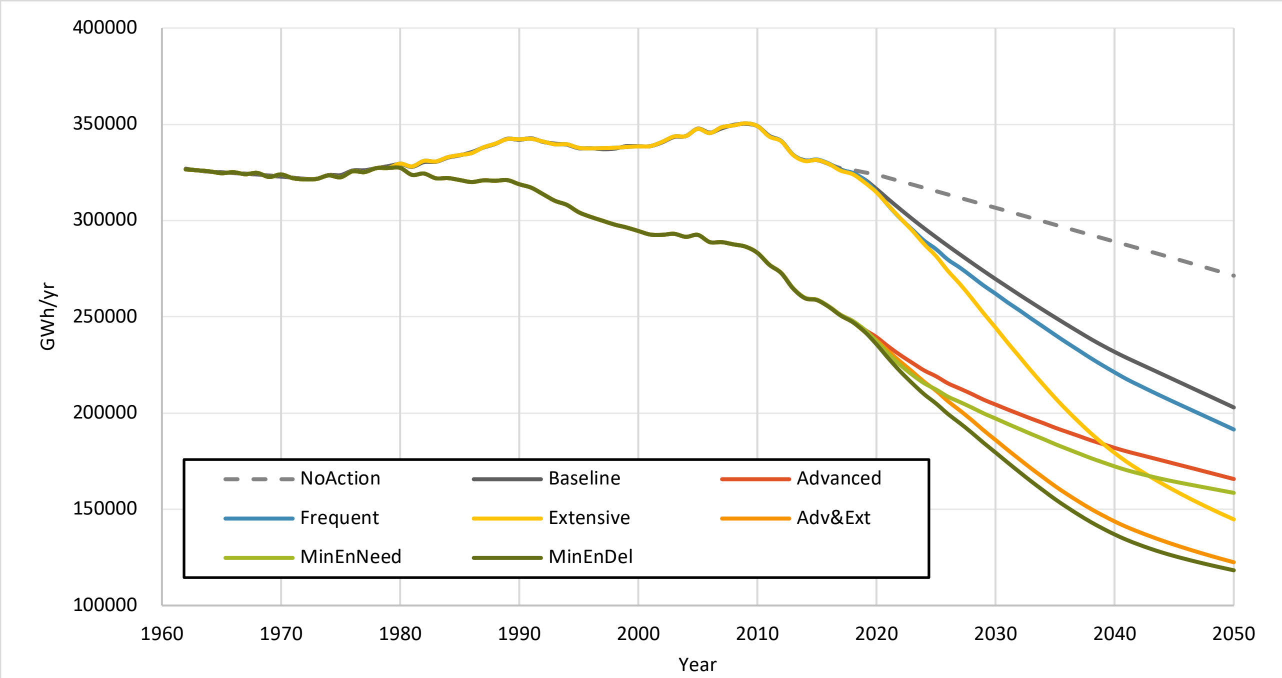
Figure 31. Development in technical delivered energy for the "Extensive use of HP and PV" scenario by energy carrier, 1960-2050 period.



The most evident change in the delivered energy mix is the development of RES marked by the striped bands. Their contribution increased from 5% of the total delivered energy consumption in 2020 to 51% in 2050. The figure goes up to 66% when considering just consumption for heating+DHW. Comparatively, for scenarios with a different renovation regime ("Advanced", "Frequent" and "MinEnNeed"), this share reaches 27-28% while in the Baseline it remains almost at 2020 levels. An increased number of HPs raised also the level of electricity demand for heating and DHW at 35%, just below that of natural gas (39%) and well above that of biomass/biofuels (26%). If also the electricity for electrical appliances is taken into account, the total share of electricity in the residential delivered energy mix goes up to 64%. Remarkably, in the scenarios with extensive RES implementation, heating+DHW consumption is so effectively reduced to push the share of delivered energy for appliances from just 19% in 2020 to 45% in 2050. This is, however, under the uncertain assumption that the demand from electricity appliances will level-off at 2300 kWh/dwelling/yr.

Figure 32 compares the development in technical delivered energy demand for all scenarios plus an extra one termed "NoAction". This describes the unrealistic development path where no extra renovation action is taken and the only improvements to the energy consumption are the ones naturally occurring from the phasing out of older building cohorts and the improvements in the average system efficiency due to new technologies. Originally, two distinct development paths can be observed that bifurcate in 1980, year of start of the renovation period 2: the lower stream, introducing a renovation based on historical standards and the upper where no renovations with energy efficiency purposes occur.

Figure 32. Scenario comparison of technical "theoretical" delivered energy at the level of the entire stock, 2020-2050.



The rationale behind this modelling choice is that, one the one hand, energy efficiency standards were historically implemented in the late '70s and have had an effect on the energy performance of a share of buildings. On the other hand, applying standard renovation archetypes as developed within the TABULA/EPISCOPE to the Baseline already in renovation period 2 (1980), resulted in a poor match with statistic. A better match was instead found assuming that in the Baseline case all renovations in between 1980-2020 did not have energy efficiency as their primary purpose.

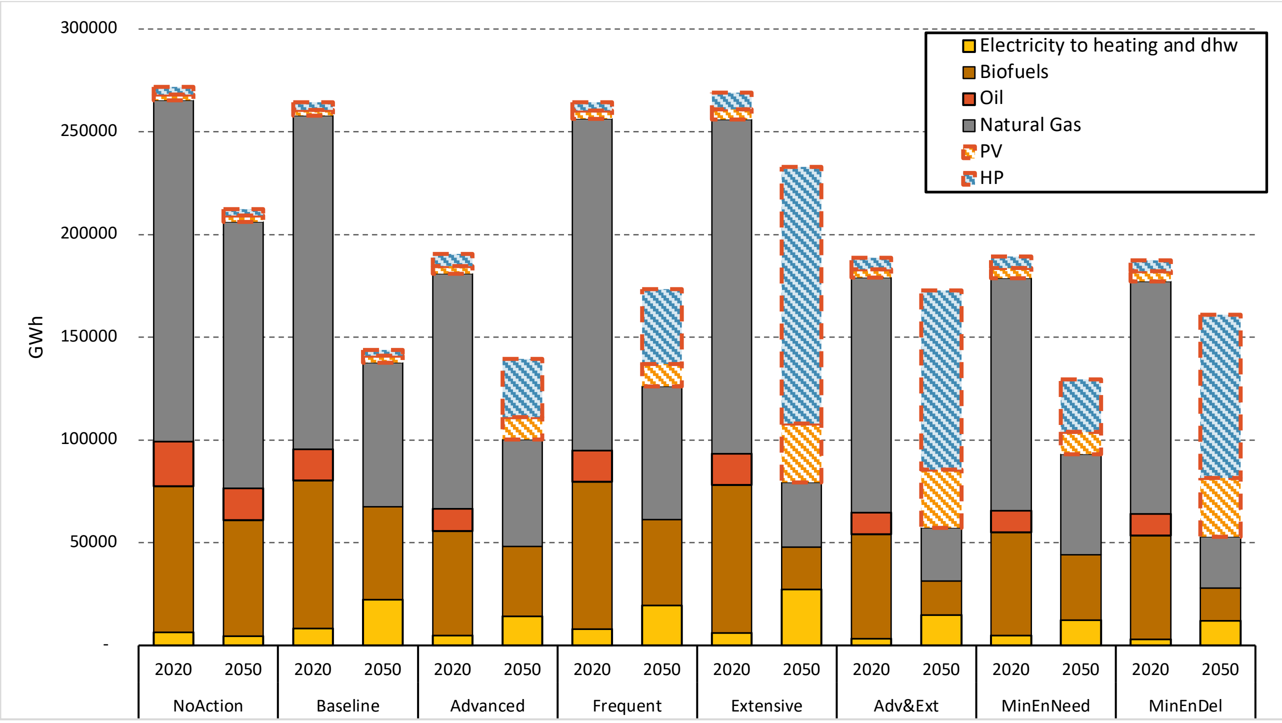
Not surprisingly, all combined scenarios perform better than the basic ones, except for the case of extensive implementation of HPs and PVs compared to minimizing the energy need. Thanks to a remarkable 2,6% yearly reduction rate, right after 2040 it overcomes "MinEnNeed" in terms of delivered energy demand. This is a first suggestion of the potential of RES technologies, and HPs in particular, compared to renovation of the building envelope to the decrease the technical energy in the future. **Figure 33** underpins this result by showing a snapshot of the delivered energy for heating+DHW purposes at the starting and final year of renovation period 3. In 2020, "MinEnNeed" delivered energy is about 75% that of the "Advanced" and the contributions from HPs and PVs very similar between the two scenarios. In 2050, while the overall energy demand (solid + dashed bars)[3] in "Extensive" remains considerably higher than of the counterpart, the actual delivered energy (solid bar) ends up being lower thanks to a 66% net "renewable" energy supply by HPs and PVs.

In relative terms, the largest reduction is achieved by the "Extensive" scenario, with an almost 70% decrease compared to 2020 levels, from 256 TWh/yr down to just 80 TWh/yr. However, this is also because of the higher starting point compared to scenarios with an advanced renovation regime. In absolute terms, the lowest demand is reached by "MinEnDel" at just above 50 TWh/yr and with a 60% difference compared to the Baseline. Following, the "AdvExt" scenario performs slightly worse

[3] With a weighted system efficiency of around 95% across all scenarios by 2050, this almost corresponds to the energy need of the stock.

than “MinEnDel” but considerably better than “MinEnNeed”. This suggests that the implementation of RES, namely HPs and PVs is essential in order to reach the maximum achievable energy reduction potential for Italian residential building stock. This result is consolidated by the better final performance of the “Extensive” scenario compared to the “MinEnNeed”, even despite a higher starting consumption level.

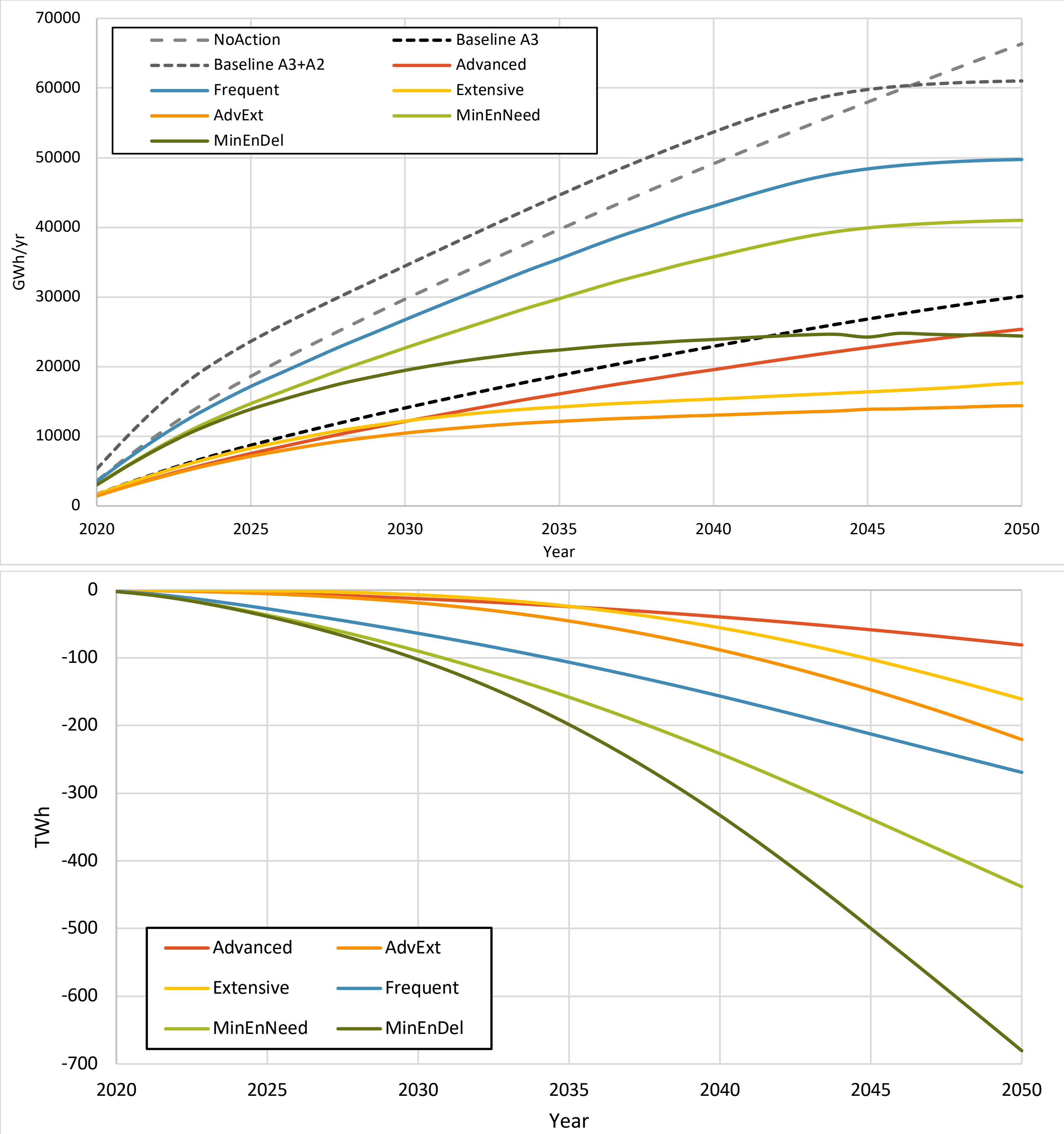
Figure 33. Scenario comparison of “theoretical” technical delivered energy in years 2020 and 2050 by energy carrier for heating and DHW demand only, whole stock.



Finally, to conclude the overview on the energy results, **Figure 34a and 34b** show the delivered energy consumption of the stock of existing buildings renovated after 2020 (C0-C7, A3) and the cumulative energy savings compared to the two Baselines. To offer a fair comparison between scenarios with standard and frequent renovation regimes, a new Baseline scenario (Baseline A3+A2) was introduced for benchmarking. In this scenario, the difference between floor area renovated under the two regimes that remains in its original state (A2) is combined to the one undergoing renovation (A3). This gives a new timeseries of delivered energy consumption that reflects the advantage of more frequent renovation scenarios by comparing their energy performance on the same amount of floor area.

With the exception of “MinEnDel”, all other scenarios with an increased renovation rate clearly manifest a higher delivered energy compared to standard renovation regimes in that the amount of renovated floor area is larger. The exceptional case of “MinEnDel” indicates that – by coupling extensive use of HPs and PVs with advanced renovation standards - the achieved energy efficiency level is so improved that the delivered energy is lower than the Baseline despite the larger number of renovated dwellings.

Figure 34 Scenario comparison of **(a)** yearly "theoretical" delivered energy for the portion of dwellings renovated after 2020 (C0-C7, A3) and (**b**) cumulative delivered energy savings compared to the Baseline scenarios.



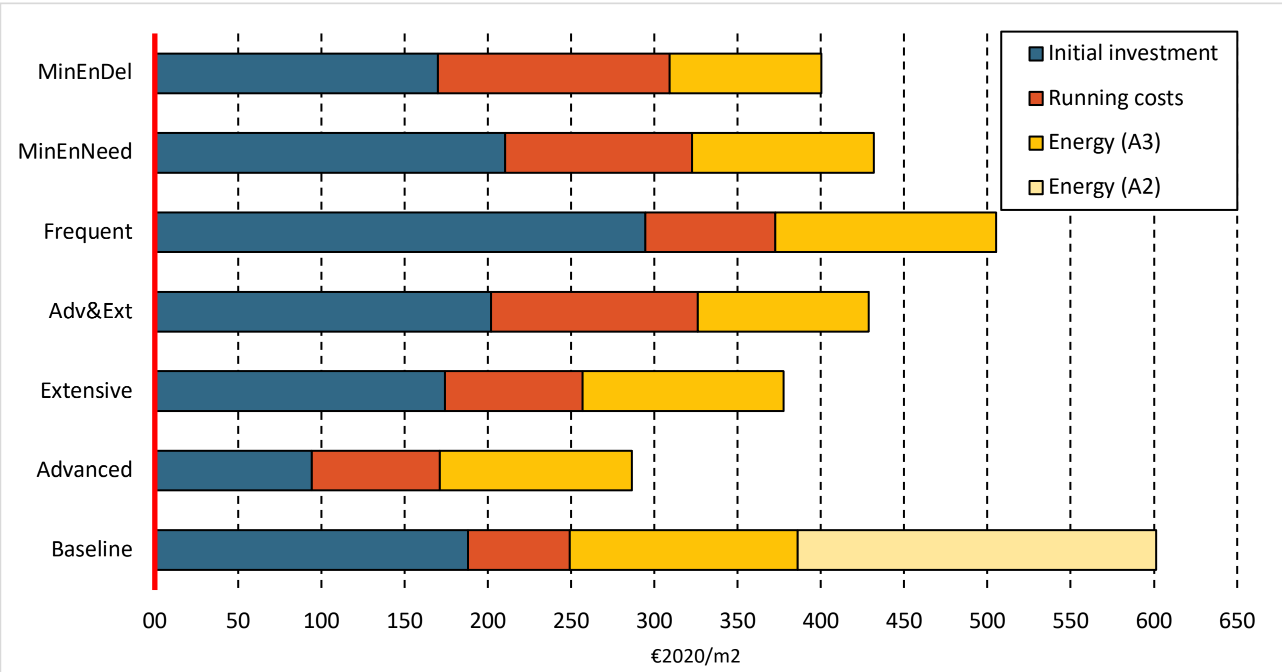
5.3 Economic Results

The economic results presented hereafter are structured in two parts: in the first one, average costs of renovation of each scenario are presented according to the financial and global perspectives. Both financial and global costs are expressed in terms of net unit costs (€/m2) at 2020 constant prices over a 30 years accounting period. In the second section, scenarios are evaluated in terms of their cost-optimality by relating the financial costs to the delivered energy intensity post-renovation. In this study, differences in economic results are essentially determined by four factors: (i) the "consumption basket" or "bundle" of products and activities during renovation, (ii) the energy performance after renovation, (iii) the timing of the investment and (vi) the geometry and age of buildings being in each segment. While it would have been interesting to explore more in depth all these factors, for the sake of conciseness, the analysis will focus on a higher level comparison across scenarios. To this end, the 14 cost categories were aggregated into 3 macro-categories (Initial investment, running costs and energy costs/savings) and the over 200 segments condensed into 7 average figures, one for each scenario.

5.3.1 Financial Costs

Figure 35 shows the 2020-2050 average financial cost of each scenario given by the weighted sum of individual costs for each segment considering a 30 years accounting period. In terms of renovation, the scenario with the lowest financial costs - at the net of residual value and subsidies - is "Advanced" renovation with 171€/m^2, followed by "Baseline" with 249 €/m^2, "Extensive" with 256 €/m^2, "MinEnDel" with 309 €/m^2, "MinEnNeed" with 322 €/m^2, "AdvExt" with 326 €/m^2 and in last position "Frequent with 372 €/m^2.

Figure 35. Scenario comparison of weighted average financial cost of investments in year 2050 over a 30 years accounting period (τ).



These results are in line with the expected outcome, which considers three main observations:

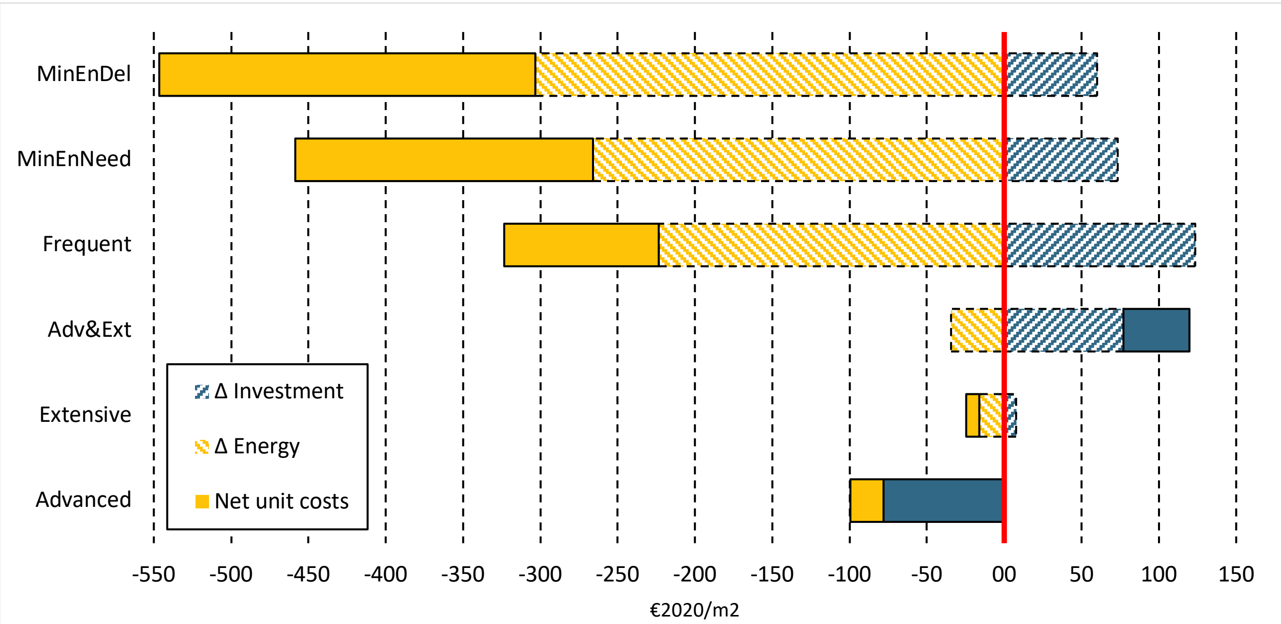
I. Despite "composite" scenarios being considerably more expensive at parity of conditions, when subsidies and residual values are taken into account the difference with the basic ones is greatly reduced;

II. Scenarios under a frequent renovation regime hence operating outside the "window of opportunity" have to bear additional indirect construction costs, however these are compensated by larger subsidies and residual value;
III. Lower than average running costs (in particular consulting and O&M costs) for "Frequent" and "Baseline" do not compensate for the lack of subsidies which penalizes these scenarios.

Another interesting result is how renovation regimes differ in the ratio between initial investment and running costs: despite scenarios under "extensive" regime have higher maintenance and replacement costs compared to those under "advanced" regime, for the latter the overall ratio is higher because of the much lower initial investment. In fact, in 2050, running costs constitute 44% of the renovation investment in the "Advanced" scenario and only 32% in the "Extensive". In the Baseline case, running costs take about 25% of the renovation investment.

When the energy costs are included, the overall financial cost of the Baseline scenario becomes 99.5 €/m^2 larger than for "Advanced" and 8.5 €/m^2 larger than "Extensive", making both basic scenarios financially positive within the 30 years accounting period. For comparison with scenarios under frequent renovation regime, the unit energy cost of buildings in A3 (dark yellow) have been averaged with those in A2 (light yellow) based on their respective floor areas. The resulting value of 352 €/m^2 (dark plus light yellow) becomes considerably higher. To better visualize the comparison, **Figure 36** compares all scenarios in relation to the Baseline.

Figure 36. Weighted average marginal costs of investment compared to the Baseline over the 2020-2050 period and considering a 30 years accounting period (τ), financial perspective.



Starting from the bottom, subsidized "Advanced" renovation ends up costing on average 78€/m^2 less than its standard unsubsidized counterpart. Interestingly, it can then be observed that "Advanced" renovation of the building envelope is the only *renovation* option which is cheaper than the Baseline. The other scenarios may also be financially positive, but only thanks to higher energy savings. When considered together, the "Advanced" unit savings over the 30 years accounting period amount to 100€/m^2. "Extensive" implementation of HPs and PVs costs about 10€/m^2 more than "Baseline" and the related energy savings energy are 5.3€/m^2 lower than those of the "Advanced" total net savings of 8.5€/m^2. Interestingly, while "Extensive" has an average delivered energy intensity lower than "Advanced" (40 against 43 kWh/m^2), it grants less monetary savings due to the higher costs of electricity compared to the other carriers. "AdvExt" is the only scenario which is not financially positive within the 30 years and this can be explained fundamentally by one observation: the marginal energy savings resulting from the combination of "Advanced" with "Extensive" renovation are minimal compared to the additional investment required. However, this does not hold true when adding a frequent renovation regime to the strategy and this gives and interesting input for later discussion. In the "Frequent" scenario, which is the most expensive in terms of renovation, the energy savings comes almost completely from the share of dwellings remaining in their original state (A2) in the Baseline. In this scenario, high renovation costs take up a large part of the energy savings, which eventually are worth 100€/m^2. "MinEnNeed" and "MinEnDel" are by large the scenarios with the overall best financial performance, delivering net savings for 193€/m^2 and 243€/m^2, respectively. Like for "Frequent", also in these scenarios most savings are related to the poor energy performance of dwellings in A2 (120 kWh/m^2/yr), however the more ambitious renovation options and the high subsidies make them a much more convenient choice than simply more renovation. *Interestingly, the addition of extensive implementation of HPs and PVs to a frequent and advanced renovation regimes, delivers considerable additional savings (53 €/m^2).*

To conclude this section on the global costs, Table 23 summarises the average net unit costs for all scenarios compared to Baseline over the 2020-2050 period.

Table 23. Summary table of weighted average net unit costs from a financial perspective, 2020-2050.

Indicator/scenario	Advanced	Extensive	Frequent	AdvExt	MinEnNeed	MinEnDel
Net unit costs [€2020/m^2]	-99.5	-8.5	-100	42.7	-193	-243

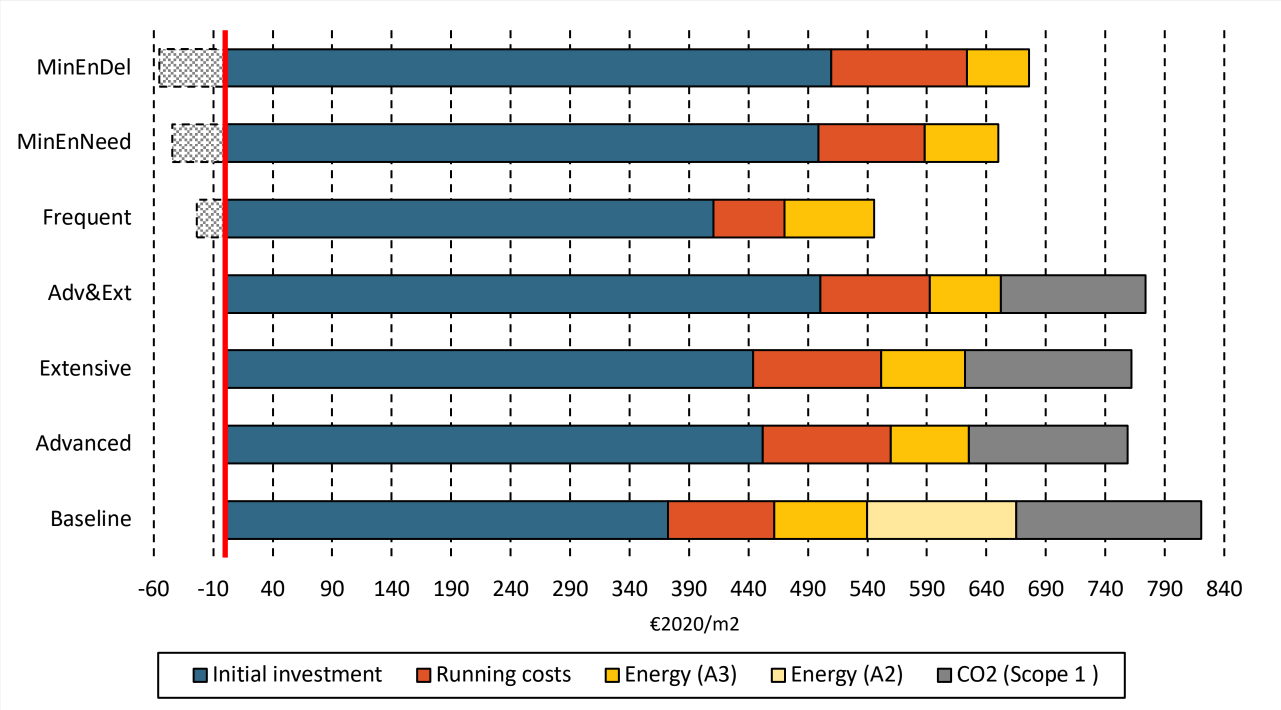
5.3.2 Global Costs

Figure 37 illustrates the weighted average renovation costs from a macroeconomic perspective. The key differences between the macroeconomic and financial perspectives are: (i) a 3.5% societal interest rate instead the 4% real interest rate, (ii) the exclusion of subsidies and VATs and (iii) the inclusion of indirect cost regardless from the length of the renovation cycle. Probably the most important difference is the inclusion of the costs of CO_2 emissions as the monetized value of the environmental damage caused by the energy-related emissions of the building. *Note that, due to time constraints, it was not possible to retrieve the actual emissions from scenarios under frequent renovation regime, but only in terms of difference with the Baseline (negative pattern grey bars). Therefore, the patterned grey bars represent the scenario-specific emissions from A3 minus the emissions from the A2 share in Baseline.*

To begin with, average global costs of renovation are 48% higher than their financial counterparts (550€/m^2 against 286€/m^2). When energy is factored in, the difference goes down to 35% (615€/m2 against 402€/m2), as a result of excluding VATs from the energy costs. The cost difference between scenarios under a frequent and standard renovation regime is much reduced because indirect costs are now considered in both cases. In fact, from a macroeconomic standpoint it does not really matter who is bearing the costs or whether they overlap with other expenses as long as the transaction, with its economic-wide effects, takes place. The effect of a lower interest rate (nominal interest rate at the net of inflation) can be seen from the much smaller incidence of running costs compared to the financial perspective (17% against 34% on average). Therefore, scenarios with higher running costs such as those under the extensive renovation regime are more convenient from a macroeconomic perspective. For instance, while the financial costs of "Extensive" renovation (excl. energy)

"Extensive" were 85.8 €/m² higher than "Advanced", from a macroeconomic perspective they become -8€/m².

Figure 37. Scenario comparison between weighted average global costs in year 2050, macroeconomic perspective (excl. cost of emissions)

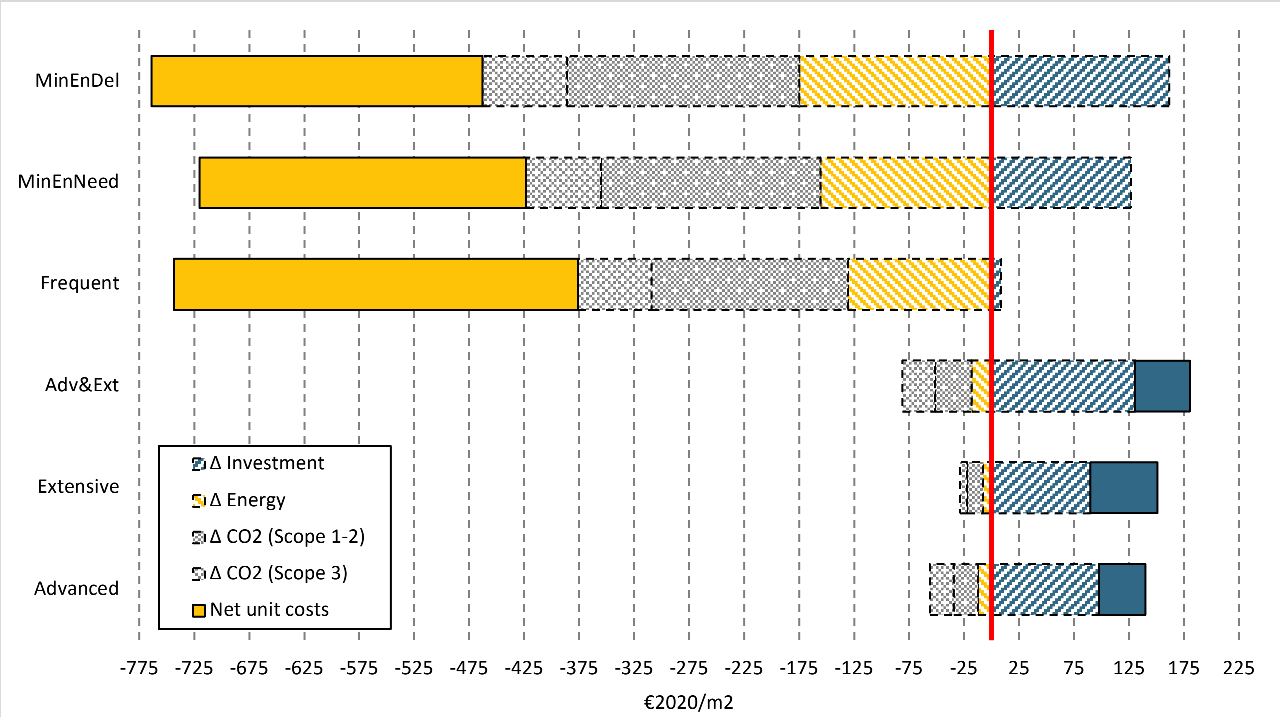


Energy costs become much less relevant in the cost structure, going down from an average 29.4% in the financial perspective to only 11%. This reflects the considerable share that taxes take on the overall energy prices, particularly for petroleum products (46%) and natural gas (39%). Comparing these values with those of taxes and levies exerted on labour (22%) or construction products (10%), it explains the lower incidence of energy costs on the total renovation investment.

Figure 38 compares all scenarios in relation to the Baseline and including the monetized and actualized costs of CO_2 over the 30 years accounting period and at the net of emissions from the renovation activity. Like in the previous figure, both the renovation and energy costs of the Baseline were subtracted from those of the other scenarios. Blue striped bars represent the marginal renovation costs. Yellow striped bars represent the share of renovation costs offset by the energy savings. Finally, the patterned grey and bars represent the share offset by the cost of emissions (31.8 €2020/ton on average between 2020-2050, for more information on the estimation of carbon prices refer to **Table 15** and **Table 16**). Finally, solid bars represent the final unit costs of investment and are marked in yellow if they are negative (net savings from energy) or blue if positive (net costs from renovation).

Compared to **Figure 37** the situation is slightly different: the two basic scenarios plus "AdvExt"" do not recoup the initial investment within the 30 years period. Therefore, scenarios not under a frequent renovation regime are particularly penalized by the exclusion of subsidies and more in general by the change in perspective. On the other hand, scenarios with a frequent renovation regime end up all being financially positive, thanks to considerable contributions from both energy and monetized carbon savings. However, while from a financial perspective more ambitious interventions ("MinEnNeed" and "MinEnDel") resulted in better economic performance, here frequent but more shallow interventions ("Frequent") seem to deliver better results. Compared to other studies, this work found carbon costing to have great deal of influence on the overall macroeconomic viability of interventions. This can be explained by one modelling choice and one model limitation: (i) the inclusion of upstream emissions and (ii) the lack of emission intensity improvements in electricity generation. The largest savings related to emissions are experienced by the scenarios under a frequent renovation regime due to the comparison with buildings remaining in their original state (A2) having natural gas has main heating fuel and characterized by very low energy performance.

Figure 38. Scenario comparison of weighted average macroeconomic cost of investments (incl. life-cycle emissions) in year 2050 and over a 30 years accounting period (τ), *compared to Baseline.*



As a last remark, scenarios under an extensive RES implementation regime seem to deliver very little carbon savings in proportion to the energy ones. As it will be more exhaustively discussed in **Chapter Chapter 6.5**, this depends on the results from IOA which have many limitations and uncertainties, especially as far the carbon intensity of future electricity production is concerned.

To conclude this section on the global costs, Table 24 summarises the average net unit costs for all scenarios compared to Baseline over the 2020-2050 period.

Table 24. Summary table of weighted average net unit costs from a macroeconomic perspective [€2020/M^2], 2020-2050.

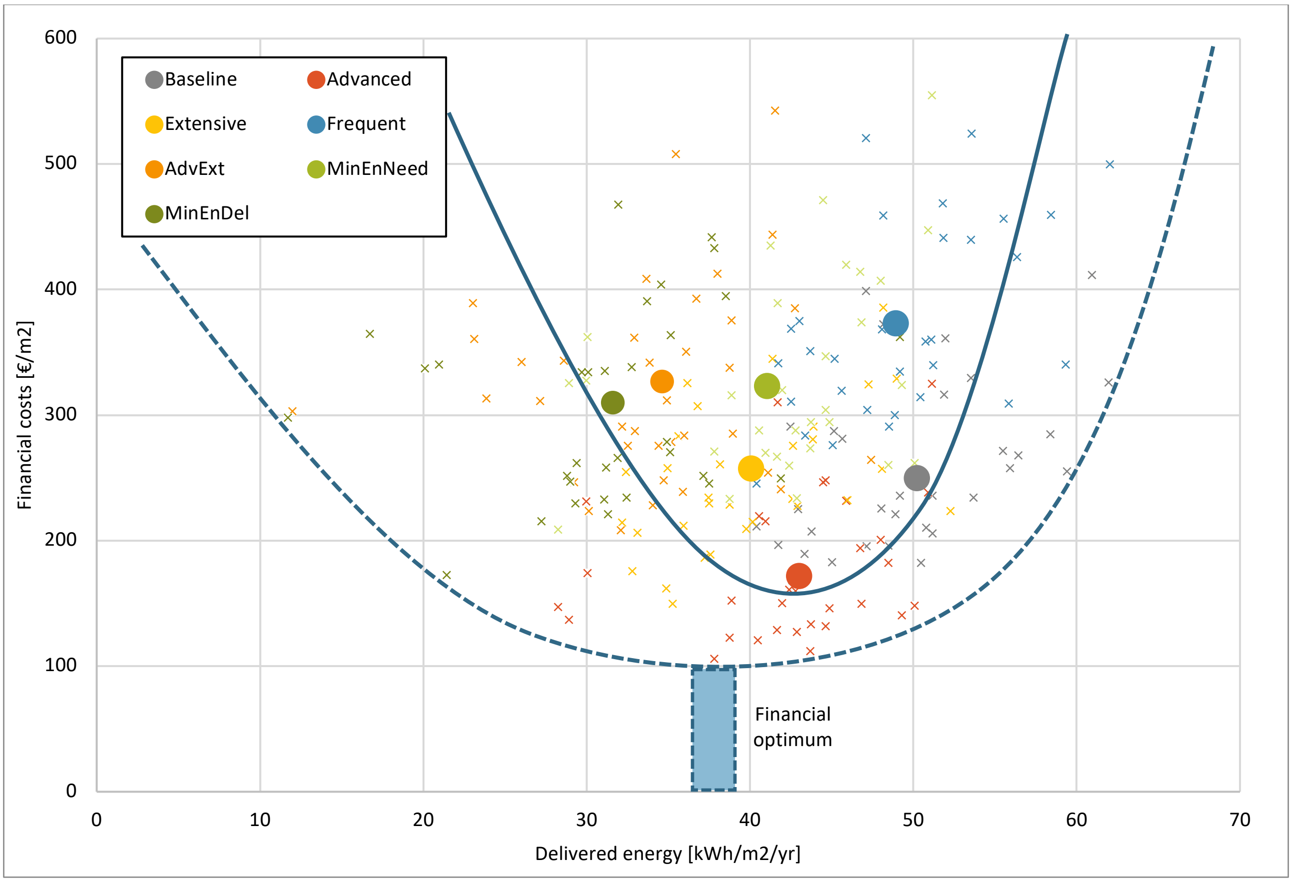
Indicator/scenario	Advanced	Extensive	Frequent	AdvExt	MinEnNeed	MinEnDel
Net unit costs (Scope 1, 2 and 3)	42.0	61.0	-367.5	47.0	-296.7	-300.9
Net unit costs – (Scope 1 and 2)	63.7	67.7	-301.2	77.1	-228.4	-224.6

5.3.3 Cost-Optimal Solutions

So far, scenarios comparisons have mainly focused on their relative performance in relation to the Baseline case. While this has the advantage of contextualizing the analysis based on expected trends, it does not inform about the actual efficiency of an investment. Moreover, since the Baseline case carries its own assumptions and uncertainty, it is relevant to evaluate each scenario in a more objective way. As in many other studies about the cost-optimal potential of renovation interventions, cost-optimality is expressed as the ratio between the financial/global cost and the energy performance per square meter after renovation (Ferrari and Zagarella 2015; Capozza et al. 2014). Average values over the 2020-2050 were taken in order to evaluate the scenarios on a level-paying field.

Figure 39 displays the relationship between delivered energy intensity after renovation (kWh/m^2) and the financial costs of renovation for all segments and for the scenario average. This plot is particularly useful to understand what solutions deliver the best energy performance at the lower costs and at parity of conditions across building types. This information can be used to prioritize action: solution at the bottom right of the plot are characterized by a very high energy performance at low investment costs and therefore represent the optimal investment while those in the upper left are combinations to avoid. In between, there are solutions delivering very good energy performances at comparatively high costs (upper left) and others that are convenient from a financial perspective, but do not untap the largest energy efficiency potential.

Figure 39. Cost-optimal curves for each segment (dashed) and scenario (solid), 2020-2050 average values. Note: three energy-negative solutions belonging to "MinEnDel" and "AdvExt" have been omitted for better visualization.



For instance, convenient solutions in the "MinEnNeed" scenario, are the combination of high efficiency condensing gas boilers coupled with solar heat collectors and high insulation in AB of recent construction or the air-water HPs in THs constructed between 1991-2005. An interesting combination in the "Advanced" scenario, instead, is represented by high envelope insulation of MFHs constructed between 2005-2020 coupled, once again, with high efficiency condensing boilers and heat collectors. The single most cost-optimal solution, however, is represented by high insulation of very old ABs (C0) in combination with a high efficiency condensing boiler. More in general, the group of interventions closer to the economic optimum are mostly represented by ABs and THs belonging to older cohorts (C0-C4) and equipped with high efficiency condensing boilers. This is not surprising for at least three reasons:

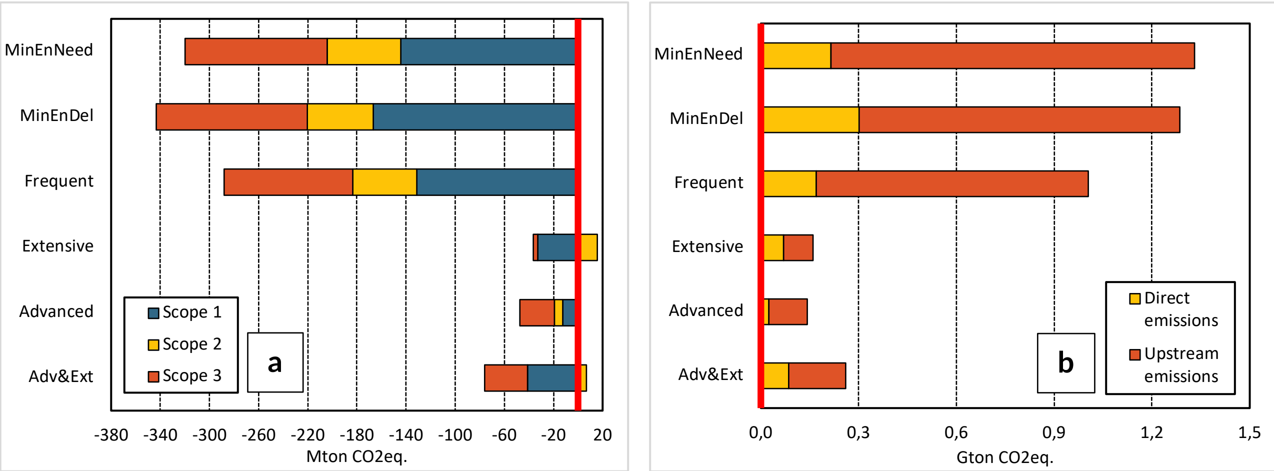
1. ABs and THs are building types with higher compactness ratio compare to MFHs and SFH respectively which brings down the unit costs especially for intervention to the building's envelope;
2. Buildings from older cohorts are characterized by a very poor energy performance and a natural need for renovation which makes them natural candidates for energy efficiency interventions; and
3. Despite, the cost of natural gas in Italy is quite high, the even higher capital costs of RES technologies make condeing boilers still a convenient option. However, this conclusion is very sensitive to the selected energy and technology costs

Overall, a key result of this study is that the economic optimum for renovation in Italy is defined by the three scenarios "MinEnDel", "Advanced" and "Baseline". "MinEnDel" incorporates the most ambitious interventions with an average delivered energy performance of 32 kWh/m^2 at an investment cost of 309 €/m^2. The Baseline scenario, representing continuation of trends, would bring the average performance of buildings renovated after 2020 at 50 kWh/m^2 for a slightly more modest unit cost of 249 €/m^2. Lastly, "Advanced" renovation of the building envelope represents the economic optimum for renovation in the Italian context with 43 kWh/m^2 at a cost as low as 171 €/m^2.

5.4 Societal Impacts

Taking a macroeconomic perspective at the evaluation of (renovation) strategies should not be limited to making economic sense of environmental impacts but possibly include broader societal aspects such as for instance, burdens sharing or, like in this study, employment generation. **Figure 40a** and **40b** show the cumulative GHG emission savings from energy reduction and the cumulative emissions from renovation activity, respectively.

Figure 40. Scenario comparison of cumulative GHG emission savings from energy-efficiency (**a**) and positive emissions from renovation activity (**b**) in year 2050.



A substantial difference can be noticed between basic and composite scenarios, with the latter delivering between 4- to 15-times more carbon savings and emitting between 4- and 9-times more during the renovation activity. This can be partially explained by the particularly low energy performance of buildings remaining in their original state (A2) and the larger use of natural gas as primary heating fuel rather than biomass. However, while there is some degree of proportionality between energy savings and emission savings of scenarios under advanced and frequent renovation regimes, the same is less true for those under the extensive regime. In fact, as shown in **Figure 40a** and touched upon in the global cost section, higher electricity consumption seems to have a particularly negative effect on emissions in the Italian context. The cause of this can be found in an electricity mix that, as of 2050 is still dominated for more than 50% by coal and gas, having emission intensities respectively of 876 and 372 ton/GWh against the 331 ton/GWh of biomass and 202.6 of natural gas for direct combustion.

Average emission savings spans from 0.7 (“Extensive”) to 11.1 Mton/yr (“MinEnDel”), corresponding to 1.4% to 23% of the yearly emissions from the residential sector in 2016 (Romano et al. 2018). This represent a reasonable result considering that, as mentioned in **Chapter 5.1.2**, the portion of stock focus of this analysis increases by 0 to around 25% of the total stock by 2050. For scenarios under frequent renovation regime, most savings come from Scope 1 (47%), followed by Scope 3 (36%) and Scope 2 (17%). In the “Advanced” scenario, the contribution from Scope 3 is much higher (59%) higher while in the “Extensive” the contribution from Scope 3 is minimal (6.5%) and the higher electricity consumption from HPs makes Scope 2 emissions larger than in the Baseline. These results suggest that the electricity generation supply chain is far more carbon intensive than its biomass and natural gas counterparts (the influence of petroleum products is minimal as they are completely phased by 2030 in all scenarios). This hypothesis is supported by a comparison of the total emission coefficients of the electricity sectors against those of the other energy carriers (**Table 25**).

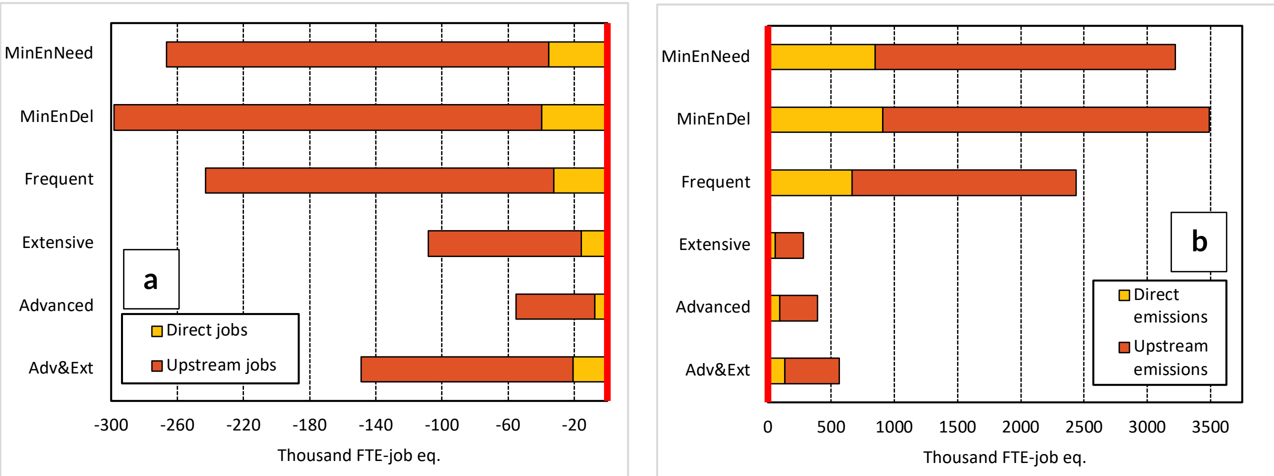
Table 25. Comparison between total emission coefficients ($b_j^l = b_i a_{i,j}$) of selected "energy products" used in this analysis. *Source: EXIOBASE*

Product	Natural Gas	Biomass	Gas/Diesel Oil	LPG	Electricity by coal	Electricity by natural gas	Electricity by biomass	Electricity by oil products
Code	p40.2.1	p20	p.23.20.f	p.23.20.i	p40.11a-l			
tCO_2/M€	275	262	1393	1401	**11544**	**4635**	**1712**	**2308**

As far as emissions from renovation activity are concerned, it can be observed that scenarios under an advanced renovation regime have lower shares of direct emissions and higher shares of upstream emissions. This suggests that sectors in the supply chain of chemical, fabricated metal products and rubber and plastic products are more carbon intensive than those related to RES technologies, namey electrical and general machinery and equipment.

Figure 41a and 41b shows the relation between total job losses in the energy sector as a result of less energy consumption and job creation as a result of the renovation activity. Job losses span from a total of 0.3 million jobs in the "MinEnDel" scenario to 60 thousand jobs in the "Advanced" scenario. One way of expressing the efficacy in reducing GHG emissions in the energy sector is to relate job losses to CO_2 savings to see which scenario saved most emissions at the lowest human costs. In these terms, the best performing scenario results the "MinEnNeed" with 1.2 ktCO_2eq. saved for every FTE-job lost. It is followed by "Frequent" (1.18) and "MinEnDel" (1.14) while the "Extensive" scenario is the worst performing with 0.19 ktCO_2eq/FTE-jobeq.

Figure 41. Scenario comparison of total employment loss in the energy sector (**a**) and employment creation from renovation activity (**b**) in year 2050.



Within the 30 years under analysis, the number of jobs created as a result of the renovation effort ranges between 278 thousand in the "Extensive" scenario to 3.5 million in the "MinEnDel" scenario. That is more than 100 thousand new jobs a year. The ratio between jobs created to GHG emitted sees the "Advanced" scenario as best the performing with 2.75 FTE-jobseq. created per ktCO_2eq.

Alternatively, emissions and employment can be related to the total renovation expenditure as summarized in **Table 26**.

Table 26. Comparison of emission intensity and efficiency of renovation investments [tCO_2eq./M€]

Indicator/scenario	Advanced	Extensive	Frequent	AdvExt	MinEnNeed	MinEnDel
GHG efficiency	-647	-325	-1187	-734	-826	-817
GHG intensity	1955	2511	4137	2748	3437	3062

6 Discussion and Conclusion

6.1 The Energy Transition in the Residential Sector

The first research question of this work wanted to investigate the relative and combined effectiveness of improved energy efficiency due to (a) more ambitious and (b) frequent renovation and (c) increased use of local renewable energy sources on improving the energy performance of the Italian dwelling stock towards 2050. To this end, the past, present and future composition of the Italian RBS was modelled with a focus on exploring the renovation activity as a natural need of an ageing stock and as a result of shortening such "natural" renovation cycle.

After reviewing the literature and upon expert judgment, 40- and 30-years renovation cycles were chosen for standard and frequent renovation, respectively. Under the first case, an average 1.2% yearly deep renovation rate could be achieved, up to 2.7% in the second case. The standard renovation rate was found to be in line with historical data, ranging between 0,16% and 2% depending on stock segment (see section H in the **Appendices**), but higher compared to the latest available data, namely 0.5% (Costanzo et al. 2016). Policy makers can use this information as a benchmark to monitor the market and private response in leveraging renovation as tool to address the energy transition in the residential sector. Future renovation rates below the natural need of renovation of the stock (<1.2%) would then be an alarming signal of inactivity. On the other hand, pushing the renovation rate up to 2.7% would increase the share of stock involved in renovation activity by 600 Mm^2, however not necessarily delivering substantial energy saving. In fact, as shown Chapter 5.2.1, frequent renovation alone is not able to move the stock towards the required low energy levels of 51-100kWh/m^2 and <51kWh/m^2. To reach these targets, frequent renovation needs to be deployed in combination with other strategies such as advanced envelope renovation and extensive implementation of RES. Additionally, as already brought up by Sandberg et al. (2017), it is important to stress how realistically renovation rate targets are being established at all societal levels. From this national study, it can be safely stated that the 5% yearly energy refurbishment rate identified by the IPPC to reach almost full decarbonization by 2050 is quite unrealistic. In Europe, the EPBD does not contain an explicit target for residential buildings, but here it is argued that the 3% yearly rate set for public buildings may represent a good balance between ambitiousness and feasibility.

Interestingly, according to this study the energy consumption of the Italian RBS is expected to experience a considerable reduction already in the Baseline scenario, decreasing by 37% from 2019 levels by 2050. This improvement is driven by standard renovation of the building envelope for buildings being in their original state and by general energy efficiency improvements of theTBSs. As mentioned above, a more frequent renovation regime alone would only add minimal improvements (40.4%) while extensive implementation of HPs and PVs has much higher reduction potential, estimated at 62% compared to 2019 levels. In terms of energy need intensity, in all these scenarios between 22.5% and 18.4% of the stock would still remain in the highly inefficient band (>150kWh/m^2/yr.), even in the case extensive implementation of RES technologies. For this reason, it becomes of primary importance to focus not just on improving the energy efficiency of buildings, but also on reducing its energy demand in the first place. It follows that advanced intervention on the building envelope in the form of improved insulation of façades, window frames and air-tightening technologies becomes almost imperative for Italy's energy transition. This is underpinned by the negative financial and macroeconomic results achieved by the Extensive scenario, suggesting that relying solely on the potential of renewable energy technologies does not appear as a workable nor sufficient solution.

At the “whole stock” level, “Advanced” renovation is expected to bring down energy consumption by 32% from 239 TWh/yr. to 166TWh/yr. Similarly to the comparison between “Baseline” and “Frequent”, more advanced and frequent renovation (“MinEnNeed”) does not deliver much additional energy savings (-35%). When, instead, advanced renovation is coupled with extensive implementation of RES, it achieves the second highest reduction with -49% from 2019 levels second only to “MinEnDel” (combination of all strategies) with -51%. *However, it should be noticed that scenarios under advanced renovation start at a considerably lower energy consumption level compared to the other (237 against 314 TWh/yr) meaning that their potential for energy efficiency savings is also lower.* It would then be interesting to repeat the analysis, this time modelling all scenarios under the same assumptions until 2020. This issue is discussed more in depth in **Chapter 6.5.** By focusing the analysis on just the portion of stock renovated after 2020 (C0-7, A3), all scenarios start from an A3 energy consumption of 0 in 2019 and hence they are all evaluated on a level-playing field. At this scope, strategies featuring a more frequent renovation rate results as much more effective in reducing the overall energy consumption due to the larger portion of stock invested. In these scenarios, the overall A3 energy consumption is higher because more renovation means more dwellings passing from Archetype 2 to Archetype 3. However, adding the share still in its original state (A2) to the comparison – the real benefits of increasing renovation rates emerge. Under these circumstances, interventions under the “Frequent”, “MinEnNeed” and “MinEnDel” scenarios would deliver 3.3, 5.4 and 8.4 times more energy savings compare the worst basic scenario (“Advanced”).

Although the energy consumption of the Italian RBS is already expected to decrease considerably at the aggregated level, the potential to meet ambitious European and national energy reduction targets lies in two specific categories: buildings subject to future deep renovation after 2020 and new construction. Under the Baseline scenario, about 50% of the stock is expected to remain unchanged between 2020-2050 (except for shallower interventions not covered in this study), either by staying in its original state or in a state of historical renovation. Another quarter of the energy potential will lie in newly constructed buildings not specifically addressed in this study and for which the EPBD recast already prescribes stringent nZEB and RES requirement starting from 2020 (EPBD recast 2010). Finally, the remaining 25+% is the potential related buildings that will need to undergo a deep renovation, critical if the EU and single MSs are to achieve the 80-95% reduction in GHG emissions compared to 1990 levels by 2050 (EC 2011). However, as highlighted in the BPIE surveys the lack of innovative financial instruments to support more ambitious deep renovations is one major limitation and concern. (BPIE 2015, 2011; Atanasiu and Kouloumpi 2013). This is because national financial programs and incentives continue to favour business-as-usual partial refurbishments that bring modest energy savings at lower costs and faster returns, but risk to close the “window of opportunity” for reaching the long-term goals.

In Italy, more frequent deep renovation (2.7% average yearly rate) has the potential to increase the share of stock exposed to activity from 25% to 40%. However, this strategy alone is not expected to bring significant additional energy savings unless coupled with more ambitious renovation standard and/or increased implementation of RES. A successful energy transition for the Italian RBSs needs to leverage the combination of “frequent”, “advanced” and “extensive” regimes for deep renovation.

6.2 Financial vs. Macroeconomic Perspective

The second research question added a monetary factor to the energy assessment by asking what scenarios would have the best economic performance, or more specifically the lower net unit costs of investment form both a micro- and macro-economic perspective. As highlighted in the context section of the **Appendices** (section A), financial issues constitute a major barrier to large scale and ambitious energy efficiency investments due to the considerable upfront capital required. Moreover, according to Eurostat, for most households the energy bills account for only 3-4% of the disposable income and thus they are not a considerable burden on the budget. Consequently, it is not always easy for renovation projects, especially ambitious ones, to meet the time-horizon expectation of households in terms of payback of the investment. Therefore, including a financial evaluation of the strategies is key to understand whether they represent a realistic option for the point of view of private investors.

From a financial perspective, the cumulative investment cost of renovations by 2050 were estimated between 126.6 G€ for the cheapest “Advanced” renovation scenario and 462.3 G€ for the most expensive “Frequent” renovation scenario. Under the Baseline scenario, 182 G€ are estimated to be spent anyways by households for the regular maintenance and upgrade of the stock. As a mean of comparison, the latest Italian Energy Strategy foresees the deployment of 110 G€ worth of investment in energy efficiency throughout all sectors between 2020-2030 (SEN 2017). According to the strategy, 42% of the energy savings (3.7 Mtoe) are expected to occur within the residential sector. Assuming a linear relationship between investment allocation and expected savings, this would translate into 46.2 G€ worth of investment by the government just in the residential sector. The average share of governmental subsidies (55-65% of the initial investment) over the total investment costs varies with time and across scenarios, ranging between 26% and 49% (at the next of VATs). By 2030, the required investment by the government to finance subsidized scenarios would then range between 17 and 78 G€. This suggest that the investment allocation foreseen by the Italian government for the residential sector would be enough to support all basic plus the “AdvExt” scenario, but not enough to support the more ambitious “MinEnNeed” and “MinEnDel” strategies. However, this conclusion does not consider that not all of the budget allocated to the residential sector is going to be invested in deep renovation projects.

Absolute figures are useful to gauge the monetary size of the renovation efforts in relation to the present policy plans, however they do not provide any information about the comparative efficacy and viability of the proposed interventions. To this end, it is useful to benchmark scenario performances in terms of net unit costs of the investment: the net amount of money per square meter that the investor is expected to gain or pay at the end of the 30 years accounting period. As it was shown in **Chapter 5.3.1 and 5.3.2**, the two scenarios with the lowest unit costs from a financial and macroeconomic perspectives were found to be “MinEnDel” and “Frequent”, respectively.

“MinEnDel” gets the best financial performance from the largest amount of subsidies, the best energy performance post-renovation and the increased number of dwellings involved in the renovation effort. All in all, the average return on investment for interventions included in this scenario is 243 €/m^2. Considering an average floor area per dwelling of 96 m^2/dwelling, this would amount to 23.3 k€ worth of savings at the net of the investment, making it an interesting option. “MinEnNeed” also delivers interesting savings estimated at 18.5 k€ while “Frequent” and “Advanced” result as less inviting investment with returns in the 10 k€ order. The savings delivered under “Extensive” implementation of HPs and PVs are just enough to recover the expense while “AdvExt” results the only scenario which does not provide any monetary benefit within 30 years accounting period. The particularly negative financial performance of “Extensive” and “AdvExt” is a signal of the relatively high price of RES technologies compared to the delivered energy savings. This is particularly true when considering that electricity consumption is much higher in these scenarios and that as of 2020 the cost per kWh of electricity is 34% higher than of natural gas, 73% higher than that of biomass and about the same of that of petroleum products. Interestingly enough, when the advanced and extensive regimes are complemented by more frequent renovation (“MinEnDel”), the result is flipped and what was the worst scenario in terms of financial costs (”AdvExt”) now becomes the best one (“MinEnDel”). *This is an interesting finding suggesting that standard renovation (“Baseline”) has better cost-benefit ratio than the most ambitious interventions combined. Only by increasing the share of renovated dwellings and benchmarking them to those remaining in their original state, these ambitious and costly solutions become economically feasible from the point of view of the investor. The extra costs introduced by operating outside the “window of opportunity”, that is to say outside the “natural” renovation cycle do not constitute a considerable barrier to the effectiveness of increasing renovation rates. These costs are in fact largely offset by the additional savings compared to a “no action” case where the building would remain in its original state.*

Closely related to the financial costs is the financial PBT of investments. A direct relationship between net unit costs and PBTs is found for all scenarios except in “Advanced” and Extensive” where the average PBT is lower compared to their unit savings. This is because subsidized “Advanced” renovation is a cheaper ption than unsubsidized standard renovation in all years while subsidized implementation of HPs and PVs results cheaper in the first 10 years. Given that PBTs can be calculated only when the initial investment is a negative cash flow, in these years the assigned PBT was set 0. This choice has the effect of bringing down the average PBT figure over the 2020-2050 period more than what reflected by the net unit costs. As a consequence, “Advanced” can be considered a financial no brainer for investors compared to the Baseline, despite the total savings are lower than those delivered by “MinEnNeed” and “MinEnDel”. Similarly, despite “Advanced” and “Frequent” having the same financial unit costs (100 €/m^2), their PBTs are very different, namely 0 and 17 years respectively. Reasonable PBTs for renovation projects are usually considered to be between 3 and 10 years depending on the investment (BPIE 2011). The results from this study show that the only 3 scenarios fall within this range while delivering also reasonable positive cash flows are “Advanced” (0 years – 100 €/m^2), “MinEnNeed” (8 years – 193 €/m^2) and “MinEnDel” (6 years – 243 €/m^2). *This trade-off between net unit costs and PBTs should serve as a reminder of the fact that more ambitious renovation investments - despite being more remunerative over the long term – can be perceived as less attractive by investors which could prefer a cheaper option with less returns in the immediate/short term rather than the other way around.*

This last finding is corroborated by the identification of the cost-optimal solution from the financial perspective (**Chapter 5.3.3**). Relating the financial costs to the delivered energy intensity post-renovation, it was found that the cost-optimal curve is defined by the three scenarios “MinEnDel” (32 kWh/m^2 – 309 €/m^2), “Advanced” (43 kWh/m^2 – 171 €/m^2) and “Baseline” (50 kWh/m^2 – 249 €/m^2) with “Advanced” representing the financial optimum. Considering that the average energy performance pre-intervention lies anywhere between 131 and 92 kWh/m^2 these values are found to be consistent with those reported in the literature. For instance, the BPIE reports average value for “standard” and “deep” renovation to be 140€/m^2 and 330 €/m^2 respectively and delivering between 30%-60% and 60%-90% energy savings. The National Agency for new Technologies, Energy and Sustainable Development (ENEA) estimated the Italian optimal cost of deep renovations between 204 and 503 €/m2 (370 €/m2 on average) with a related minimum energy performance between

23.3 and 71.8 kWh/m2/yr, depending on the building typology and climatic area (Corrado et al. 2014b). In very general terms, the group of interventions closer to the economic optimum are mostly represented by ABs and THs belonging to mid-aged cohorts (C2-C6) and equipped with high efficiency condensing boilers and soar heat collectors. Very effective but relatively more expensive solutions (depending on the scenario) comprise advanced insulation of the building envelope coupled with either ground-source HPs or biomass/gas boilers in combination with PV panels in older MFHs and SFHs.

As far as the macroeconomic costs are concerned, “Frequent” renovation gets its best performance mainly from two factors: the exclusion of subsidies and VATs and the absence of the concept of “window of opportunity” and thus the inclusion of indirect costs in all scenarios. Because of the latter, “Advanced”, “Extensive” and “AdvExt” do not recoup the investment within the 30 years, despite the inclusion of the monetized cost of the carbon savings. Surprisingly, the returns in terms of macroeconomic costs are higher than the financial ones: for “Frequent” renovation this would amount between 29 k€ and 35k€ depending on the emission scope included for monetization. “MinEnDel” and “MinEnNeed” have very similar returns estimated between 21.6 k€ and 28.9 k€. As explained in **Chapter 5.3.2**, the low “macroeconomic unit cost” of this scenario compared to the Baseline and the scenarios under frequent renovation regime originates from two facts: the particularly low energy performance of buildings in their original state (A2) and the absence of the “window of opportunity” (inclusion of indirect costs in all scenarios) and subsidies. Therefore, when evaluating investment from a societal perspective this study suggests that more frequent and less ambitious interventions seem to be the single best option. These results are found to be particularly optimistic since usually standard carbon prices are found not to be very influencing on the final costs (Ferrari and Zagarella 2015). Limitations and uncertainties to the approach for including carbon costs in the macroeconomic calculations are mentioned in the model’s limitations.

To conclude the discussion on the differences between financial and macroeconomic perspectives, the carbon and social impacts of scenarios are addressed. The inclusion of employment as criterion of social performance is argued to extend the boundaries of the macroeconomic analysis as intended in the SEE to a broader societal perspective. This aspect is particularly important considering the bad converge that the Italian construction sector, and the job market at large, is experiencing in recent years. In fact, the latest National Energy Strategy specifically addressed the need for a better evaluation of the socio-economic impact of the decarbonization process (SEN 2017). On this point, this study roughly estimated that total amount of additional new jobs as a results of renovation strategies is in the range of 2.7 and 7.6 FTE-jobeq./M€. In the most ambitious scenario, this would translate into the creation of 100 thousand net new jobs per year.

In terms of cumulative carbon emissions, there is a 4- to 15- times difference between scenarios under a frequent renovation regime and the other, both in terms of savings from energy reduction and in terms of emissions from renovation activity. Not surprisingly, most savings were found to occur as a result of reducing Scope 1 emissions (from combustion of residential fuels), and natural gas in particular (46%). Contributions from Scope 2 (electricity purchases) were the lowest (17%) since in half of the scenarios the electricity share in the residential heating mix remains at relatively low levels (20%). Surprisingly, scenarios with higher electricity consumption (extensive renovation regime), performed more poorly than the others. However, this result is influenced by limitations in modelling the energy system development. Nevertheless, this result should serve as a critical remainder for the fact that electrification of the heating and energy mixes should be pursued after a sufficient decarbonization of the generation mix. In Italy, despite the recent momentum in RES implementation, 50% of the energy mix is still expected to be powered on natural gas and carbon by 2050. Of the greenhouse gases included in this analysis, CO_2 is by far the most abundant. Other compounds that should require more careful analysis especially in terms of respiratory and effect related to human health are NMVOCs and PMs form biomass combustion.

To provide a more objective comparison, results were considered in terms of efficiency and intensity of the investments; where with the former is intended the amount of CO_2eq. saved per M€ invested and with the later the amount of CO_2eq. emitted throughout the renovation life-cycle per M€. In these terms, “Frequent” results the investment with the highest GHG efficiency at 1.2 ktCO_2eq./M€ while “Advanced” the one with the lowest GHG intensity at 1.95 ktCO_2eq.

6.3 Trade-offs in Renovation Strategies

The introductory sections underlined the importance of a systemic evaluation for large-scale complex strategies such as action plans for the renovation of national RBSs. In this thesis, the requirement is translated into a dashboard of indicators aimed at covering 4 key evaluation criteria: energy, carbon, money and employment. Although just representative, these criteria cover a cross-section of what are considered to be the dimensions of sustainability as well as the lenses of the industrial ecology analytical approach: environmental, social and techno-economic. **Table 26** lists the set of indicators estimated in this study, grouped by evaluation criteria and with a short description.

Table 27. Summary table of indicators by evaluation criteria with short explanation. *Source: Own elaboration*

Criteria	Indicator	U.M.	Explanation
Energy	Delivered energy reduction (C0-C8, A1-A3)	TWh	Delivered energy reduction at the stock level in the 2020-2050 period
	Delivered energy reduction (C0-C7, A3)	TWh	Delivered energy reduction in the 2020-2050 period only by dwellings renovated after 2020
Money	Net financial costs of investment	€/m^2	Average unit costs/savings in the 2020-2050 and considering a 30 years accounting period
	Net macroeconomic costs investment	€/m^2	Average unit costs/savings in the 2020-2050 and considering a 30 years accounting period
	Financial PayBack Time	Yrs.	Average financial payback time of the investments over the 2020-2050 period. Years where investment is negative (compared to the baseline) are given 0 years PBT
Environ mental	GHG efficiency of investment	tCO_2eq./ M€	Total GHG savings from energy reduction over total renovation investment
	GHG intensity of investment	tCO_2eq./ M€	Total GHG emissions from renovation activity over total monetary investment
	Carbon PayBack Time	Yrs.	Average carbon payback time of the investments over the 2020-2050 period
	Energy PayBack Time	Yrs.	Average energy payback time of the investments over the 2020-2050 period
Social	Job creation	FTE-job eq./M€	Average Net jobs created per M€ invested over the 2020-2050

In this chapter, the four criteria so far presented separately are comparatively addressed by means of an indicators dashboard (**Table 27**). This expected to provide a meaningful answer to the third research question about the relation between economic/financial viability and socio-environmental effectiveness of the energy renovation scenario. The colour scale allows for an intuitive understanding of which scenarios performed better in each category and for how many indicators. For each indicator, dark blue and red cells represent the best and worst performance, respectively.

In terms of energy, the most ambitious strategy ("MinEnDel") is by far the one delivering most delivered energy savings in absolute terms. This is true both for the case of a "whole stock" comparison (C0-C8, A1-A3) and for just the existing portion of stock renovated after 2020 (C0-C7, A3). While from the "whole stock" perspective, the difference between basic and combined scenarios is evident, when looking at just the renovated stock after 2020, the rank changes. "Frequent" goes from the worst performing to average performance while the opposite is true for "Advanced". Similarly, "AdvExt" drops from the second to the fourth position. This change is driven by two factors: Firstly, scenarios under the advanced renovation regime get most of their energy saving from the portion of the stock that underwent historical standard renovation between 1980-2020. In the other scenarios, this portion of the stock is instead still in its original state by 2020.

Table 28. Indicators dashboard. Colour scale from blue for best performing figures to red for worst performing figures. All indicators except for the energy ones are average values across the 2020-2050 period. For more information refer to **Table 22** or to the methodology Chapter.

INDICATORS DASHBOARD				Advanced	Extensive	Frequent	AdvExt	MinEnNeed	MinEnDel
Group	**n°**	**Indicator**	**U.M.**						
Energy	**1**	Delivered energy reduction (C0-C8, A1-A3)	[TWh]	1786	1091	337	2455	2090	2737
	2	Delivered energy reduction (C0-C7, A3)	[TWh]	81	161	269	221	438	680
Monetary	**3**	Net financial costs	[€/m^2]	-100	-8	-100	43	-193	-243
	4	Net macroeconomic costs	[€/m^2]	42	61	-368	47	-297	-301
	5	Financial PBT	[yrs]	0	11	17	69	8	6
Environmental	**6**	GHG efficiency	[tCO2eq./M€]	-647	-325	-1187	-734	-826	-817
	7	GHG intensity	[tCO2eq./M€]	1955	2511	4137	2748	3437	3062
	8	Carbon PayBack time	[yrs]	3.0	7.7	3.5	3.7	4.2	3.7
	9	Energy PayBack time	[yrs]	10.3	3.6	20.3	5.1	17.4	12.4
Social	**10**	Employment creation	[FTE-job/M€]	4.6	2.7	6.4	4.4	7.6	7.6

The consequence is two-fold: on the one hand "Baseline", "Extensive" and "Frequent" (scenarios without advanced renovation regime) have a much higher energy efficiency potential after 2020, on the other the exclusion of historical savings from indicator 2 penalizes much more the scenarios under advanced renovation regime. Secondly, in indicator 2, the additional part of stock renovated in scenarios under frequent renovation regime is compared against its counterpart remaining in its original state (A2) which gives them a large edge compared to the other. Interestingly enough, "MinEnNeed" and "MinEnDel", which integrate both an advanced and frequent regime are much more affected by the "positive" than the "negative" effect.

In monetary terms, a large variation can be observed between results for the three indicators. "Advanced" renovation results the most financially attractive solution from the point of view of the private investor not much for the 100€/m^2 worth of savings but for being an "economic no-brainer" (PBT equals 0). However, energy-related savings in "Advanced" make up only a small part of the total (on average 25%) and this is going to penalize this scenario under the macroeconomic perspective. Following, "MinEnNeed" and "MinEnDel" are the most remunerative scenarios within the 30 year and characterized by fairly low PBTs. Conversely from "Advanced", these scenarios require a large initial capital investment, which is paid off by the consistent energy savings from the extra share of renovated dwellings. "AdvExt" results as the least attractive solution across all three monetary indicators due to the fact that the additional energy savings coming from advanced envelope renovation and extensive implementation of HPs and PVs do not make up for the large initial and running capital required.

In environmental and social terms, performances across scenarios and indicators are also quite scattered. Investment in “Advanced” renovation has a particularly low GHG intensity and the lowest carbon PBT while it performs within the average in terms of GHG reduction per M€ as well as in terms of energy PBT. The “Extensive” scenario delivers the lowest amount of GHG saving per M€ spent hence its highest carbon PBT. However, it also characterized by the lowest energy PBT due to the good ratio between low embodied energy of investment and delivered energy savings. Conversely, the GHG intensive investment structure of “Frequent” is compensated by the highest GHG efficiency, resulting in a carbon PBT within the average (3.5. years). “Frequent” is also the scenario with the highest energy PBT, suggesting that the high (embodied) energy of the investment is scarcely offset by its modest delivered energy savings. More generally, it can be observed that scenarios with frequent and advanced renovation regimes are characterized by higher energy PBTs and this suggest that intervention to the building envelope (walls and windows) involving chemical, plastic and metal products are more energy intensive than electrical machineries and equipment. Moreover, scenarios under a frequent renovation regime are characterized by relatively higher energy than carbon PBTs. On the other hand, they also generate the largest number of FTE-jobs per M€ invested, namely 7.6 for “MinEnDel” and “MinEnNeed” and 6.4 for “Frequent”. Overall, it can be stated that from a socio-environmental perspective, scenarios characterized by a combination of different strategies have a more homogeneous performance across the indicators and can therefore be considered as more balanced and sustainable choices.

Overall, despite some trade-offs within and between the renovation scenarios some clear general conclusions can be drawn. Advanced renovation of the building envelope is most likely the most appealing solution from the point of the consumer due to its negative marginal investment and decent savings. The very low carbon PBT makes it also a safe environmental option, however it falls short in the key motivation behind the investment, namely the reduction in energy consumption. “Extensive” implementation of HPs and PVs falls short on almost the whole set of indicators, demonstrating that relying solely on renewable energy technologies is not a viable nor sustainable option by itself. A “Frequent” renovation regime has its own advantages, namely a good performance at the societal level due a low carbon PBT and a good amount of new job created. However, under this renovation strategy as well the delivered energy savings are not very promising, especially considering the very high energy PBT. “AdvExt” represents a curious case characterized by a very good energy performance at the whole stock level but below average when focusing on renovation after 2020. Despite its good environmental performance, the financial unfeasibility undermines any possibility of real implementation. “MinEnNeed” is characterized by considerable energy savings at both levels, good financial performance and a positive societal impact due to the considerable amount of jobs created. On the negative side, both its carbon and energy PBTs are below average. Finally, bringing together the advantages of all three basic strategies, “MinDelEn” stands out as the most effective renovation strategies from both a financial and socio-environmental perspective. Compared to “MinEnNeed”, this scenario will cut 35% more energy consumption and granting 21% more savings on households’ energy bills hence resulting more attractive for both governmental institutions and private investors. All this while generating 100 thousand net new jobs per year at an fairly low impact on the environment.

6.4 MODEL LIMITATIONS

Many are the limitations related to this work. Here, a comprehensive list of them is provided but only the main ones are briefly addressed. Suggestions for improvements and further research are also mentioned

The dwelling stock and energy model is based on a single climatic region (E) out of the 6 defined by the Presidential Decree no. 412/1993. Although building typologies specific for each climatic area could be found in the literature, the decision of not including them is based on two motivations:

- By increasing the number of regions from 1 to 5-6, the amount of input data needed for the model would easily surpass the time availability for the present work. Moreover, the correspondence between building and dwelling census data by ISTAT and climatic areas is not straightforward and would require a statistical elaboration at the provincial, if not at the communal level. To reduce the error introduced by this limitation, an adaption factor based on the national average HDDs was applied.
- The energy performance calculations as presented in TABULA are transparent, while those behind the new building types in Madonna & Vincenzo (2014) and Capozza and colleagues (2014) are performed through offline calculation. Therefore, given the decision of relying on pre-calculated energy need intensities, the use of more transparent data was preferred.

Another main limitation related to the use of the dwelling stock and energy modelling is that no adaption factor for changes in user behaviour was developed due to the considerable amount of empirical data required to building the adaptation trendline.

Probably the major limitation of this work is found in the link between the energy and economic models. In particular, the development in the unit costs of interventions was based on an assumed linear growth between manually estimated data points for 2020 and 2050. This is a rough approximation compared to a more proper "automated" approach based on the following 4 steps (the same used in the manual procedure):

1. Create a list of technologies with fuel and combustion efficiency as attributes (amongst the other);
2. For every year, gather from the stock energy model input sheet data about: the segment-specific energy mix and efficiency by energy carrier and shares of dwellings having HPs and PVs/SHCs installed;
3. From the model's output, for every year gather the development in the share of dwellings undergoing renovation in each segment;
4. For every year, use the shares of renovated dwellings/floor area by segment as allocation/weighting factors (3) to randomly assign the list technologies (2) to each segment using the data gathered in 2 as constraints;

As a first improvement to this model, the steps described above could be formulated in the form a multi-objective linear problem and algorithm developed to solve it.

Two main limitations are related to the financial assessment of scenarios, one related to the time-horizon of the analysis and the other to the estimation of the payback times. The first limitation is that all results of the economic model are extremely uncertain because they *had to* cover a very long future time-span (2020-2050-2080). The reason why they had to is because a single year analysis, say for year 2020 (hence until 2050 due to the 30 years accounting period for economic calculations), would have made no sense because of the long-term character of the scenarios: Just as an example, in the "Extensive" scenarios, the core investment is determined by the implementation of HPs and PVs, which in turn follow the development illustrated in **Figure 25** and **Figure 26**, respectively. As a result, the investment in the 2020-2030 and the related energy savings are extremely low compared to the 2030-2050 so that a comparison based on 2020 would have seen this investment as particularly ineffective or at least not representative of the whole scenario. Moreover, a single year analysis would have also suffered more from the second limitation described next. Simply put, this issue can be interpreted as the trade-off between performing an uncertain analysis with a level-playing for all scenarios, or a less uncertain at the expenses of a fair comparison. The second limitation arises from the following issue: the stock model estimates the renovation activity on a rolling basis for each segment and for every year it computes the new aggregated energy performance of that segment. This makes it hard to follow or trace back the energy performance of a segment as a result of an intervention taken place in a specific year. As a consequence, the estimation of the financial and environmental PBT had be based on the assumption that the energy and carbon savings calculated for the first year would repeat every year and only change as a result of changes in the energy price and price development rates. Other limitations related to the economic part of the environmentally-extended economic model is related to the absence of technological learning curves especially for renewable energy technology and uncertainty related to their development trends.

Finally, there are several limitations related to the connection between the economic data and the environmental-extended input-output database. First and foremost, the use of household final demand as the vector activated by the renovation stimulus constitutes a rough simplification. In reality, households do not directly purchase the products used in the renovation activity, but they rather purchase a renovation service. Within EXIOBASE, this renovation service is probably included in the gross fixed capital formation of the renovation sector which is a black-box of construction activity. In order to improve on this model, the link between the renovation expenditure should be based on a disaggregation of the gross fixed capital formation of construction into its construction and renovation shares. The resulting vector of gross fixed capital formation of construction could then be endogenized in the intermediate transaction matrix as to represent the renovation sector. Then, economic transactions within the intermediate coefficients matrix should be allocated to the new vector as to represent the monetary inputs and outputs from and to this new economic sector. Finally, the stimulus represented by the renovation investment of households could be properly applied. Other limitations related to the environmentally-extended model are the assumptions and estimations of the end-use coefficients which do not change over time. Similarly, also the carbon intensity of electricity generation technologies is assumed to remain constant so that the overall carbon intensity of electricity only varies as a result of changes in the electricity mix.

6.5 CONCLUSION

If Italy is to deliver on its long-term commitments to reducing energy and GHG emissions, the energy transition in the residential sector needs to happen and fast. The long lifetime of buildings and the capital-intensive nature of energy efficiency investments threatens to lock-in the country if fast, radical and effective action is not taken. This is true for renovation of the existing building stock, as well as for new constructions which together define the operating space for this transition to taken place. With the aim of supporting the residential energy transition, this study evaluated three basic plus three combined renovation regimes in terms of their financial viability and socio-environmental effectiveness along the 2020-2050 period. It concluded that no basic renovation strategy alone, whether it involves advanced renovation of the building envelope, more frequent standard renovation or extensive implementation of renewable energy technologies is at the same time an feasible and effective solution. A successful strategy will need to combine the advantage of single regimes: advanced renovation of the building envelope to decrease the energy need of buildings in the first place, extensive implementation of HPs, PVs and SHCs to further bring down the delivered energy consumption, and finally a more frequent activity rate to increase the number of dwellings involved in the renovation effort.

In this work, such deep renovation effort is identified with the "Minimizing Delivered Energy" scenario. Requiring a total investment of 78 G€ by 2050, this strategy is estimated to deliver cumulative energy savings for 680 TWh, thereby reducing the energy consumption of dwellings renovated after 2020 by 60% compared to the Baseline case. In the context of the last National Energy Efficiency strategy which foresees to reach 3.7 Mtoe/yr worth of (cumulated) energy savings in the residential sector by 2030, this scenario would allow to hit the target already in 2026 and to reach the 7.5 Mtoe/yr by 2030. As a result, it would cut on average 11 $MtCO_2eq$ per year and at the same time generating 100 thousand net new FTE-jobs in the sector involved in the renovation activity and their supply chains. All this while also providing an attractive investment option for households thanks to a PBT of 6 years and financial savings in the order of 23 k€ within a 30 year period. However, in order to deploy this strategy, the estimated 42.6 G€ of investments allocated by the Italian government for energy efficiency in the residential sector would need to be at least doubled within the considered timeframe. Despite not resulting as the absolute cost-optimal scenario ("Advanced"), "MinEnDel" seems to represent both a viable and effective strategy for the deep renovation of the Italian RBS; one that could improve the dwindling national energy security while boosting economic growth and employment.

From a methodological standpoint the bottom-up, dynamic and segmented dwelling stock energy model developed by NTNU has proven useful for the long-term analysis of energy efficiency strategies at the aggregated RBS level. Based on the conceptual and mathematical formulations of MFA, this tool lies at the intersection of Industrial Ecology and the emerging field of Building Epidemiology. It allows for a careful representation of the building stock and its development over time by means of reference buildings and a Time-Cohort-Archetype segmentation. Thanks to a cyclic renovation function, it is able to estimate the need for renovation as a result of the natural need for maintenance of the ageing stock. As opposite to most other studies, this allows to avoid the use of externally defined and sometimes unrealistic renovation rates. The energy analysis relies on pre-calculated energy need intensities for the reference buildings taken from the TABULA/EPISCOPE project in combination with energy mix and efficiency parameters, among the others. Climatic and user behaviour effects can be taken into account by means of adaptation factors, which however require considerable amount of data to be estimated. On the negative side, the model falls short in explicitly accounting for the effect of housing and energy policies as well as for more specific factors related to user behaviour which have a great influence the building “real” (as opposed to “technical”) energy consumption.

The methodological objective of this work was to integrate this MFA-based model with another toll from the field of Industrial Ecology, environmentally-extended input-output analysis. The aim was to complement the stock and energy analysis with an assessment of the life-cycle carbon, energy and employment implications. The link between the stock energy and the environmental model was established on the basis of economic cost data and the use of SEE. Here, the life-cycle costs of renovation options were quantified trying to take into account the time value of money. They were then mapped to the products/sectors in the input-output database and used to estimate the GHG and employment impacts. Despite the many limitations of this novel method, it has proven suitable to provide a rough estimate the economic and socio-environmental benefits and burdens related to the strategies. The general principle of linking data of physical characteristics (e.g. average heated floor area), energy performance (e.g. energy need intensities), economic value (e.g. product and energy prices) and environmental impact (e.g. emission intensities) to provide an integrated assessment of a stock of buildings should be further developed and refined. The resulting hybrid MFA-IOA approach could represent a valuable complement to the more established LCA for assessing the impact of larger stocks of buildings at the national and sub-national levels as opposed to the individual building level. Both approaches could be improved even further if combined, for instance, with an approach based Geographic Information Systems.

To conclude, this work attempted to bridge a research gap in the field of RBS stock modelling by proposing and developing an underrepresented approach based on Material Flow Analysis, Standard Economic Evaluation and Environmentally-extended Input-Output Analysis. The result of applying this model to evaluate the individual and combined effectiveness of 6 energy renovation strategies towards 2050 is the following: Large improvements in the aggregated energy performance of Italian buildings are only achievable if nearly zero energy new construction is supported by fast and deep renovation of existing buildings. At its most ambitious level, the latter represents a 78G€ challenge and opportunity that will significantly contribute to the large scale decarbonization of Italian housing stock while at the same time improving its energy security, cutting expenditure on households’ energy bills and boosting economic growth by creating new employment.

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