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Active managed Buildings with
Energy performaNce Contracting

Deliverable 4.2 (D4.2)

Report on the Methodology of creating the scenario's, integrating the models and adopt assumptions

The AmBIENCe Consortium

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EXECUTIVE SUMMARY

Deliverable D4.2 "Report on the Methodology of creating the scenarios, integrating the models and adopt assumptions" analyses the impact that the adoption of active control within the EU-27 building stock will have until 2050. This analysis serves the purpose to both understand how active control can shape the energy system and to describe the decarbonization pathways enabled by it.

The focus of the scenario analysis is to study the impact of some enablers of active control: renovating the EU-27 building stock (to a level allowing electrification), its electrification and the impact unlocked by the active control within the building stock. The quantification of its impacts (e.g., CO_2 emissions reduction) will then be compared at an overall aggregated and disaggregated levels – EU-level vs individual country. In the context of the energetic and climatic targets for 2050 this report attempts to lay out a policy-driven analysis by providing a quantifiable data and extracting insights on the EU-27 building stock's key role in achieving such targets and shaping the energy system decarbonization.

Concerning the later approach, the agnostic methodological framework consisted in describing the approach to gather all the required inputs for a simulation tool such as ABEPeM – although no simulation results were obtained from the project's tool, it aims to make this analysis possible resourcing to any other tool with the same capabilities.

These scenarios were built or fully developed from publicly available data sources: reports, papers and publicly available data from multiple sources. Following the series of data transformation steps and assumptions considered, and described, the focus is to study the energy system's impact of the adoption of active control within the building stock. For such an analysis the two main metrics used are:

- Carbon intensity (e.g., CO_2 emissions),
- Renovation costs.

Despite being developed in the context of AmBIENCe project, the KPI calculation tool will be available upon request while the scenarios' data will be publicly available for different purposes.

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1. INTRODUCTION: BACKGROUND AND SCOPE

1.1. THE CONTEXT

Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the European Union (EU) [1]. Energy efficiency measures are essential to improve building's energy, indoor quality and environmental performance by taking advantage of available technologies, without compromising the comfort and well-being of the building's users. Besides lowering energy use, using energy in a smarter manner, e.g. using local and/or renewable energy sources (RES), is a complementary approach to reduce buildings emissions. Developing new smart energy services that use flexibility from demand-side resources in different sectors is essential in order to fully unlock the potential of buildings towards energy cost savings and CO_2 emissions reduction, while meeting the climate goals. The use of information and communication technologies (ICT) solutions and tools can trigger significant CO_2 emission and cost savings with reduced investment, coupled to renovation of the existing building stock.

A new concept for performance guarantees of Active Buildings, combining savings from energy efficiency measures and the active control of assets, leveraging the use of flexibility is developed within AmBIENCe. The combination of Demand Response (DR) with current Energy Performance Contract (EPC) schemes establishes the Active Building EPC (AEPC) concept [2]. The project aims to extend the concept of Energy Performance Contracting to Active Buildings, which are buildings equipped with active control options that can actively participate in demand response and energy efficiency programmes and make it available and attractive to a wider range of buildings. Active control-based services can contribute to both demand response reacting to market/price signals or contractually external regulation of electricity demand based on the (heat and electricity) storage potential of the building. Introducing flexibility and DR in more buildings, allowing energy to be used when prices are low as more RES are available, will decrease the CO_2 emissions and reduce the energy cost of buildings.

1.2. PURPOSE AND SCOPE

Deliverable 4.2 falls within the scope of Work Package 4, "Energy System Impact Assessment Calculation Methodology and Tool", with the main objective to assess the impact on the upstream energy system of active control in buildings. As far as they are distributed in the market, active control-based services can contribute to demand response by reacting to market/price signals, for example. For this assessment, the assumptions on adoption of active control strategies (flexibility control, via DR) within the market and the building stock need to be developed. These assumptions, aligned with the defined future AmBIENCe scenario, feed a KPI calculation tool that assess the energy system impact of the adoption of active control within the building stock.

The building stock information database described in Deliverable 4.1 [3] includes data on the EU27 building stock and its reference buildings as well as parameters that allow to calculate the impact of active control in the energy system with a KPI calculation tool. Deliverable 4.2 describes the methodology and assumptions taken into consideration for defining the scenarios of adoption of active control in buildings and its impact on the energy system. For the creation of the methodological framework, a set of relevant data will be gathered to feed to the KPI calculation tool supplemented with the Active Building Energy

Performance Modelling (ABEPeM) platform, [4], or any other simulation tool with the same capabilities.

This report explains:

- The development of scenarios for adoption of active control in buildings;
- The calculation of the impact of active control adoption on the energy system:

Considered inputs, and relevant assumptions considered for the adoption of active control in the market and the building stock development;

- The outputs of the energy system impact assessment framework, or Key Performance Indicators (KPIs);
- The information and data sources used for all of the above-mentioned inputs and outputs.

2. CURRENT STATUS OF THE ENERGY SYSTEM

2.1. INTRO

In order to be able to draw the evolution for the time-frame analysis period, a clear depiction of the current situation must be done. This encompasses the current building stock and technical systems, the current energy system and markets, and the current situation with regard to DR and energy policies.

2.2. TECHNICAL SYSTEMS

The goal of assessing the impact of the adoption of active control strategies within the EU-27 building stock in the year 2050 requires a prior assessment of the current state of the building stock. With this in mind and having an extensive description of the current state of said building stock in the previous deliverable 4.1 [3],this section aims at extending the scope of the database of grey-box model parameters by including a detailed and accurate depiction of the building stock in what regards the presence of technical systems, called the 'Energy systems 'database – this database is publicly available and can be found in AmBIENCe's public deliverables [5]. This will allow to establish, posteriorly, assumptions for the time-frame analysis period enabling which in turn will enable the energy system impact calculations.

'The energy systems' database was prepared with outputs from the EU projects TABULA-EPISCOPE (2009-2017) [6] and Hotmaps (2016-2020) [7]. It includes information about heating, Domestic Hot Water (DHW) and cooling systems for every building typology featuring in the building stock database prepared for the deliverable 4.1, named "Database of grey-box model parameter values for EU building typologies" in short AmBIENCe database. The typologies covered encompass all the 27 EU MS, and are classified according to the following parameters:

- For **Residential buildings:**
    - **Size**: *Single-family buildings, Multi-family buildings, and Apartment blocks*
    - **Construction periods**: *Differing among countries, both in number and length*
- For **Non-residential buildings:**
    - **Use**: *Office, Trade, Education, Health, Hotels and restaurants, Other non-residential buildings,*
    - **Construction periods**: *Before 1944, 1945-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2010, 2001-2009, 2011 and after*

2.3. BASIC ASSUMPTIONS

A series of assumptions were made to optimize the accuracy and quality of the provided data while simplifying the preparation process to ensure clarity and consistency. These are:

- Each building typology (represented by the country, the building use and the construction year period) can have a maximum of 3 different heating and DHW systems defined.
- Following the Hotmaps approach for non-residential building typologies, 4 groups of countries were established. Each of these groups share common building energy systems for heating and DHW,

based on those from the countries featuring in TABULA from each group[1]. The groups are:

- Group 1 ("Central Europe"): AT, BE, DE, FR, IE, NL & LU → Represented by a selection of energy systems from AT, BE, DE, FR, IE & NL
- Group 2 ("Eastern Europe"): BG, CZ, HR, HU, PL, RO, SI & SK→ Represented by a selection of energy systems from BG, CZ, HU, PL, SI & SK
- Group 3 ("Southern Europe"): CY, EL, ES, IT, MT & PT → Represented by a selection of energy systems from CY, EL, ES, & IT
- Group 4 ("Northern Europe"): DK, EE, FI, LT, LV & SE → Represented by a selection of energy systems from DK, NO[2] & SE

- The share or prevalence of each technology within each building typology can adopt a series of limited fractions: 1/1 (100%), 1/2 (50%), 1/3 (33%), 1/4 (25%), 1/5 (20%), 2/3 (67%), 2/5 (40%), 3/4 (75%), 3/5 (60%) and 4/5 (80%) based on Hotmaps authors' statements [8] in this regard (which define the degree of prevalence of the different technologies and fuels in each typology with the expressions "Most widespread", "Widespread", "Less widespread" and blank). Table 1 explains the fractions adopted for each of the 7 combinations of expressions that can be found in Hotmaps.

TABLE 1. CRITERIA EMPLOYED TO DETERMINE THE SHARE OF PREVALENCE OF ENERGY SYSTEMS FOR EACH BUILDING TYPOLOGY BASED ON HOTMAPS' PROJECT EXPRESSIONS

	System 1	System 2	System 3
Combination No.1	*Most widespread*	*Blank*	*Blank*
	100%	*0%*	*0%*
Combination No.2	*Most widespread*	*Less widespread*	*Blank*
	75%	*25%*	*0%*
Combination No.3	*Most widespread*	*Widespread*	*Blank*
	67%	*33%*	*0%*
Combination No.4	*Most widespread*	*Less widespread*	*Less widespread*
	60%	*20%*	*20%*
Combination No.5	*Widespread*	*Widespread*	*Blank*
	50%	*50%*	*0%*
Combination No.6	*Widespread*	*Widespread*	*Less widespread*
	40%	*40%*	*20%*
Combination No.7	*Widespread*	*Widespread*	*Widespread*
	33%	*33%*	*33%*

[1] An exception was made for the efficiency value of RES-powered systems, as TABULA disregards this field. For the case of solar collectors (the sole RES-powered technology featuring in this database) an average annual value of flat plate and evacuated tubes technologies at different transfer fluid temperatures (60 and 90°C) was applied, obtained from the following source: https://www.e3s-conferences.org/articles/e3sconf/pdf/2020/67/e3sconf_fpepm2020_02007.pdf

[2] Even if Norway doesn't belong to the EU, it was considered that the characteristics of their technical systems were in line with those from DK and SE and would be helpful to complement the set of systems selectable from the Group 4, as it is the group with the least number of countries used as a basis to make up a selection.

- In the particular cases when overlapping between construction periods from Hotmaps and from the AmBIENCe database occur, a calculation was based on the proportion of years from each Hotmaps period, and the result was rounded up to the nearest fraction from those listed above. In each of these particular cases, a comment made in the cell of the percentage of prevalence is made so to justify the result of the final fraction adopted.
- When in a single building typology there were more than 3 technical systems described[3] according to the Hotmaps database (either for heating or for DHW), the most compatible ones were merged (for example, individual and central non-condensing boilers). In this way the number of systems was reduced to three.

2.4. HEATING SYSTEMS

For heating (and also for DHW) systems, the following parameters are provided in the 'Energy Systems' database:

- **Technology** (providing the full name given to it);
- **Dimensions**: *Individual, Central or District;*
- **Fuel used**: *Gas, Liquid, Solid, Electricity, Biomass and RES;*
- **Efficiency**: Expressed in %, defined as useful energy/used energy, meaning:
    - **In the case of boilers, stoves, electric heaters and solar collectors:** *Useful energy means the energy gained by the conditioned space, and used energy means the amount of input energy used by the device.*
    - **In the case of heat pumps (for cooling or for heating):** *Useful energy means the heat extracted from (cooling)/ provided to (heating) the conditioned space, and used energy means the amount of electricity used by the device to do so.*

Heating technologies vary for each of the four defined geographical groups described in the previous section. The tables below show possible characteristics of the different heating systems per technology and per group of countries.

[3] This only happened on very few cases, and a justifying comment was always provided in the database cell.

TABLE 2. HEATING SYSTEMS IN THE GROUP 1 (AT, BE, DE, FR, IE, NL & LU)

Technology	Dimensions	Fuel	Efficiency
Central heat pump air source old	Central	Electricity	263%
Central heat pump air source new	Central	Electricity	385%
Central gas low temperature non-condensing boiler	Central	Gas	81%
Central gas condensing boiler	Central	Gas	94%
Central fuel oil non-condensing boiler	Central	Liquid	81%
Central fuel oil condensing boiler	Central	Liquid	89%
District heating gas boilers high temperature	District	Gas	70%
Individual wood stove	Individual	Biomass	59%
Individual electric convector heater	Individual	Electricity	94%
Individual electric underfloor radiant heating	Individual	Electricity	98%
Individual air/water heat pump	Individual	Electricity	233%
Individual gas stove	Individual	Gas	72%
Individual gas low temperature non-condensing boiler	Individual	Gas	78%
Individual gas condensing boiler	Individual	Gas	93%
Individual fuel oil stove	Individual	Liquid	51%

TABLE 3. HEATING SYSTEMS IN THE GROUP 2 (BG, CZ, HR, HU, PL, RO, SI & SK)

Technology	Dimensions	Fuel	Efficiency
Central biomass boiler old	Central	Biomass	50%
Central biomass boiler new	Central	Biomass	72%
Central gas non-condensing boiler	Central	Gas	81%
Central gas condensing boiler	Central	Gas	97%
Central fuel oil boiler old	Central	Liquid	74%
District heating gas boilers	District	Gas	95%
District heating coal station non-CHP	District	Solid	99%
Individual electrical night storage heater	Individual	Electricity	100%
Individual gas condensing boiler	Individual	Gas	85%
Individual gas non-condensing boiler	Individual	Gas	86%

TABLE 4. HEATING SYSTEMS IN THE GROUP 3 (CY, EL, ES, IT, MT & PT)

Technology	*Dimensions*	*Fuel*	*Efficiency*
Central gas non-condensing boiler old	Central	Gas	64%
Central gas non-condensing boiler new	Central	Gas	84%
Central gas condensing boiler	Central	Gas	100%
Central fuel oil non-condensing boiler	Central	Liquid	75%
Individual electric convector heater	Individual	Electricity	94%
Individual gas non-condensing boiler	Individual	Gas	74%
Individual gas condensing boiler	Individual	Gas	100%
Individual fuel oil stove	Individual	Liquid	49%

TABLE 5. HEATING SYSTEMS IN THE GROUP 4 (DK, EE, FI, LT, LV & SE)

Technology	*Dimensions*	*Fuel*	*Efficiency*
Central heat pump air-water	Central	Electricity	323%
Central gas non-condensing boiler	Central	Gas	88%
Central gas condensing boiler	Central	Gas	95%
Central fuel oil boiler	Central	Liquid	90%
District heating gas boilers old	District	Gas	94%
District heating gas boilers new with heat recovery	District	Gas	97%
Individual electric convective heater	Individual	Electricity	100%
Individual heat pump air to air	Individual	Electricity	250%
Individual gas condensing boiler	Individual	Gas	95%
Individual fuel oil boiler	Individual	Liquid	87%

2.5. DHW SYSTEMS

With respect to DHW systems, an identical approach to that for heating systems was taken (see 2.4). The following tables contain the information about the different DHW systems present in the 'Energy Systems' database.

TABLE 6. DHW SYSTEMS IN THE GROUP 1 (AT, BE, DE, FR, IE, NL & LU)

Technology	*Dimensions*	*Fuel*	*Efficiency*
Central heat pump air to water	Central	Electricity	278%
Central gas low temperature non-condensing boiler	Central	Gas	83%
Central gas low temperature condensing boiler	Central	Gas	85%
Central fuel oil non-condensing boiler	Central	Liquid	62%
Central fuel oil condensing boiler	Central	Liquid	90%
Individual electric heated DHW tank	Individual	Electricity	90%
Individual heat pump with auxiliary resistance heating	Individual	Electricity	119%
Individual gas low temperature non-condensing boiler	Individual	Gas	74%
Individual gas condensing boiler	Individual	Gas	93%
Individual gas condensing boiler	Individual	Liquid	61%
Individual fuel oil condensing boiler	Individual	Liquid	85%
Individual solar collectors	Individual	RES	68%

TABLE 7. DHW SYSTEMS IN THE GROUP 2 (BG, CZ, HR, HU, PL, RO, SI & SK)

Technology	*Dimensions*	*Fuel*	*Efficiency*
Central gas low temperature non-condensing boiler	Central	Gas	83%
Central gas condensing boiler new	Central	Gas	98%
District heating gas-powered station	District	Gas	95%
District heating coal-powered station	District	Solid	87%
Individual electric heater	Individual	Electricity	100%
Individual gas non-condensing boiler	Individual	Gas	65%
Individual gas condensing boiler old	Individual	Gas	85%
Individual gas condensing boiler new	Individual	Gas	98%

TABLE 8. DHW SYSTEMS IN THE GROUP 3 (CY, EL, ES, IT, MT & PT)

Technology	*Dimensions*	*Fuel*	*Efficiency*
Central gas non-condensing boiler	Central	Gas	70%
Central gas low temperature condensing boiler	Central	Gas	85%
Central fuel oil non-condensing boiler	Central	Liquid	88%
Individual electric heater	Individual	Electricity	97%
Individual gas non-condensing boiler	Individual	Gas	70%
Individual gas condensing boiler	Individual	Gas	81%
Individual gas condensing boiler	Individual	Liquid	88%
Individual solar collectors	Individual	RES	68%

TABLE 9. DHW SYSTEMS IN THE GROUP 4 (DK, EE, FI, LT, LV & SE)

Type and full name	*Dimensions*	*Fuel*	*Efficiency*
Central biomass non-condensing boiler	Central	Biomass	80%
Central heat pump air to water	Central	Electricity	250%
Central gas non-condensing boiler	Central	Gas	91%
Central gas condensing boiler	Central	Gas	95%
Central fuel oil non-condensing boiler	Central	Liquid	85%
District heating gas boilers old	District	Gas	94%
District heating gas boilers new with heat recovery	District	Gas	97%
Individual electric boiler	Individual	Electricity	98%
Individual heat pump air to water	Individual	Electricity	250%
Individual gas non-condensing boiler	Individual	Gas	91%
Individual gas condensing boiler	Individual	Gas	95%

2.6. COOLING SYSTEMS

Due to the lack of information available, cooling systems are much more simply described in the database. Information on cooling systems includes only their share within each building typology in a coarser way than that of heating and DHW systems. Therefore, the only parameter provided with respect to these systems is the mere prevalence of the cooling systems within the building stock. Qualitative information provided in Hotmaps have been converted to the fractions in the following way (Table 10).

TABLE 10. FRACTIONS ASSIGNED TO QUALITATIVE INFORMATION ON SHARE OF COOLING SYSTEMS (PROVIDED BY [7])

Most cases yes	100%
Half of cases yes	50%
Most cases no	0%

In case of overlaps between the construction year periods from the 4.1 database typologies' and those from Hotmaps, a calculation of a fraction based on the proportion of years from each Hotmaps' period involved was made, following the same logic than for heating and DWH systems. In each of these particular cases, the typology in question receives the denomination "special case".

2.7. CURRENT STATUS OF DEMAND RESPONSE (DR)

In the context of AmBIENCe project, in [9], an assessment of current status of DR services offered by (clusters of) buildings throughout the EU-27 countries was carried out. In this section a brief summary of that assessment is presented.

Four key areas were identified for the critical assessment of the status of DR serviced offered by clusters of buildings, which are:

1. DR access to markets, measuring to what extent demand response is allowed as a resource within the different national electricity markets (i.e., wholesale, balancing, ancillary services, capacity mechanism, and strategic reserves).
2. Service providers access to markets, measuring how direct is the access of consumers to independent service providers, alongside retailers. In particular, it focuses on progress towards fair and standardised arrangements between retailers and aggregators.
3. Product requirements: reflecting how well are the available products/programmes enabling demand-side resources to participate.
4. Measurement and verification procedures, measuring how standardised and transparent rules on how Demand Response events should be measured.

Below, in Figure 1, is presented a mapping of the status of DR serviced offered by clusters of buildings in the EU-27 countries – with the exception of Cyprus and Estonia since "they are characterized by a complete absence of a regulatory framework allowing DR access to the market" [9]. The categories presented in Table 11 aim to reflect and to score the countries according to each one of the four key areas. For a more in-depth analysis concerning the methodology to score the countries see [9].

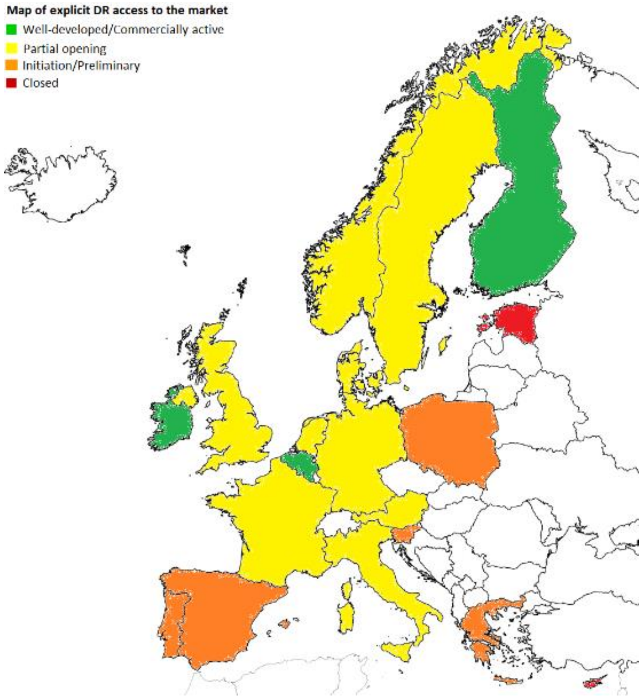


FIGURE 1: STATUS OF BUILDING'S FLEXIBILITY ASPECTS FOR DR SERVICES FOR THE COUNTRIES REPRESENTED IN THE EU. COMBINED FROM [7]

Below, in Table 11, a summary of the overall status and what does each category highlighted in the map mean.

TABLE 11: SUMMARY OF DEVELOPMENT STATUS OF DR SERVICES OFFERED BY CLUSTERS OF BUILDINGS, FOR ALL EU-27 COUNTRIES. ADAPTED FROM [7]

<table>
<tr><th>Well-developed/ Commercially Active</th><th>Partial Opening</th><th>Initiation/ Preliminary Development</th><th>Closed</th></tr>
<tr><td>Finland
Ireland
Belgium</td><td>United Kingdom
France
Norway
Sweden
Germany
The Netherlands
Austria
Denmark
Italy</td><td>Greece
Slovenia
Poland
Portugal
Spain</td><td>Estonia
Cyprus</td></tr>
<tr><td colspan="2">Defining characteristics
DR participation allowed in multiple electricity markets;
Product requirements well established according to the criteria of “technological neutrality”;
Positive cooperation between stakeholders (new market actors, regulators and retailers).
Benefits for small customer still rather small: revision of requirements ongoing to reduce minimum bid sizes.</td><td colspan="2">Defining characteristics
Regulation is slow to appear, it needs a faster adoption to enable DR services.
Insufficient market players (aggregators)
No dedicated flexibility market;
High minimum bid size on the existing market (AS market);
The huge energy-saving potential of building stock has not been realized;
Lack of economic and contractual incentives;
Privacy issues for data to be solved;
High cost for the qualification and Measurement and Verification equipment to create flexibility from demand side;
DR participation mainly reflected at the level of research programs.</td></tr>
</table>

2.8. CURRENT STATUS OF ENERGY POLICIES

In the context of AmBIENCe project an assessment was conducted concerning the current state of the regulatory framework and supporting policies to the Active Building EPC, in [7]. In this section a brief overview is summarized. For a more in-depth analysis [9] provides a broader outlook.

The ETIP SNET VISION 2050[4] [10] is a “low-carbon, secure, reliable, accessible, cost-efficient, and market-based pan-European integrated vision for an energy system that supplies the whole economy and paves the way for a fully CO_2-neutral and circular economy by the year 2050” [9]. In this vision, European citizens are regarded as the main actors and agents of change in this energetic transition. This central role is made possible by the active participation in consumption and production – prosumers. Additionally, demand flexibility, as a service and a product, plays a key role throughout this transition. According to [9], “the active role of consumers as prosumers is fully implemented in the mechanisms of DR, through which the user is made an active participant in the management of network contingencies, as well as in reducing energy consumption through applications such as zero energy buildings or renewable energy communities”.

In line with this, in 2019 the European Commission (EC) passed the Clean Energy Package for all Europeans which brings a set of initiatives and directives who aim to boost the energy transition competitiveness and shape the future European energy sector. The Clean Energy Package is composed by eight legislative acts concerning different areas of the energy sector, [9]:

1. Reshaping the European electricity market, with four packages: Regulation on risk preparedness in the electricity sector (EU 2019/941), Regulation establishing a European Union Agency for the Cooperation of Energy Regulators - ACER (EU 2019/942), Regulation on the internal market for electricity (EU 2019/943) and the Recast of Electricity Market Directive on common rules for the internal market for electricity (EMD II - Directive 2019/944) [8]. This EMD II aims for the construction of a true internal electricity market governed by common rules, accessible to all and in which all consumers can directly participate by adjust their consumption based on market signals . The directive aims to “qualify consumers as “active customers”, who can operate directly or in aggregate manner, sell self-produced electricity, including through agreements for the purchase of electricity and participate in flexibility and energy efficiency mechanisms” [4]. Thus, lower electricity prices and incentives are the main drive. Another important concept introduced by the EMD II is the “Citizen Energy Community ”.
2. Renewable energy, regulated within the revised Renewable Energy Directive (RED II - Directive 2018/2001) [9], paying special attention to self-consumption and renewable energy, providing that consumers can also be able to produce, store and sell the renewable electricity produced in surplus, both individually and through aggregators, introducing the concept of “Renewable Energy Community” .

[4] European Technology & Innovation Platforms (ETIPs) were been created by the EC in the framework of Integrated Roadmap Strategic Energy Technology Plan (SET Plan) by bringing together stakeholders and experts from the energy sector. The ETIP Smart Networks for Energy Transition (SNET) role is to guide Research, Development & Innovation (RD&I) with the key mission to set-out a vision for RD&I for Smart Networks and engage stakeholders, to support the energetic transition.

3. Energy efficiency regulated within the revised Energy Efficiency Directive (new EED – Directive 2018/2002) [10]. Here the aim is to update the current provisions directly linked to the achievement of 2030 objectives while introducing new rules which aim at extending the consumer rights and improve access to smart metering, smart billing and consumption information [7].
4. The recast of the Energy Performance of Buildings (EPBD - Directive 2018/844) [11]. The focus point of the recast of the EPBD is to set new standards for minimum energy performance requirements, energy certification, verification methods and monitoring and control of energy use in the building sector. By adopting the concept of smart readiness indicator and a methodology by which it is to be calculated are established, it aims to assess the capabilities of a building to adapt its operability to the needs of occupants and of the grid, improving its energy efficiency and overall performance.
5. Request to Member States to draw up a "National Energy and Climate Plan" covering a time horizon of 10 years (from 2021 to 2030), as expressed within the Governance of the energy union and climate action Regulation EU 2018/1999 [12]. The purpose being encouraging and leveraging cooperation between each Member State to achieve the EU's objectives and targets.

3. DEFINITION, DESIGN AND MAPPING THE SCENARIOS

3.1. THE ENERGY ROADMAP 2050

In this section the considered energy related scenarios are described. From this, we can draw some useful insights from which the assumptions to adopt active control can be built upon.

In the 'Energy roadmap 2050' [15] the EC explores routes towards the decarbonisation of the energy system, to which it is committed. This seeks to develop an illustrative long-term European technology-neutral framework through which it is possible to "examine the impacts, challenges and opportunities of possible ways of modernising the energy system" [15] until the year of 2050, which coincides with the time-frame analysis period considered for in this work.

Thus, the developed scenarios provide an outlook on how the energy sector would look in the time-frame analysis period considered in this task – 2050.

For the scope of this work five different scenarios were considered (a reference scenario and four decarbonisation scenarios), out of the seven developed scenarios from the EU energy roadmap – one additional reference scenario and one decarbonization scenario which focused on Carbon Capture and Storage (CCS) were opted out to simplification reasons, since the two scenarios were not considered relevant for this work. The considered scenarios under this task are as follow:

- Reference scenario. This scenario is equivalent to one of the reference scenarios considered in EU's 2050 Energy Roadmap [15], Current Policy Initiative. From here on forward we will call this scenario Reference Scenario, this scenario acts as a benchmarking for energy scenarios achieving the EC's objective to reduce greenhouse gas (GHG) emissions by 80-95% below the 1990 level;
- High Energy Efficiency scenario. This scenario is based on the homonymous scenario in EU's 2050 Energy Roadmap [15]. This scenario is driven by a political commitment of very high primary energy savings by 2050. It includes a very rigorous implementation of the Energy Efficiency Plan;

- Diversified Supply scenario. This scenario is based on the homonymous scenario in EU's 2050 Energy Roadmap [15] and is driven by carbon prices and carbon values, which in turn influence technology choices and demand behavior;
- High RES scenario. This scenario is based on the homonymous scenario in EU's 2050 Energy Roadmap [15] and is driven by the objective of achieving a very high RES penetration and share in power generation – around 90% share and close to 100% related to final consumption;
- Low nuclear scenario. This scenario is based on the homonymous scenario in EU's 2050 Energy Roadmap [15] and is driven by the low public acceptance of nuclear power plants, leading to cancellation of investment projects and no nuclear plants lifetime extensions after 2030.

We can distinguish two different groups of scenarios, first the Reference scenario that will serve as a benchmark which reflects current trends while the remaining scenarios will be considered as the "decarbonization scenarios", which reflect the various strategic possible directions and trends towards a decarbonised European energy system.

In the context of these scenarios, some general assumptions were considered regarding macroeconomics and demographic trends and energy import prices:

- Both scenario groups (reference and decarbonization scenarios) are based on the same macro-economic and demographic assumptions. Concerning demographics, the key drivers are mainly a higher life expectancy, low fertility and inward migration and they follow projections from Eurostat. The macro-economic projections reflect the long-lasting effects of the 2008 financial crisis, which result in a "sluggish recovery" [16] of gross domestic product (GDP) growth rates throughout the EU-27 countries.
- Energy import prices: there's a clear distinction in the stochastically modelled projections between the reference scenario and the decarbonization scenarios. The projections in the reference scenarios reflect international fuel – oil, gas and coal – prices developments to grow over the time-frame analysis period (2050), in a context of economic recovery and "without decisive climate action in any world region" [16], which can "to a great extent influence the investment choices taken by investors in the power sector " [16]. Focusing on the decarbonization scenarios, the trends and projections reflect a "global climate action" price trajectories for oil, gas and coal reflecting that global action on decarbonisation will reduce fossil fuel demand worldwide and will therefore have a downward effect on fossil fuel prices. Oil, gas and coal prices are therefore lower than in the Reference scenario" [16].

A more in-depth and detailed description of each assumption and sensitivity analysis are available in [16].

In the next sub-sections, the developments of each considered scenario are mapped out. The focus of each subsection is the considered and adopted policies for each scenario, distinguishing them from each other, and defining the different trends, projections and pathways for the decarbonization of energy sector for the time-frame analysis period.

3.2. REFERENCE SCENARIO

In addition to the role as a trend projection, this Reference scenario, acts as a benchmarking for energy scenarios achieving the EC's objective to reduce GHG emissions by 80-95% below the 1990 level. Thus, the Reference scenario attempts to depict the outlook of the energy sector in 2050, taking into consideration the demographic and economic assumptions mentioned above, as well as a "high volatile of energy import price environment" [16]. In addition, it's important to highlight that the main economic drivers are market forces and technology progress, in the framework of EU and national measures.

Trends and policy measures included in the Reference scenario are listed in Table 12, with a respective summary/explanation.

TABLE 12: POLICIES CONSIDERED FOR THE REFERENCE SCENARIO. ADAPTED FROM [16].

Measure	Summary
Regulatory Measures	
Energy efficiency	Based on EU directives and regulation measures with focus on tackling energy efficiency in various fronts, at a "moderate rate" [14]. Covering appliances and product groups, such as the ecodesign framework directive (boilers, water heaters, air-conditioning, etc) with gradual requirements until 2015 and up to full effect by 2030/2035, the stand-by regulation, household lighting regulation, office/street lighting regulation, TVs regulation, electric motors regulation, freezers/refrigerators regulation, labelling directives and other voluntary labelling programs (e.g. the European Energy Star Programme [15]), directive on end-use energy efficiency and energy services. Building's directive and the recast of the (EPBD. High renovation rates for existing buildings due to financing mechanisms for public buildings. Gradually higher passive house standards penetration after 2020. Obligation for public authorities to procure energy efficient goods and services. EU27 national-level support measures in cogeneration. Greater role of Energy Service Companies (ESCOs) and utilities in increasing energy-savings. Mandatory energy auditions in the industry sector. Obligation of choosing the best available technology, as is defined in Industrial Emissions Directive [18]. Prioritizing Combined Heat and Power (CHP) technology, by a mandatory obligation of electricity distribution system operators and transmission system operators to provide priority access and dispatch to CHP. Better information and targeted actions for consumers, public awareness and small and medium-sized enterprises

Energy markets	Internal liberalized electricity and gas market regimes with optimal use of interconnections, leading to a high price convergence at a multi-country market level. In both markets, regulatory measures considered also focus on transparency, integrity and security of supply. In the gas market a higher degree of competitors is considered, leading to a "lower oligopoly" [16]. European Emission Trading System (ETS) based on the EU ETS directive, as a corner stone of EU's policy to mitigate and combat climate change and GHG emissions. RES directives which result in legally binding national targets for RES share in the gross final energy consumption mix. The 2020 goals are assumed to be achieved. This directive also contemplates RES subsidies to decline after 2020 starting with the phasing out of operational aid to new onshore wind by 2025; other RES aids to decline to zero by 2050 at different rates according to technology; increasing use of RES co-operation mechanisms is assumed and should help to reduce RES costs. Thus, policies on facilitating RES penetration will continue. Energy taxation directive, which set EU minimal or higher national taxation rates on energy. Switch from volumetric-based to energy-content-based taxation and the inclusion of CO_2 tax component. Directives which limit emissions, pollutants and energy recovery from waste treatment. Geological storage of CO_2 regulatory framework. Water framework directive, protecting all water bodies as defined in the directive and which might limit the potential deployment of hydropower and consequently impact generation costs.
Transport	Based on directives and regulation measures, it poses suggestions and impose limitations on the transport sector. Including, but not limited to: Limitations on emissions from new cars, commercial vehicles, light and heavy-duty vehicles. Suggestive support mechanisms for the use of biofuels in transports 10% target for RES in transport to be achieved for EU27, in 2020. Implementation of standards of measurement regarding CO_2 from vehicles in real-life conditions.
Infrastructure	Regulation and policy measures which facilitate a faster deployment of energy-related infrastructure with consequential slight lowering of costs. More funding available, from the EU budget to energy-related infrastructure. Gradual deployment of smart metering and smart grids, enhancing RES integration and energy efficiency in the system.
Oil and Gas	Slight increase of production costs due to offshore oil and gas platform safety standards;

Financial Support	
Financial support mechanisms	Based on directives, regulations, decisions and articles the EU pledges full support and financial support mechanisms to: Transborder energy interconnections, according to the Trans-European Networks of Energy (TEN-E) guidelines [19] . Research and development for innovative technologies and demonstrator plants, RES technologies, nuclear and energy efficiency. National measures to facilitate and speed up uptake of RES technologies and energy efficiency.
National measures	
Strong RES Policies	EU-27 national level policies which support and incentivize RES integration such as feed-in tariffs, quota systems, green certificates, subsidies and other costs incentives.
Nuclear	Nuclear is considered to compete with other energy sources for power generation in accordance with each member state constraint: while Austria, Cyprus, Denmark, Estonia, Greece, Ireland, Latvia, Luxembourg, Malta and Portugal are considered not to opt for nuclear, nuclear investments are possible in Czech Republic, France, Finland, Hungary, Lithuania, Romania, Slovakia, Slovenia and Spain. In Germany, Belgium and Sweden the nuclear phase out plan is respected according to nuclear plant's lifetime. Increase in generation costs due both the incorporation of waste management costs and stress and other safety measures in the aftermath of Fukushima. Risk premium in new nuclear plants.
Electric Vehicles	Gradual Electric Vehicles (EV) penetration reflecting developments of national support measures and programs. Funding research and development demonstrator projects to promote alternative fuels.

3.3. DECARBONIZATION SCENARIOS

The decarbonization scenarios aim to depict the different energy related decarbonization strategic pathways/directions to reach the 85% domestic energy related CO_2 emissions reduction by 2050, as compared to 1990 levels. This is consistent with the required contribution of developed countries to limit global climate change to a temperature increase of 2°C compared to pre-industrial levels.

In addition to the policies assumption present in Table 12, the decarbonization scenarios also include policies common to all of them. These common decarbonization policies are presented in Table 13.

TABLE 13: COMMON POLICIES PRESENT IN ALL DECARBONIZATION SCENARIOS. ADAPTED FROM [14]

Measure	Summary
Climate policies	Climate policies for respecting carbon constraints to reach 85% energy related CO_2 reductions by 2050 (40% by 2030), consistent with 80% reduction of total GHG emissions according to the "Roadmap for moving to a competitive low carbon economy in 2050", in a cost-effective way.
Stronger RES facilitation	These facilitating RES policies include for example the availability of more sites for RES, easier licensing of RES installations, greater acceptance and support deriving from the improvement of local economies and industrial development; operational aids remain at the same level as in the Reference scenario.
Transport	Energy efficiency standards, internal market, infrastructure, pricing and transport planning measures leading to more fuel-efficient transport means and some modal shift. Encouragement on the deployment of clean energy carriers by establishing the necessary supporting infrastructures.
Financial	Financial supporting mechanisms for first-of-a-kind commercial plants and early demonstrator in innovative low-carbon technologies in the energy sector (including CCS, nuclear, RES and their infrastructure needs, etc).
Interconnections	Increasing interconnections capacity will allow higher RES penetration and handling excess variable generation.
Storage	A higher penetration of RES, with variable generation, leading to occasional excess energy will be result in the increase of storage use. Considered options for storage are hydro pump storage and “green” hydrogen. Two approaches are considered for using the green hydrogen: either the hydrogen is stored and transformed back to electricity when the demand exceeds supply or hydrogen is stored and fed into the natural gas grid, reducing carbon content of the gas delivered to the final consumer, thus enabling emission cuts.

The difference between each scenario then lies in the main strategic direction (energy efficiency, RES, and nuclear) towards a decarbonised European energy system, underlying the fact that there are different pathways which may lead to reaching the same level of decarbonisation.

3.4. HIGH ENERGY EFFICIENCY SCENARIO

This scenario is driven by a political commitment of very high primary energy savings by 2050. It includes a very rigorous implementation of the Energy Efficiency Plan. Strong energy efficiency policies are also pursued after 2020.

TABLE 14: POLICIES INCLUDED IN HIGH ENERGY EFFICIENCY SCENARIO (IN ADDITION TO TABLE 13). ADOPTED FROM [14]

Measure	Summary
Energy efficiency	Additional strong minimum standards for new appliances. The effects would be gradually noticeable life cycle of old appliances have to be taken into consideration. High renovation rates for existing buildings due to greater financing and tougher requirements for public sector (more than 2% refurbishment per year). After 2020 all new houses will comply with passive house standards with energy needs being supplied to a large extent by RES. Inducing more energy efficiency mainly in residential and tertiary sectors. Increased and marked penetration of ESCOs and higher financing availability, enabling a gradual decrease of discount rates for household consumers. Strong minimum requirements for energy generation, transmission and distribution. By mandating the best available technology strategy every time their permit needs to be updated, less efficient power plants will be removed from generation portfolio. In case of CCS deployment efficiency losses might be allowed.
RES	Significant and higher decentralized RES generation (small wind, solar and small hydro) than in reference scenario.
Infrastructure	Full roll-out of smart grids and smart metering, to be able to enable a more efficient and decentralized RES.

3.5. DIVERSIFIED SUPPLY SCENARIO

This scenario is driven by carbon prices and carbon values (equal for ETS and non ETS sectors), which in turn influence technology choices and demand behaviour. This scenario is characterized by the acceptance of nuclear, CCS and development of RES facilitation policies.

TABLE 15: POLICIES INCLUDED IN THE DIVERSIFIED SUPPLY SCENARIO (IN ADDITION TO TABLE 13). ADOPTED FROM [14]

Measure	Summary
CCS	All member states and investors have confidence in CCS as a commercially viable and credible technology. High acceptance of CO_2 storage and CO_2 network.
Nuclear	Investors and members states (MS) who have not ruled out the use of nuclear have the confidence in nuclear as safe and adequate. Nuclear waste issues are solved.

3.6. HIGH RES SCENARIO

This scenario is driven by the objective of achieving a very high RES penetration and share in power generation – around 90% share and close to 100% related to final consumption. Enabling such high RES share and penetration and considering the requirements to have a secure supply of energy, significant increases would be needed in domestic RES supply, off-shore wind (in the North Sea), significant developments on concentrated solar power (CSP), significant developments on storage, significant increase in the electrification of heating in residential sector (heat pumps) and significant micro power generation (which include photovoltaic (PV) cells, small scale wind, etc.).

TABLE 16: POLICIES INCLUDED IN THE HIGH-RES SCENARIO (IN ADDITION TO TABLE 13). ADOPTED FROM [14]

Measure	Summary
RES facilitation	RES facilitating policies include, for example, lower lead times in construction, and involve greater progress on learning curves (e.g. small scale PV and wind) based on higher production. RES preferential access to the grid. Use of cooperation mechanisms or convergent support schemes coupled with declining costs/support result in optimal allocation of RES development, depending also on adequate and timely expansion of interconnection capacity resulting in a bigger RES trade in energy markets. Higher use of heat pumps, significant penetration of passive houses with integrated RES and RES building renovation/refurbishment requirements also considered to impact and enable a higher RES share in final energy consumption.
Infrastructure, back-up, storage and demand	Substantial increase in interconnectors and higher net transfer capacities including Direct Current (DC) lines from North Sea to the center of Europe. Back-up functions done by biomass and gas fired plants. Sufficiency storage capacity is provided (mainly from pumped storage, CSP and hydrogen). Smart metering allows time and supply situation dependent electricity use (peak/off-peak) reducing needs for storing variable RES electricity. All these measures allow for exploiting greater potentials for off-shore wind in the North Sea

3.7. LOW NUCLEAR SCENARIO

This scenario is driven by the low public acceptance of nuclear power plants, leading to cancellation of investment projects and no nuclear plants lifetime extensions after 2030. This will lead to a higher deployment of CCS, from fossil fuels, on economic grounds.

TABLE 17: POLICIES INCLUDED IN THE LOW NUCLEAR SCENARIO (IN ADDITION TO TABLE 13). ADOPTED FROM [14]

Measure	Summary
Nuclear	Due to political decision based on the perceived risks associated with waste management and safety issues (especially after Fukushima accident) no new nuclear plants being built. No extension of nuclear plants lifetime after 2030, on economic grounds.
CCS	All member states and investors have confidence in CCS as a commercially viable and credible technology. High acceptance of CO_2 storage and CO_2 network.

3.8. AMBIENCE SCENARIO

In this section the AmBIENCe scenario is detailed. The AmBIENCe scenario consists in the policy framework and the decarbonization pathways which are envisioned for 2050. In line with the decarbonization policies and pathways described above, the AmBIENCe scenario strongly focuses on the reduction of the energy related CO_2 equivalent emissions, ensuring a "competitive low carbon economy in 2050" [16]. It does so by focusing on a minimal renovation to allow for electrification of the building and using DR to flexibly use the energy provided by RES – further detailed in section 4.1. As such, , the scenario will be directed towards achieving the decarbonization of the EU-27 building stock. The decarbonization pathways and policy framework for such scenario are presented below in Table 18.

TABLE 18: POLICIES AND DECARBONIZATION PATHWAYS INCLUDED IN THE AMBIENCE SCENARIO.

Measure	Summary
Climate policies	Respecting the updated carbon constraints goals for 2050, the necessary climate policies will enable to reach climate neutrality by 2050 alongside the intermediate targets of achieving 40% CO_2 emissions reduction by 2030 [20], compared to an historical baseline (corresponding to the year 1990). These targets are consistent with the GHG emissions targets endorsed to comply with the Paris Agreements.
Energy efficiency	New buildings will comply with passive house standards, while also promoting a significant integration of RES which will in turn impact and enable a higher RES share in final energy consumption [16]. High renovation rates for existing buildings due to greater financing and tougher requirements for public sector [16]. To achieve carbon neutrality in the EU by 2050, the annual renovation/refurbishment rates should increase up 3%, which includes both shallow, medium and deep renovations of the present EU building stock [21]. Building renovation standards to comply with EPBD standards [16]. The buildings retrofitting and renovations will further enable a continuous and incremental electrification of the building stock (e.g., increase the use of heat pumps).

RES	There is a very high RES penetration and share in power generation by 2050 [14], with intermediate target of achieving at least 32% share of renewable energy in the final energy consumption by 2030 [20]. Enabling such high RES share and penetration and considering the requirements to have a secure supply of energy, significant increases would be needed in domestic RES supply, off-shore wind (in the North Sea), significant developments on CSP, significant developments on storage, significant increase in the electrification of heating in residential sector (e.g., heat pumps) and significant decentralized generation, which include solar (PV), small scale wind, small hydro) [16]. Decentralized RES generation would benefit preferential access to the grid. RES facilitating policies include, for example, lower lead times in construction, and involve greater progress on learning curves (e.g. small scale PV and wind) based on higher production. Use of cooperation mechanisms or convergent support schemes coupled with declining costs/support result in optimal allocation of RES development, depending also on adequate and timely expansion of interconnection capacity resulting in a bigger RES trade in energy markets. A higher penetration of RES, with variable generation, leading to occasional excess energy will be result in the increase of storage use, mainly hydrogen with "two approaches are considered for using the green hydrogen: either the hydrogen is stored and transformed back to electricity when the demand exceeds supply or hydrogen is stored and fed into the natural gas grid, reducing carbon content of the gas delivered to the final consumer, thus enabling emission cuts" [14].
Infrastructure, back-up, storage and demand	To allow for a higher RES share it's crucial to ensure a substantial increase the interconnectors and net transfer capacities, including DC lines from North Sea to the center of Europe [14]. Sufficiency storage capacity is provided (mainly from pumped storage, CSP, hydrogen and residential storage systems) [14]. Full roll-out of smart grids and smart metering, enabling a more efficient decentralized RES integration. This will impact the costs in the distribution grid, electricity prices and overall costs of the energy system [14]. DR services are to be gradually implemented and available throughout each of the EU-27 MS with an also gradual uptake and acceptance of such services among end-customers. DR will ensure active control within the building stock while at the same time providing more flexibility to the energy system.

4. ASSUMPTION ON ADOPTION OF ACTIVE CONTROL STRATEGIES

To calculate the impact of renovation, electrification and the uptake of active control on the energy system, a KPI calculation tool (section 4.1) was developed. The approach followed is explained step by step in the sections below, along with the assumptions that were made. The DR response control strategies and cash flows are described in sections 4.7. Additionally, in Annex I and Annex II two analyses were conducted for both the building stock renovation requirements and for the demand response cashflows that could be used agnostically in a simulation tool such as ABEPeM. In Annex III depicts a KPI framework which can be used agnostically to assess the active control impact in the energy system.

4.1. KPI CALCULATION TOOL

The following section focuses on the description of the methodology and assumptions which were considered for the KPI calculation tool, developed under the scope of T4.2. These assumptions frame the quantitative analysis on the energy system impacts of the building stock and its renovation. The general flow of the KPI calculation tool is shown in Figure 2 below.

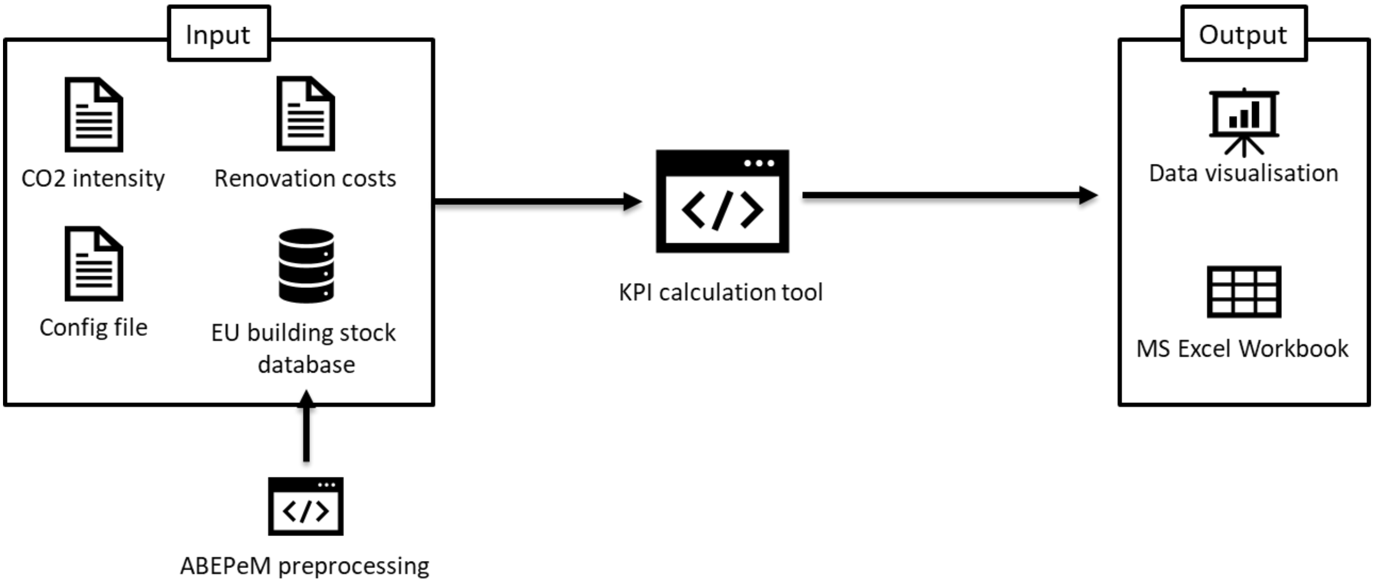


FIGURE 2: SCHEMATIC OVERVIEW OF THE KPI CALCULATION TOOL

In order to simulate the impact of the different scenarios outlined earlier, a KPI calculation and analysis tool was developed in Python 3.7 [22]. The tool itself is compiled as an executable which requires no further Python knowledge or software requirements on behalf of the user.

Different parameters and input values can be modified by the user to evaluate the impact of different scenarios (input part in Figure 2). A number of files are required to run a calculation which are:

- A electricity carbon intensity table (csv) which lists for all countries the initial carbon intensity as well as the declination rate;
- A renovation cost file including the costs of renovation (per m²) for roof, walls and windows;
- A cost index file, which contains the renovation cost index for each country;
- A simulation configuration file (cfg) in which all simulation parameters like renovation rates, uptake of Demand Response, … are listed. An example can be found in Annex VI;
- A building stock database, which is a modified version of the database developed in T4.1. The specific modifications are discussed below;

The building stock database used in the KPI calculation tool is an expanded version of the database of grey-box models parameters [5]. Additional columns have been added. These include:

- Information on the thermal energy system and fuel used, see sections 2.4, 2.5 and 0
- The suggested renovation measure for each building typology. This was determined by a pre-processor, which is described in the paragraph;
- CO_2 emission reduction by enabling DR. This is a percentage of how much the CO_2 emissions of a building can be reduced when applying DR. These values were calculated by ABEPeM (see Section 4.7) by comparing the baseline scenario (renovated building without smart heating) versus the smart heating scenario (same building but optimized heating strategy to limit CO_2 emissions without violating comfort constraints).

The logic of the Python tool is as follows:

- The user provides configuration and input files are read and processed. A Pandas DataFrame [21] is generated which contains the relevant information for each building typology. This includes the number of buildings (both non-renovated and renovated) which use a given fuel as well as the total energy need per fuel and associated CO_2 emissions;
- The outer loop starts which runs over the calculation time span from the initial year (defined by the user) till the final year (also defined by the user);
- For each year a loop is done over all the building typologies in the DataFrame. For each building the following strategy is applied:
    - Based on the required renovation measure the renovation rate is calculated by interpolating the user-defined renovation uptake measures for the initial year and final year.
    - Based on this value a number of non-renovated building is transferred to the renovated category. This number can be calculated in two ways:
        - In the static mode the number of buildings to be renovated is calculated as $N_{renovated,i+1} = N_{initial} r_{renovation}$. Here, $N_{renovated,i+1}$ is the number of buildings that are renovated between year *i* and *i+1*, while $N_{initial}$ is the initial number of buildings in year 0. Finally, $r_{renovation}$, is the renovation rate, expressed in %. Hence the initial number of buildings is multiplied by the renovation rate. It should be noted that the number of remaining buildings cannot be negative.

- In the dynamic mode the number of buildings that is renovated is calculated as $N_{renovated,i+1} = N_{non-renovated,i} r_{renovation}$. The number $N_{non-renovated,i}$ is the total building of numbers that has not yet been renovated in year *i*. Hence, the number of buildings that are renovated between year *i* and *i+1*, $N_{renovated,i+1}$, depends on the renovation rate and the number of non-renovated buildings in year *i*.
- After $N_{renovated,i}$ is known, part of the buildings will be equipped with a heat pump and thus electrified. This will change the fuel used and emissions in these buildings. This factor can be defined by the user in the configuration file;
- Finally, a fraction of the buildings equipped with a heat pump will apply DR and emit less carbon compared to the baseline scenario. This DR uptake fraction can also be defined through the configuration file;
- Special care is given to buildings not requiring renovation. Electrification is still considered here as well as DR.

- All information is stored in dedicated DataFrames after each iteration;
- After the loops have been finished, the information is exported in a MS Excel file, allowing further processing of the results on building, country and fuel type level. General analysis graphs are also generated, as well as country specific graphs.

A database pre-processing tool was used to determine the most suitable renovation measure for each building type as follows:

- The initial K-value of the building was calculated. This value depends on the compactness of the building, which is defined as: $C = \frac{V_{building}}{A_{building\ enveloppe}}$, with $V_{building}$ the heated volume of the building and $A_{building\ enveloppe}$ the area of the building envelope prone to heat losses. Hereby it is assumed that the entire building is heated.
- The K-value is defined as:

$$K = 100\, U_m \; if\; C \leq 1$$
$$K = \frac{300}{C+2} U_m \; if\; 1 < C \leq 4$$
$$K = 50\, U_m \; if\; C > 4,$$

- In the equations above U_m is the global heat loss coefficient, which is calculated as follows:

$$U_m = \left[\frac{1}{3} A_{floor} U_{floor} + A_{walls} U_{walls} + A_{windows} U_{windows} + A_{roof} U_{roof}\right] \Big/ A_{building\ envelopee}$$

- The U-values of the walls, windows, floor and roof individually are calculated as:

$$U_{component} = 1 \Big/ \left(\frac{1}{23} + R_{component} + \frac{1}{8}\right)$$

with

$$R_{component} = \frac{1}{U_{component}}$$

- The building stock database contains all information required to calculate the K-value of the building.
- Next, all the possible renovation measures and combinations thereof are applied to a given building typology. When a given component (windows, roof, walls) is renovated, the $R_{component}$ of this component will change as follows:
$$R_{component}^{renovated} = R_{component}^{initial} + \frac{d_{insulation}}{\lambda_{insulation}}$$
with $d_{insulation}$ the thickness and $\lambda_{insulation}$ the thermal conductivity of the additional insulation. Note that in case of window renovation one has to use U-value of the new windows.
- The K-value of the building after a given renovation measure is now calculated again and will be lower than the initial value. The first measure that results in K-value for the building that reaches a K-value of at most 40 is selected as the suggested renovation measure and this selection is then added to the building stock database along with the initial and renovated K-values. In case the combination of all three renovation measures doesn't result in a K-value lower than 40, the keyword "impossible" is written into the dataset. Contrary, if the initial K-value is already lower than 40, "none" is registered.
The threshold of 40 is generally adopted as the limit for a building to be suitable for heating using a heat pump and was therefore chosen to perform this analysis.

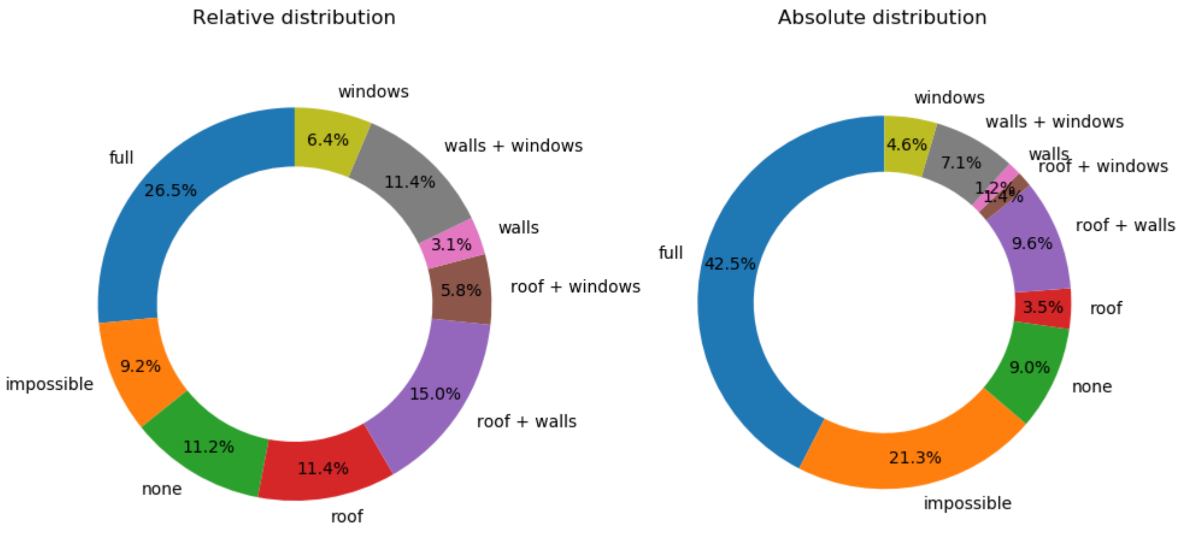


FIGURE 3: RELATIVE DISTRIBUTION OF RENOVATION MEASURES REQUIRED BY BUILDING TYPOLOGY (LEFT). ABSOLUTE DISTRIBUTION OF RENOVATION MEASURES REQUIRED WITHIN THE EU-27 BUILDING STOCK (RIGHT)

Figure 3 shows the distribution of renovation measures required in the EU-27 building stock from two different perspectives. On the left, the relative distribution is shows, where each building type defined in the building stock has the same weight. On the right, the absolute distribution is shown. In this last case, the contribution of each building typology is weighted by the number of buildings of this type.

From the right chart it can be seen that almost 2/3 of the entire EU-27 building stock requires either full renovation or can't reach an insulation level suitable for electrification when considering the proposed measures. 9% of the building stock is currently suitable for heating using a heat pump. Within this part of the building stock, 20.4% is already equipped with a heat pump (Figure 4). The share of buildings only requiring shallow renovation measures (only roof, windows or walls) is 9.3% and almost equals the part that is already suitable for electrification. The remaining 18.1% of the building stock requires a deeper renovation by combining at least two distinct renovation measures.

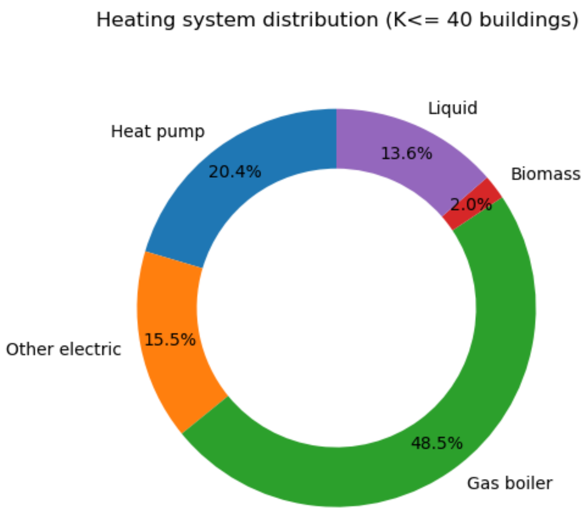


FIGURE 4: DISTRIBUTION OF HEATING SYSTEMS IN BUILDINGS WITH A K-VALUE OF AT MOST 40 AND THUS NOT REQUIRING RENOVATION

On the next sections the methodological approach and the considered assumption will be further detailed.

4.2. RENOVATION RATES AND COST ASSESSMENT

One key measure to achieve and accomplish the above defined targets is through the improvement of the energy performance of the building stock. The building sector is today "the largest single energy consumer in Europe" [24]. Since the bulk of the building stock "was built without significant energy performance requirements" [24] it offers a high potential of energy savings. Hence, to better understand the impact of the adoption of active control within the building stock, one important aspect to consider deals with its renovation. For the purposes of this study, energy renovations [21] are considered, which consist in the refurbishment of the building envelope elements which impact the building's energy performance. Hence, the energy renovation measures considered include:

- Installation of thermal insulation on the roof;
- Replacement of windows;
- Installation of thermal insulation on the façade, including the cavity wall insulation;
- Combinations of two or all individual measures;

These can be further grouped within different categories which relate to the impact of the renovation measure in the building's primary energy demand [21]:

- Light/shallow renovations – the energy renovations classified as light renovations encompass renovations which impact the primary energy demand of a building by decreasing it between 3% and 30%;
- Medium renovations – the energy renovations classified as medium renovations encompass renovations which impact the primary energy demand of a building by decreasing it between 30% and 60%;
- Deep renovations – the energy renovations classified as deep renovations encompass renovations which impact the primary energy demand of a building by decreasing it more than 60%.

Within the context of the KPI calculation tool, as described above, the considered building envelope renovations were grouped in accordance with the building's envelope element affected. It's required to define both the start renovation rate (the rate at which building elements are renovated at the start date, 2020) and end renovation rate (the rate at which building elements are renovated by the analysis time-frame, 2050). These will serve as inputs to enable the simulations performed by the KPI calculation tool:

- Roof renovation rate – classified as a light renovation measure, it corresponds to the renovation rate of the single envelope element (roof). It's required to define both the start renovation rate (the rate at which the roof is renovated at the start date, 2020) and end renovation rate (the rate at which the roof is renovated by the analysis horizon, 2050);
- Walls renovation rate – classified as a light renovation measure, it corresponds to the renovation rate of the single envelope element (walls, including cavity wall insulation);
- Windows renovation rate – classified as a light renovation measure, it corresponds to the renovation rate of the single envelope element (window);
- Roof and walls renovation rate – classified as a medium renovation measure, it corresponds to the renovation rate of a "renovation package" which consists in renovating both the roof and walls;
- Roof and windows renovation rate – classified as a medium renovation measure, it corresponds to the renovation rate of a "renovation package" which consists in renovating both the roof and windows;
- Walls and windows renovation rate – classified as a medium renovation measure, it corresponds to the renovation rate of a "renovation package" which consists in renovating both the walls and windows;
- Full renovation – classified as a deep renovation measure and consists in the renovation of all the considered building envelope elements (roof, walls and walls).

It is necessary, thus, to define the scenarios through which we can assess the impact of the renovation of the building stock. The EUCalc project [25] provided the base to define the scenarios for such assessment. From [24] we could gather the current total building stock renovation rate (consisting of residential and non-residential buildings) which is close to 1%, which coincides with the Ambition 1 scenario from EUCalc [25]. Thus, through it we defined the renovation rates at the start year (2020) for all of the above defined measures: annual renovation rate of 1%, of which 80% are shallow renovations (equally divided between the three types of shallow renovations described above), 15% are medium renovations (equally divided by the three medium renovations described above) and only 5% are deep renovations. The scenarios will then be constructed by defining different end renovation rates, see Table 19.

TABLE 19: AMBIENCE SCENARIOS, WITH FOCUS ON THE BUILDING STOCK RENOVATION RATES.

AmBIENCe Scenario	Description
Scenario 1 (AS1)	Scenario 1 corresponds to the Ambition Level 2 in [25]. It is defined by the total annual renovation rate at the time-frame analysis period, 2050 (i.e., end year renovation rate) of 1.5%, of which: • 20% are shallow renovations, equally divided by the three considered shallow/light renovations • 60% are medium renovations, equally divided by the three considered medium renovations • 20% are deep/full renovations
Scenario 2 (AS2)	Scenario 2 corresponds to the Ambition Level 3 in [25]. It is defined by the total annual renovation rate at the time-frame analysis period, 2050 (i.e., end year renovation rate) of 2.0%, of which: • 10% are shallow renovations, equally divided by the three considered shallow/light renovations • 70% are medium renovations, equally divided by the three considered medium renovations • 20% are deep/full renovations
Scenario 3 (AS3)	Scenario 3 corresponds to the Ambition Level 4 in [25]. It is defined by the total annual renovation rate at the time-frame analysis period, 2050 (i.e., end year renovation rate) of 3.0%, of which: • 0% are shallow renovations • 30% are medium renovations, equally divided by the three considered medium renovations • 70% are deep/full renovations
Scenario 4 (AS4)	Those of AS3.
Scenario 5 (AS5)	Those of AS3.

Regarding Scenario AS4, it takes into account a different electrification rate, further explained in section 4.3. Scenario AS5 considers a different DR uptake, further explained in section 4.4.

Additionally, a cost assessment analysis is conducted within the KPI calculation tool, focusing on the costs associated to the building stock renovation. For such cost analysis to be enabled, AmBIENCe Partner BPIE provided guidance on cost analysis of the renovation measures above described [26]. Below, in Table 20 it’s possible to observe reference prices for the country of Spain, while the same construction prices for other EU-27 countries can be calculated through [26]. This cost assessment is transversal to all scenarios, with no updates other than updating the costs values resourcing to a constant 2,5% inflation rate.

TABLE 20: ORIENTATIVE CONSTRUCTION COST GUIDE FOR THE COUNTRY OF SPAIN, PER RENOVATION TECHNOLOGY FOR EACH ELEMENT CONSIDERED FOR THE BUILDING STOCK RENOVATION. SOURCE: GENERADORDEPRECIOS.INFO DATABASE

Building Element	Technology	Price
Walls	Air chambers filling (walls)	12-18 EUR/m2 (40mm) + 1,4 EUR/m2 for each extra 10mm
Roofs	Internal insulation of roofs	17-42 EUR/m2
Windows	Glazing replacement with 8-20-6mm glazing low emissive (1,4 W/m2/K)	160 R/m2

4.3. ELECTRIFICATION

The refurbishment/renovation of the building stock fosters energy efficiency while at the same time fosters the adoption of electrification within the building stock. The electrification of processes, equipment and technologies within the building stock context can play a key role in achieving the decarbonization targets and ultimately, changing the energy system: “electrifying (…) buildings, while simultaneously transitioning the electricity mix to renewable energy sources, can lead to necessary emission reductions in this sector” [28]. In the context of the overall AmBIENCe scenario (see section 3.8) and future prospect pathways for the decarbonization of the energy system, power generation sector and the GHG climate targets, it is relevant to identify the impact generated by the uptake of electrification technologies. Hence, within the KPI calculation tool, as previously explained, the electrification uptake is considered for the impact assessment. To enable the analysis, including an electrification perspective, two distinct scenarios are considered, based on different outlooks on the adoption of electrification technologies throughout the building stock – the electrification uptake values translate a large or small adoption of electrification technologies throughout EU-27 countries.

TABLE 21: ELECTRIFICATION UPTAKE CONSIDERED IN AMBIENCE SCENARIOS 1-4. VALUES ARE OWN ASSUMPTIONS

AmBIENCe Scenarios (AS)	Electrification uptake (%)
AS1 – AS3	80%
AS4	40%

4.4. DR ADOPTION

Although the building stock’s renovation and electrification promotes energy efficiency and the increased electrification, it also fosters DR mechanisms. As extensively reported and described throughout literature, “energy flexible buildings with electric heating, smart demand-side management and efficient thermal energy storage are one of the most promising strategies to deploy low-carbon technologies which can benefit the electricity system by reducing the need of reinforcing existing networks and their ability to use electricity in times of low demand and high supply” [29]. Hence, the same approach of the building stock’s electrification is used. Here the quantification lies with the % of the adoption of DR services which, according to 3.8, will be available to end-users gradually. The input parameters of the KPI calculation tool reflect that gradual adoption, represented by a percentage – 0.01 as 1%.

TABLE 22: DR UPTAKE CONSIDERED IN THE AMBIENCE SCENARIOS 1-5. VALUES ARE OWN ASSUMPTIONS

AmBIENCe Scenarios (AS)	DR uptake 2020 adoption – 2050 adoption
AS1 – AS4	0.02-0.2
AS5	0.1-0.35

4.5. CARBON INTENSITY OF ELECTRICITY GENERATION

As described above, one of the inputs considered in the KPI calculation tool developed within the scope of this task and which enables the impact assessment is the carbon intensity (CI) of electricity generation. The CI of electricity generation measures the amount of GHG which were emitted per unit of electricity produced. According to [30], "the EU electricity sector is expected to provide one of the most significant contributions to climate mitigation targets by 2030 and be a cornerstone for the Union to reach net climate neutrality by 2050".

This parameter will serve the purpose of quantifying the necessary changes in the energy sector to be able to achieve the GHG emissions targets defined for the AmBIENCe scenario, described in the previous section 3.8. In short, this parameter will reflect the renewable energy share within the energy mix of each country. The CI start year parameter defines the current state of the electricity generation while the CI end year parameter (for 2050) will depict the electricity generation sector's CI, to comply with targets above defined.

Hence, it was necessary to gather the historical baseline (1990) and current status (2020) of each individual EU-27 country, through the European Environmental Agency [30]. In Figure 5, it's possible to observe both the historical baseline as well as the current CI for each EU-27 country – which will serve the input for each individual country. Alike the renovation rates, the CI by the end year of 2050 will define how will the energy sector evolve, reflected by the CI declination rate parameter. A simplified approach considered in the scope of this work is to define the declination rate of each country as a function of the intermediate GHG emissions reduction target of 2030, where a 55% reduction is expected. The EEA [30] provides overall European-level indicative CI targets, for the intermediate year of 2030, which enables the EU to achieve the intermediate climate targets previously described in 3.8. The minimum indicative level was assumed to be the target, from an optimistic perspective of reaching the targets: average EU-27 CI of 110 gCO_2/kWh. Assuming the same relationship between the current average EU-27 CI and all member states' (MS) CI, the 2030 disaggregated CI target is defined for each country. A minimum of 50 gCO_2/kWh is defined. However, for every MS whose CI target is lower than 50, it will be attributed the minimum allowed CI and the difference will be equally distributed among the rest of the countries. Ensuring that the necessary overall decrease of CI at the EU-27 scale is proportionally compensated by the country's share of GHG emissions – for such purposes Eurostat [31] provided a source to account for the current status of power generation and, consequently, carbon intensity of each EU-27 MS. Thus, the targets are defined and the declination rate, per year, will also be defined accordingly. If cases were noticed where, through this simple methodological approach, the CI target defined according to the intermediate goal of 2030 is already reached, each country will further develop its CI to achieve the 2050 carbon neutrality goals, through the same approach. Otherwise, the CI declination rate between 2030 and 2050 is assumed to decrease at the same rate as it is defined to enable the MS to be able to achieve the 2030's targets. Below, in Figure 5 we can observe the historical baseline, current status and CI targets for 2030 for each individual MS and for the aggregated macro EU-27 level (i.e., EU-27 average).

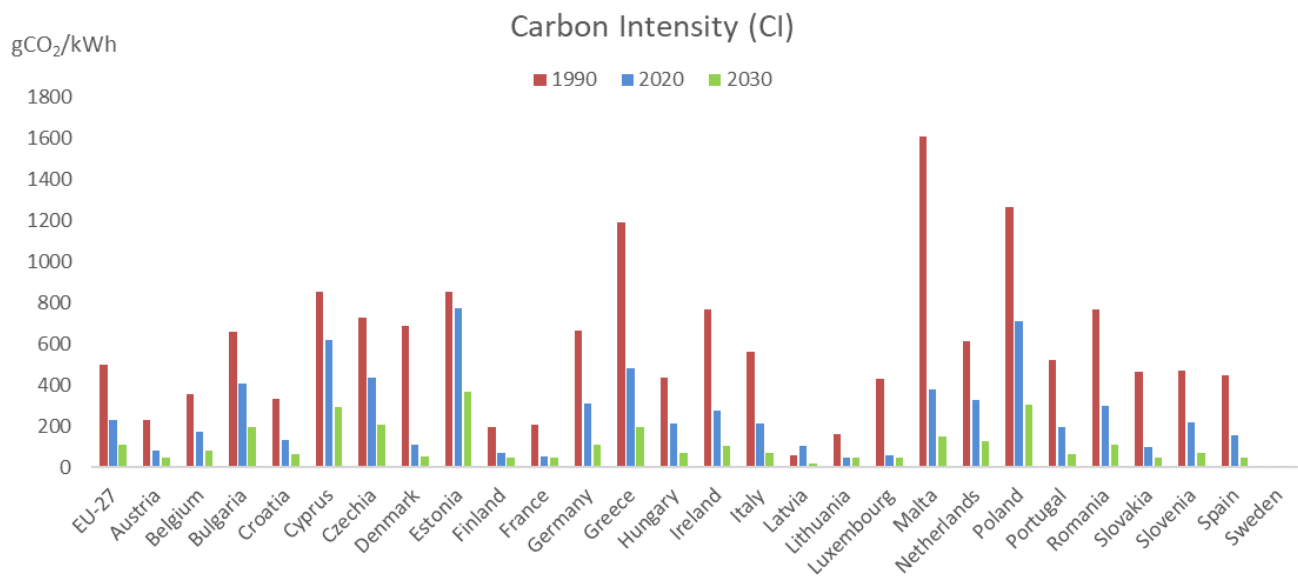


FIGURE 5: HISTORICAL BASELINE, CURRENT STATUS AND 2030'S TARGET FOR THE CI AT THE EU-27 LEVEL (AVERAGE) AND FOR EACH MS. DATA FROM [30] AND OWN CALCULATIONS.

4.6. SUMMARY AMBIENCE SCENARIO

The AmBIENce scenario considers the "ideal" perspective of the decarbonization pathways described throughout section 3 – with active control enablers and building stock renovations assumed to evolve optimistically. The impact assessment considers the following case: if all buildings that are able to be electrified, are renovated to allow their electrification, and consequently DR is available and resourced to, what would be the energy system's impact for the time frame analysis period? Below, in Table 23 the Ideal AmBIENCe scenario is detailed. Additionally, in Table 24 containing the summary overview of all the considered scenarios and its details is displayed**.**

TABLE 23: IDEAL AMBIENCE SCENARIO DESCRIPTION

AmBIENCe scenario	Description

Ideal Scenario (AS5)	**Renovation Rates:**
	- Start year renovation rate (2020) of **1%**, of which:
	    - 80% shallow renovations
	    - 15% medium renovations
	    - 5% deep renovations
	- End year renovation rate (2050) of **3%**, of which:
	    - 0% are shallow renovations
	    - 30% are medium renovations, equally divided by the three considered medium renovations
	    - 70% are deep/full renovations

	- CI methodology to reach climate neutrality targets (i.e., 85% reduction of GHG emissions).
	- Electrification uptake: 80%
	- DR adoption: 0.1-0.35

TABLE 24: SUMMARY OF ALL AMBIENCE SCENARIOS CONSIDERED IN THE CALCULATION TOOL AND ITS RESPECTIVE INPUTS.

AmBIENCe Scenario (AS)	Renovation rates	Carbon intensity	Electrification uptake	Flexibility uptake
SCENARIO 1 (AS1)	Start year renovation rate (2020) of **1%**, of which: - 80% shallow renovations - 15% medium renovations - 5% deep renovations End year renovation rate (2050) of 1.5%, of which: - 20% are shallow renovations - 60% medium renovations - 20% deep/full renovations	As a function of GHG targets (see Annex II)	80%	Start year (2020): 0.02 End year (2050): 0.2
SCENARIO 2 (AS2)	Start year renovation rate (2020) of **1%** (like **AS1**): End year renovation rate (2050) of **2.0%**, of which: - 10% shallow renovations - 70% medium renovations - 20% deep renovations	As a function of GHG targets (see Annex II)	80%	Those of AS1
SCENARIO 3 (AS3)	Start year renovation rate (2020) of **1%**, (like **AS1**): End year renovation rate (2050) of **3.0%**, of which: - 70% medium renovations - 30% deep/full renovations	As a function of GHG targets (see Annex II)	80%	Those of AS1
SCENARIO 4 (AS4)	Those of AS3	As a function of GHG targets (see Annex II)	40%	Those of AS1
SCENARIO 5 (AS5)	Those of AS3	As a function of GHG targets (see Annex II)	80%	Start year (2020): 0.05 End year (2050): 0.30

4.7. EU WIDE IMPACT ANALYSIS – EMISSION REDUCTION USING ABEPEM

Following the discussion on DR adoption and CI of electricity generation, this section discusses the impact study of adoption of PV panels and smart management of heating, post renovation of the EU building stock. The impact study computes GHG emission reduction of the building stock by employing simulations via ABEPeM platform. Then the GHG reduction metrics integrates into KPI Analysis tool (described in the sections above, Figure 2) of the EU-27 building stock. The building stock comprises of 2200+ buildings with a mix of different building types (Residential, Office, Commercial, etc.) from each of the 27 EU countries. Additional information on building stock is provided in previous deliverable D4.1 [3].

The impact analysis involved running a full year simulation for each of these buildings, to compute carbon emission reduction after adoption of PV panels and smart heating using the tool ABEPeM. Automating the ABEPeM simulation essentially reduces the time needed for the simulations by at least a third. Considering we must do the simulation twice for each building (baseline and smart heating), it takes 112 hours or 5 days approximately. The emission reduction mechanisms and inputs are discussed below followed by results.

The mechanisms to reduce emissions and DR control strategy are below:

- Increase of self-consumption of PV panels: At moments in time when PV panels produce more electricity than is consumed by the building infrastructure, electricity is injected into the electricity grid. In terms of emission reduction, CI of solar energy is lower than CI of other traditional sources of energy (gas, coal, etc). So, when the energy produced by the PV on the building is self-consumed, it leads to substantial emission reduction of the building.
- Smart Control of heating/cooling: Substantial operational reduction in emissions occur when smart control of heating/cooling achieves in minimizing consumption of offtake electricity from the grid by maximizing self-consumption of electricity generated by PV, and shifting offtake from the grid to times when the CI of electricity production is low. Maximizing self-consumption of solar energy reduces GHG emissions because it corresponds to less consumption of offtake electricity which usually has higher CI.

The inputs for simulation with the ABEPeM platform are:

- CI of Electricity production (Figure 5);
- Electricity tariff structure: We consider 3 different prices, electricity offtake day-time price and nighttime price, and electricity injection price. For the simulations, the following prices were used: Electricity offtake price (day) = 0.25 €/kWh; Electricity offtake price (night) = 0.19 €/kWh; Electricity injection price = 0.05 €/kWh.
- Thermal comfort limits of the building: Target temperature settings for the building with upper and lower limits. Especially at times when the indoor temperature is not critical (e.g., at night and the weekend), it is important to allow for a large margin between the upper and lower limit. This limit is allowed to be narrow during the day. For the impact analysis, the day-time temperature was maintained between 23 degrees Celsius and 21 degrees Celsius. The night-time temperature was maintained between 23 degrees Celsius and 18 degrees Celsius.

- PV panels sizing: PV panels size (area) is a function of roof area of the building. Since roof area of EU building stock was available in the database [3] ,the information was used to size the PV panels area in an automated way. Typically, 65-75% of the roof area is used to install solar panels. A conservative 65% of the roof area was considered as the size (area) of the PV panels in m^2.
- PV electricity production data profile: a solar radiation profile is used for each specific EU country and scaled to the expected year production of the planned PV system (sizing) and with a production efficiency of 26%.
- Simplified model of a heatpump based heating system: Based on the maximum power of 500 kW and approximate performance coefficient (Coefficient of Performance ~COP 3), a simplified heat pump model was considered.
- Dynamic thermal model: Resistance and Capacitance parameters of each building from the building stock was determined using the grey box modelling tool. These parameters were used for automated optimization of each building from the stock. It should be noted that these parameters differ from those included in the D4.1 database since renovation measures have been included, which impact the model parameters. For each building renovation measures are applied to get to at least a K-value of 40.
- Weather information: Time series weather information on external temperature and solar radiation for each country is used for the automated optimization, depending on the building and which EU country it is located. The weather data for each country is taken from EnergyPlus.

The automated ABEPeM tool found a solution for around 60% of the EU building stock, meaning around 40 % remain unsolved. This shouldn't be interpreted as these buildings cannot have emission reduction but rather these buildings need in-depth individual analysis. Therefore, the GHG emission metrics on some of the buildings remain inconclusive. The result pertains to 60% of the buildings, which is approximately 1320 buildings out of 2200+.

The results are summarized by the bar chart in Figure 6.

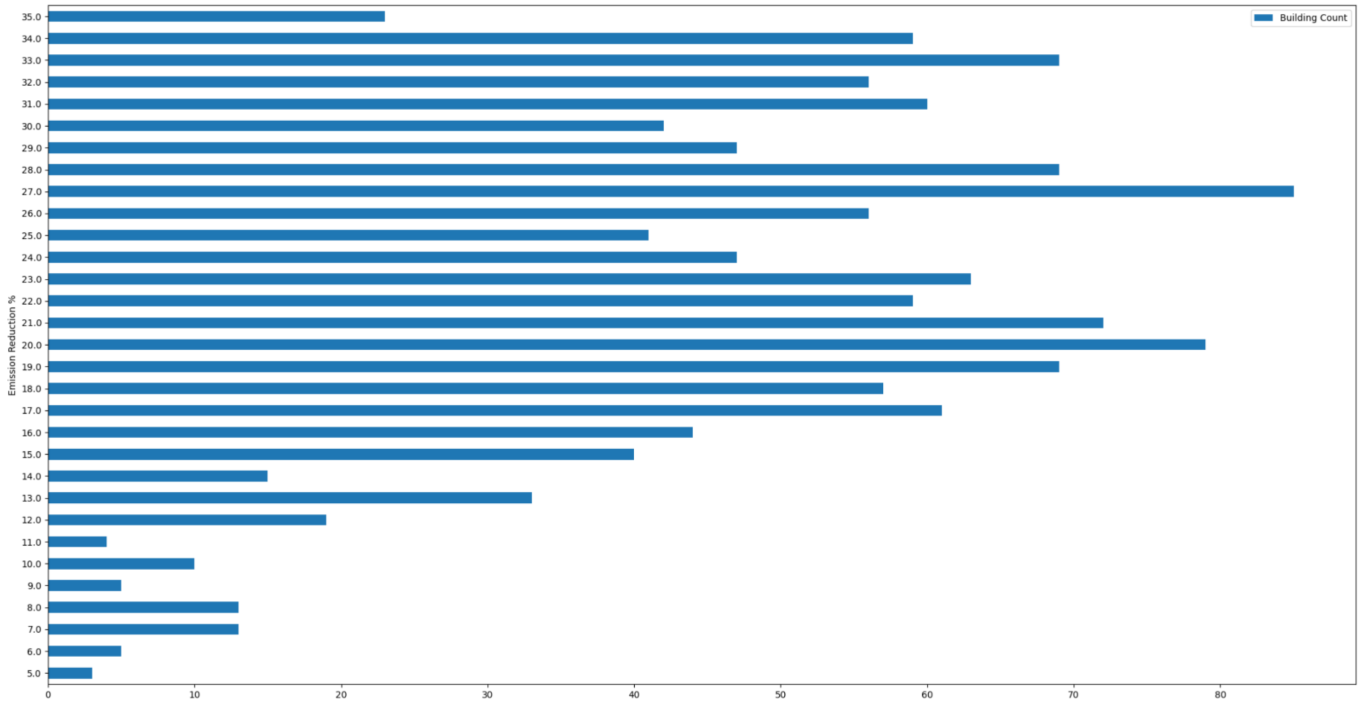


FIGURE 6: EMISSIONS REDUCTION (%) RESULTS FOR 60% OF THE BUILDING STOCK – RESULTS FROM ABEPEM TOOL.

On the y-axis are the % of emission reduction and on the x-axis are the number of buildings types (or building type count). The minimum emission reduction is 5% with a building count of around 4 and the maximum is 35% with a building count of around 24. The average emission reduction is around 20%, the median of the data is around 80 buildings and with an emission reduction of around 20%. Around 85 buildings have an emission reduction of around 27% making it the mode of the data with the highest frequency of buildings (building count).

The results above are summarized for the sake of concise discussion, but the emission reduction % of each building with its unique building id is integrated into the KPI calculation tool for a comprehensive analysis.

4.8. ENERGY SYSTEM IMPACT ANALYSIS WITH THE KPI CALCULATION TOOL

In the following section the results obtained for the energy system impact analysis, through the KPI calculation tool and its respective inputs described above, are discussed.

In the context of this work, the focus of the analysis is to assess the energy system impact of the adoption of active control within the building stock, mainly focusing on emissions and carbon intensity. Concerning the ideal AmBIENCe scenario (Table 23), in the figures below the evolution of the total CO_2 intensity for each EU-27 country is represented, for the timeframe analysis period of 2020-2050.

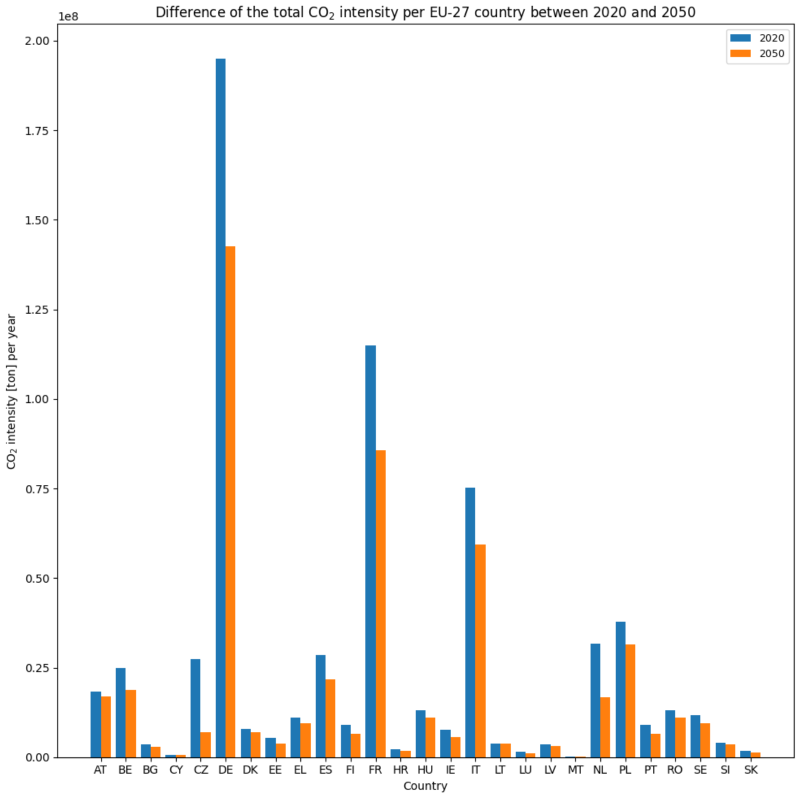


FIGURE 7: AMBIENCE SCENARIO 5 (AS5) TOTAL CO_2 INTENSITY OF EACH EU-27 COUNTRY – CURRENT STATUS *VS* 2050 RESULTS.

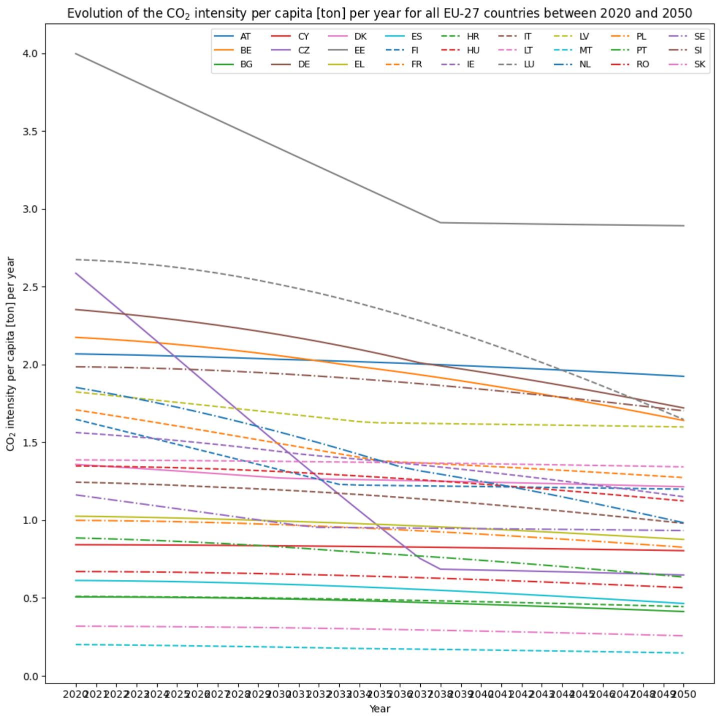


FIGURE 8: AMBIENCE SCENARIO 5 (AS5) EVOLUTION OF CO_2 INTENSITY PER CAPITA, FOR EACH EU-27 COUNTRY

Achieving the ideal AS5, which translates into the adoption of active control strategies within the building sector enabled by the building stock renovation, consequential electrification, the adoption of flexibility services as well as the decrease in the CI of electricity generation, would contribute with an overall yearly CO_2 emissions reduction of 26%, when comparing with 2020 levels (Figure 7) – the implementation of the AEPC can prove to be instrumental to achieve such results. It is possible to observe that every country is characterized by its own declination rate. From both figures above it's also clear that the most carbon intensive countries are the ones which will play a greater role in terms of contributing to the reduction of CO_2 emissions – whether it's per capita or in an absolute metric, the most carbon intense countries suffer the biggest CI declination and generate the biggest contributions for the overall CO_2 emissions reduction. Additionally, in the Figure 9 we can observe the evolution of the CO_2 intensity for each building typology considered within the EU-27 building stock (D4.1 database [3]) through the time frame analysis period.

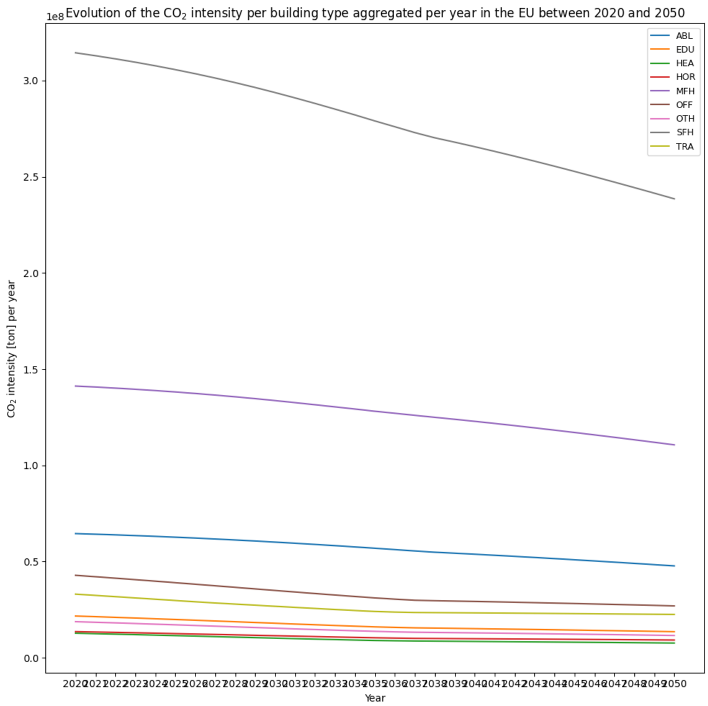


FIGURE 9: AMBIENCE SCENARIO 5 (AS5) EU AGGREGATED CO_2 INTENSITY OF EACH BUILDING TYPOLOGY, PER YEAR.

SFH – SINGLE FAMILY HOUSE; MFH – MULTIFAMILY HOUSE; ABL – APARTMENT BLOCK; HEA – HEALTH; HOR – HOTELS AND RESTAURANTS; OFF – OFFICES; TRA – TRADE; EDU – EDUCATION

From the Figure 9 it's possible to observe that, in an EU-level aggregated manner, the residential building sector will play a very important role in the decarbonization of the building stock. The carbon intensity evolution of the residential building typologies (SFH, MFH and ABL) is higher and suffers a much steeper decrease than the non-residential buildings. This evident decrease in the overall emissions related to the residential sector can be attributed to the building stock renovation/refurbishment, consequentially its electrification and ultimately the adoption of active control/flexibility. Below, the impact of these three focus areas will be further analyzed.

Concerning the building stock renovation, in Figure 10 we can see the AS5 achieved renovation rates and the corresponding required monetary investment, per country.

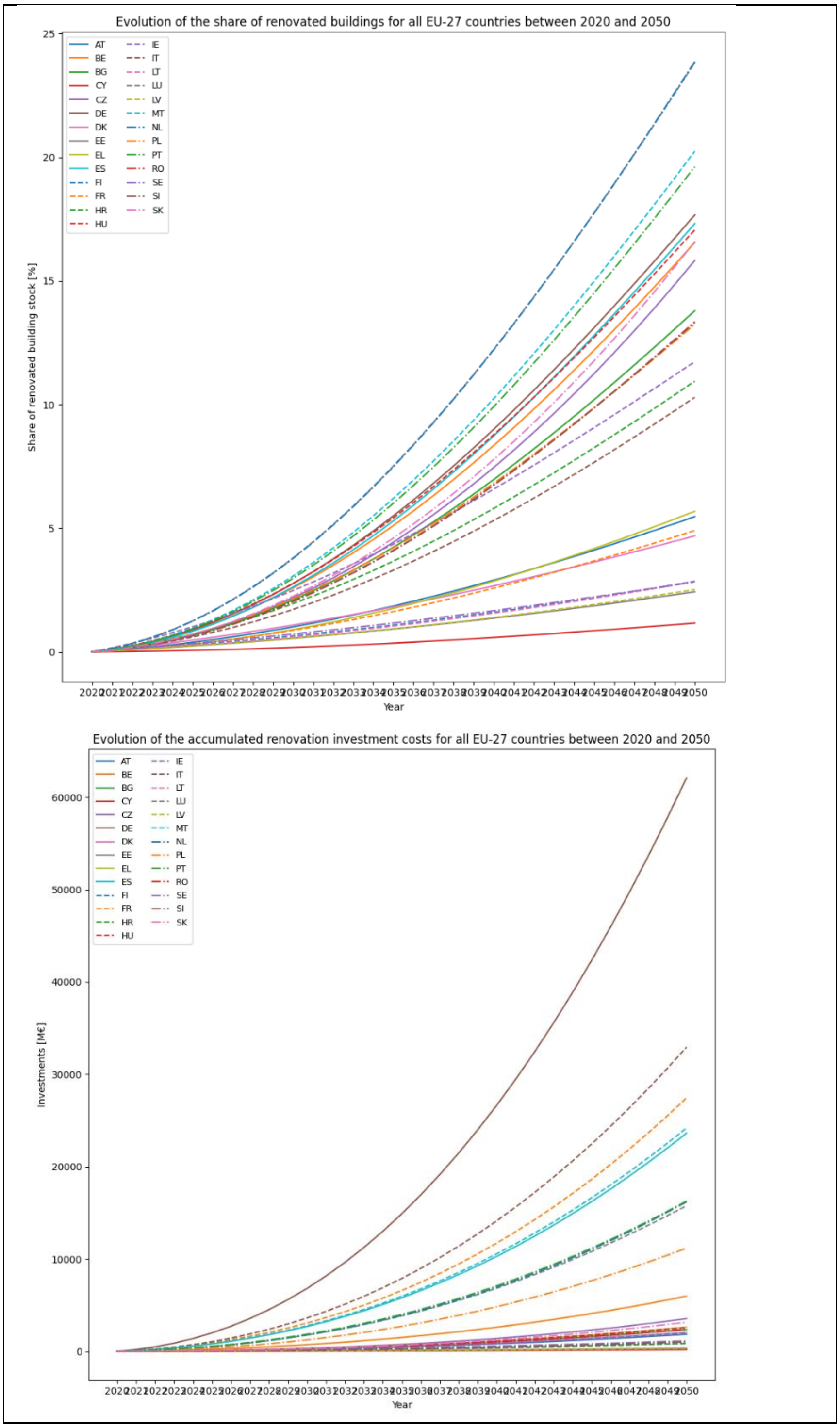
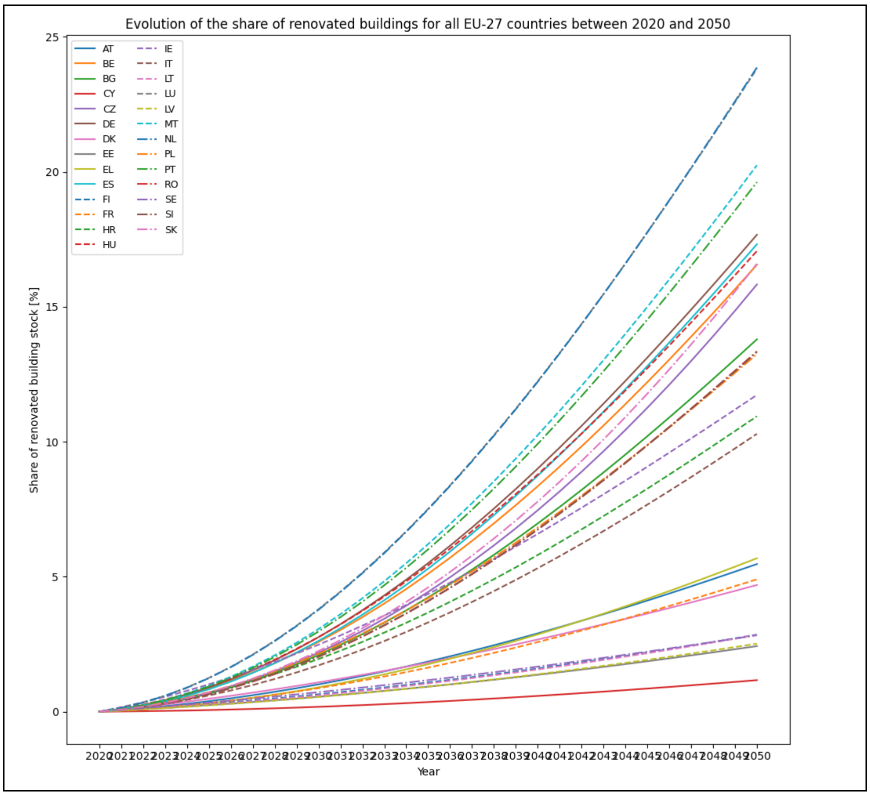


FIGURE 10: AMBIENCE SCENARIO 5 (AS5) SHARE OF RENOVATED BUILDINGS AND CORRESPONDING NECESSARY INVESTMENTS, FOR EACH EU-27 COUNTRY

As expected, we see an evolution of the total percentage of renovated buildings, across each country's building park, as renovation rates increase. Alongside with the increase of each country's renovation rates the cumulative renovation costs, associated with the increasing renovation rates, increase proportionally. To achieve the AS5 scenario, by 2050 the required cumulative total investment cost for the renovation of the EU-27 building stock will have to achieve 2.74 trillion € – around 19% of the current European Union's GDP [32].

Below we can see a comparison with the AS3, AS2 and AS1 scenarios renovation rates, Figure 11 to Figure 13 respectively. We can see the same behavior described above – renovation rates and required investments rising, although for AS1 and AS2 at a smaller scale when compared with AS5. While AS1 total required investment at the EU-level reaches 0.9 trillion €, AS2 renovation costs amounts to 1 trillion € and reaching the ideal 3%, AS3 and AS5, would amount to 2.74 trillion euros - the necessary amount required to be able to renovate and enable the building stock's decarbonization.



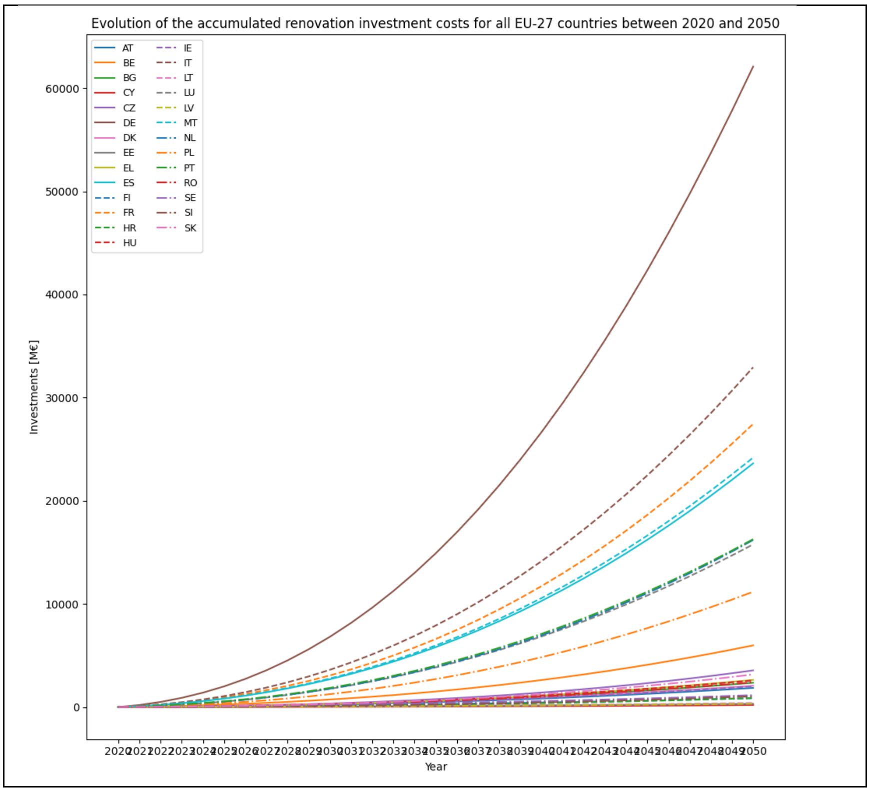
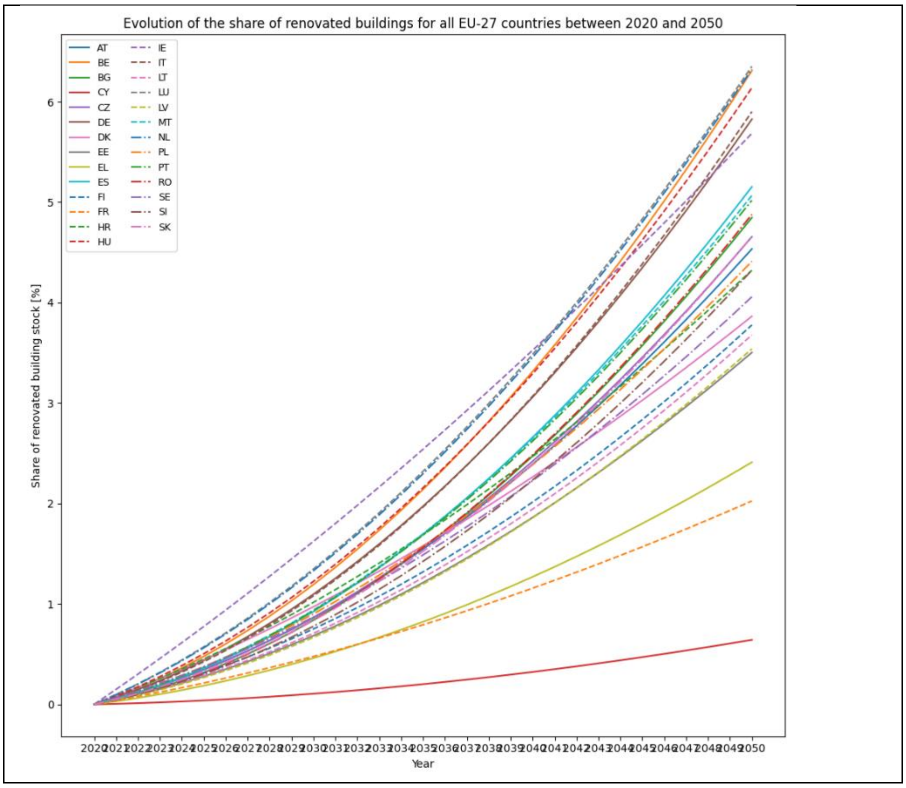


FIGURE 11: AMBIENCE SCENARIO 3 (AS3) SHARE OF RENOVATED BUILDINGS AND CORRESPONDING NECESSARY INVESTMENTS, FOR EACH EU-27 COUNTRY



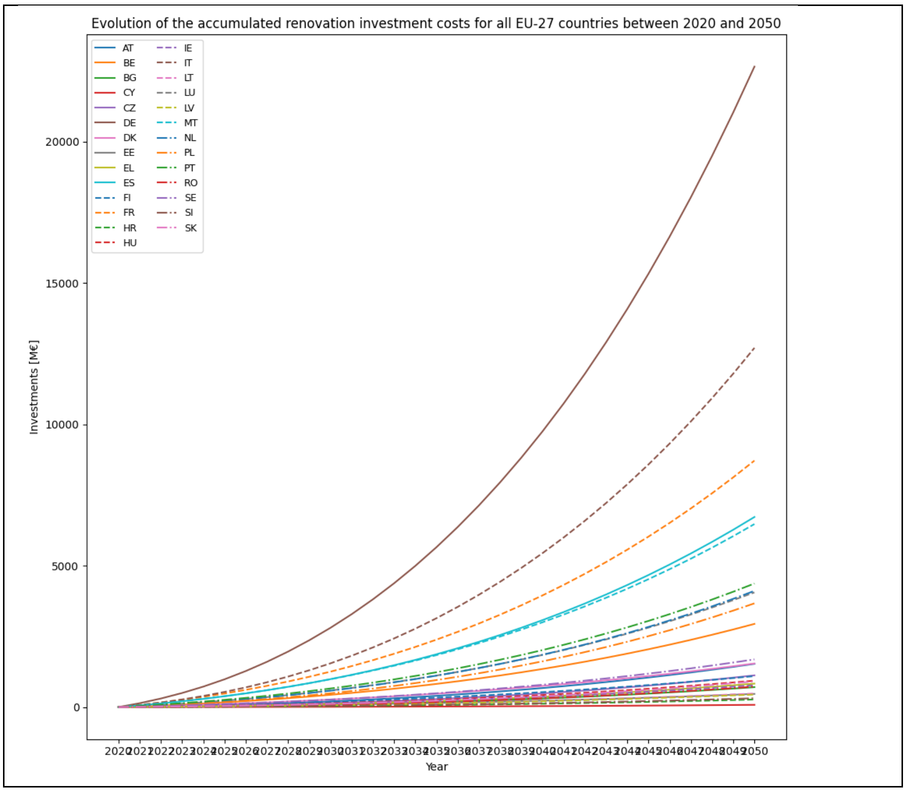
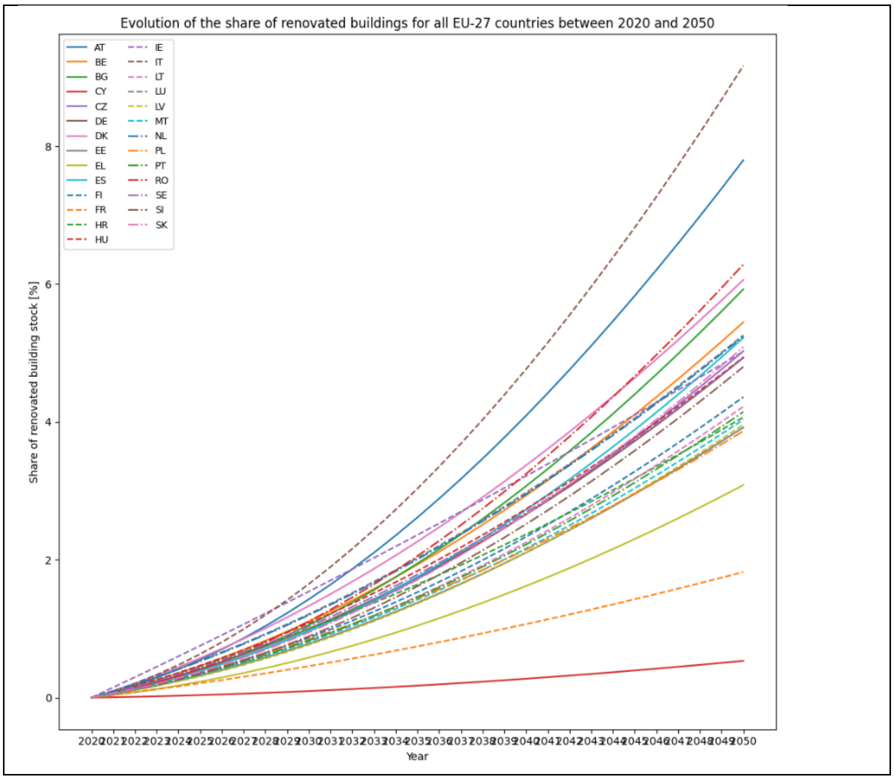


FIGURE 12: AMBIENCE SCENARIO 2 (AS2) SHARE OF RENOVATED BUILDINGS AND CORRESPONDING NECESSARY INVESTMENTS, FOR EACH EU-27 COUNTRY



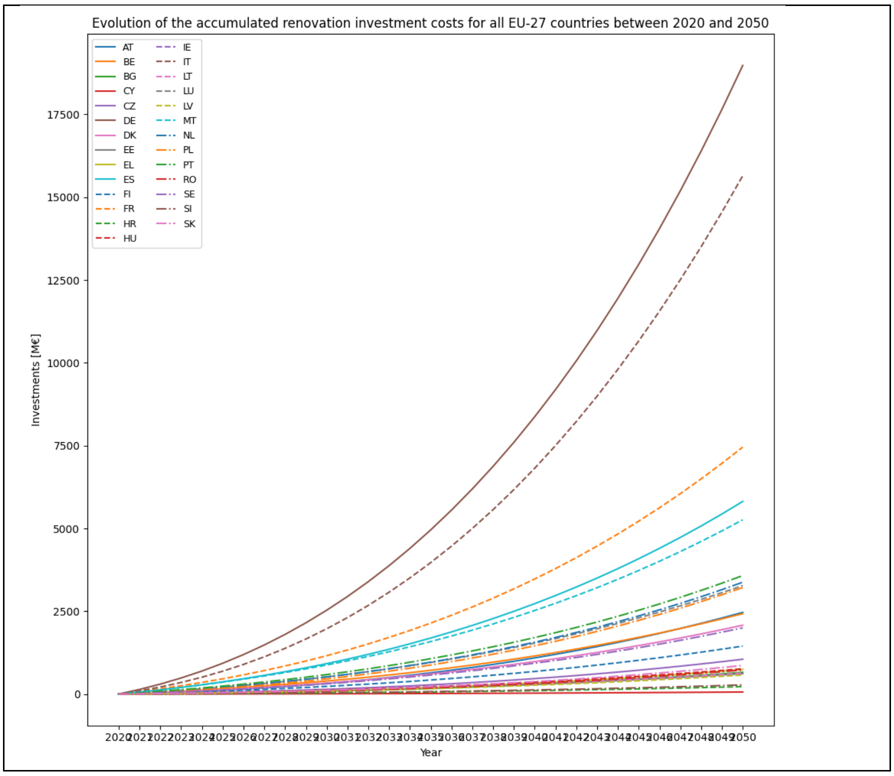


FIGURE 13: AMBIENCE SCENARIO 1 (AS1) SHARE OF RENOVATED BUILDINGS AND CORRESPONDING NECESSARY INVESTMENTS, FOR EACH EU-27 COUNTRY

As visible from the comparison of all figures above, with the increment of the renovation rates the share of the building stock which is renovated increases. Hence, a direct comparison between AS1, AS2 and AS3 scenarios may provide some insights on the direct impact of renovation rates in the decarbonization of the building stock (i.e., CO_2 emissions) since the only difference between each it's the incremental increase of the renovation rates.

Hence, in Figure 14 below we can see the yearly percentage decrease in emissions for the timeframe analysis period, due to achieving the ideal AmBIENCe scenario renovation rate of 3% – the difference between AS1 and AS3.

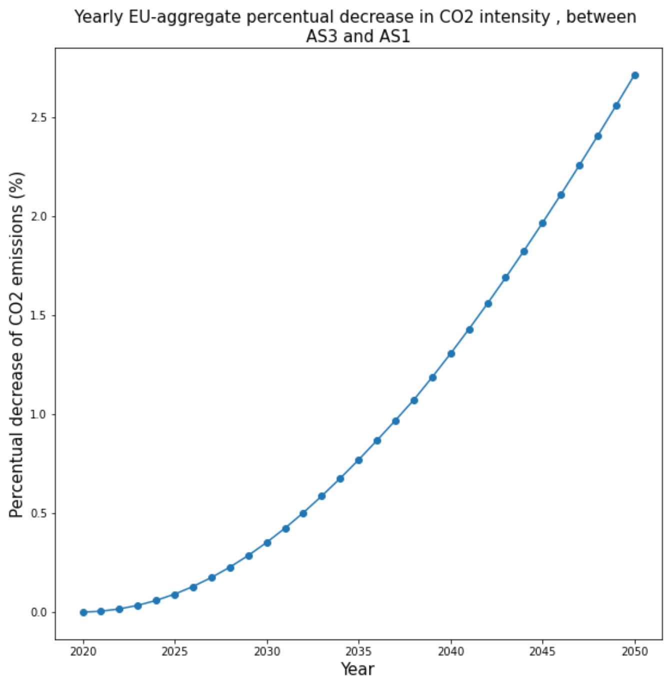


FIGURE 14: YEARLY EU-AGGREGATE PERCENTUAL DECREASE OF CO_2 INTENSITY OF DIFFERENCE BETWEEN AS3 AND AS1.

This comparison unlocks the quantification of the energy system impact that the increase of renovation rates to be able to reach the ideal 3% for renovation rates would amount to. Figure 15 displays the evolution of total accumulated CO2 emissions avoided on the EU-27 aggregate level. By reaching the ideal 3% (AS3) of renovation rates, comparing with the sub-optimal renovation rate of 1.5% (AS1) would contribute with 823 kiloton of CO_2 emissions avoided by 2050.

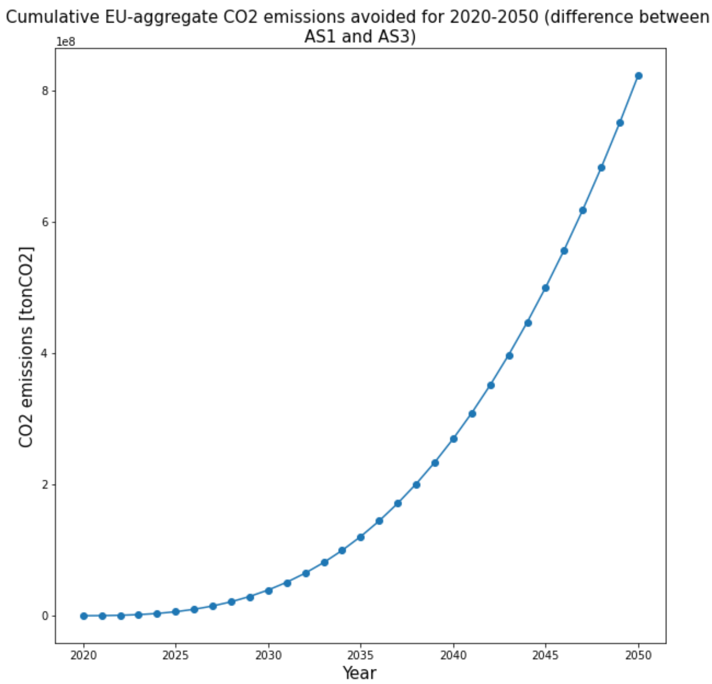


FIGURE 15: TOTAL CUMULATIVE EU-AGGREGATE CO2 EMISSIONS AVOIDED BY THE TIMEFRAME ANALYSIS PERIOD, DIFFERENCE BETWEEN AS3 AND AS1

We can further disaggregate this total cumulative difference between AS3 and AS1 for each EU-27 country, like seen below. This allows us to visualize that the most CO_2 intensive countries will play a key-role in reaching the energy and climate targets for 2050.

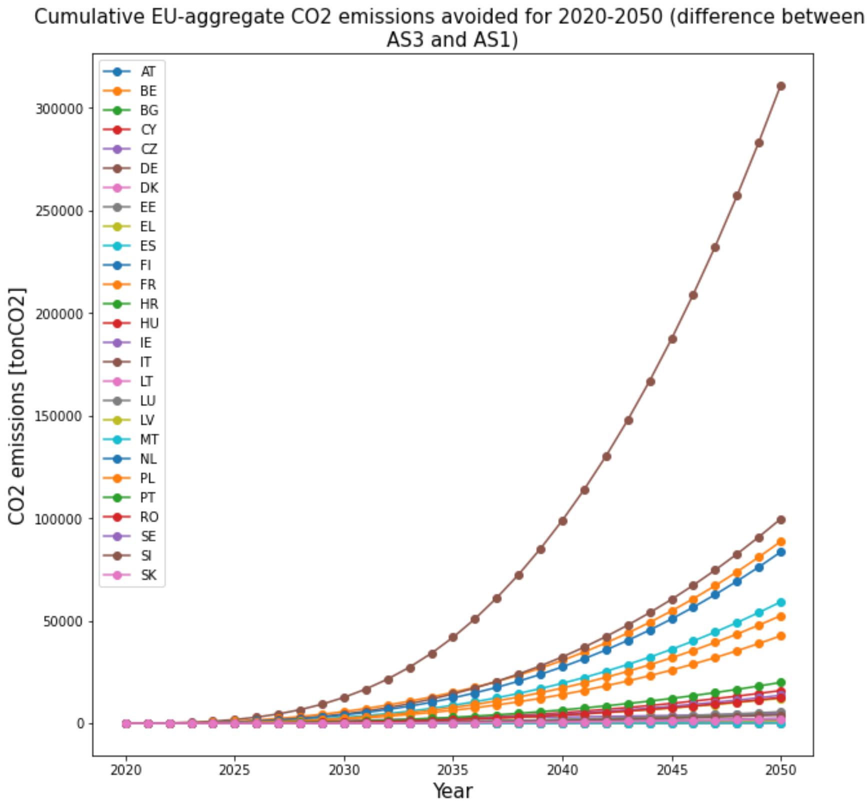


FIGURE 16: DISAGGREGATED CUMULATIVE CO_2 EMISSIONS AVOIDED FOR THE TIME FRAME ANALYSIS PERIOD FOR EACH EU-27 COUNTRY, DIFFERENCE BETWEEN AS3 AND AS1

Analogous, results from the KPI tool show that an increment of only 0,5% in the renovation rates – translated and quantified by the difference between AS1 and AS2 – would generate in a total accumulated avoided CO_2 emission of 13 kiloton of CO_2 by 2050.

Besides promoting energy efficiency, the building stock renovation further promotes its electrification. The adoption of electrification within the building stock is, like previously seen, a key step in achieving a successful building stock's decarbonization. Hence, the adoption of electrification was accounted for in the KPI calculation tool simulations. Figure 17 shows the effects of the electrification at the individual country level for the ideal scenario (AS5) for the countries represented in the AmBIENCe consortium: Belgium, Italy, Spain and Portugal respectively.

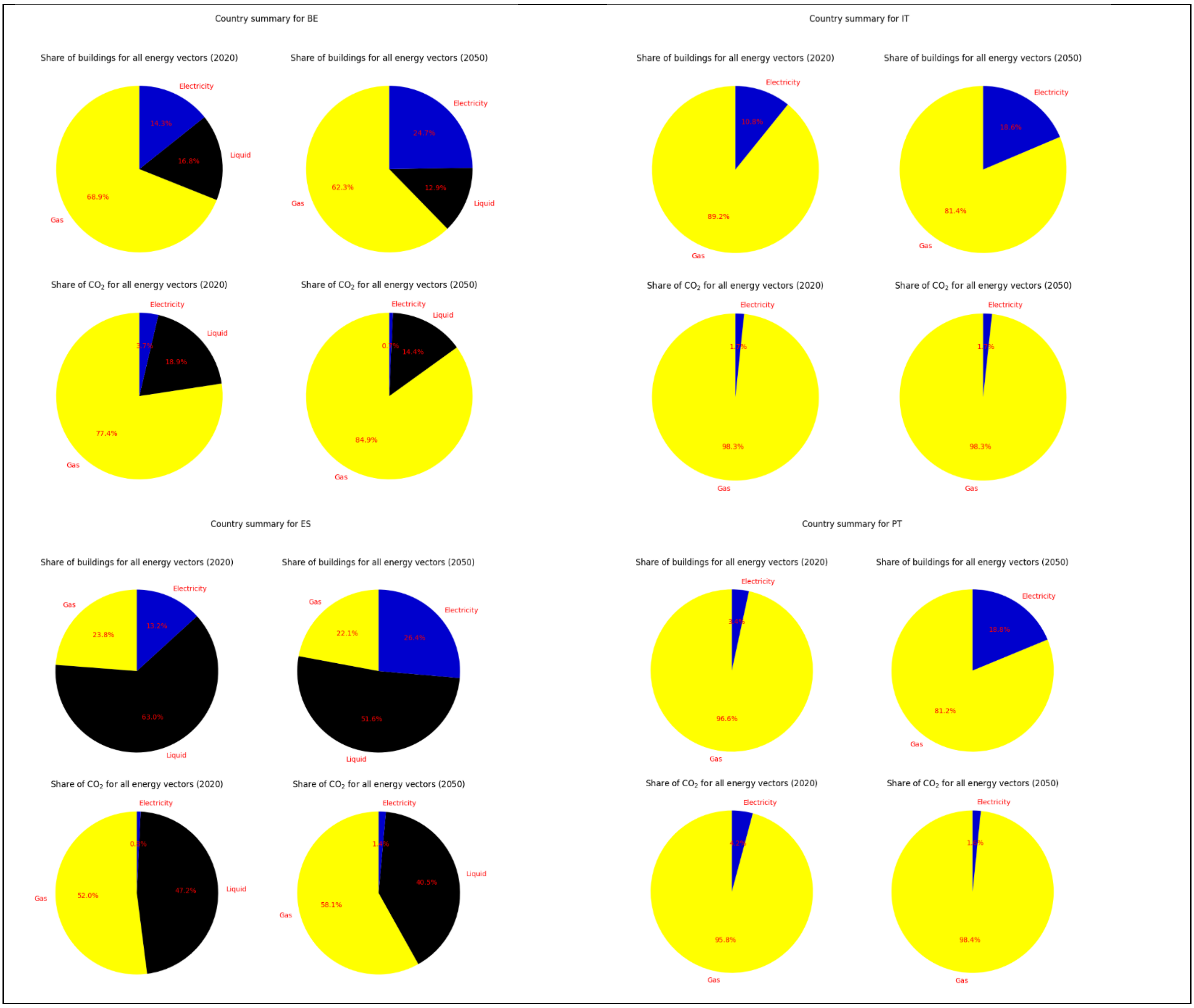


FIGURE 17: COUNTRY SUMMARY FOR AS5, FOR THE COUNTRIES REPRESENTED IN THE CONSORTIUM: BELGIUM (BE), ITALY (IT), SPAIN (ES) AND PORTUGAL (PT)

It's possible to observe the effects of electrification uptake: for all four countries in display, the share of buildings with electricity as its energy vector increases from 2020 to 2050. The CO_2 share for the energy vector in focus (electricity) tends to decrease. In the case of Italy, the CO_2 share remains constant despite the increase of 70% in electricity usage in buildings, in comparison to the levels observed in 2020. In Spain, electricity usage in buildings increases two fold, hence the slight increase (0,6%) in the share of CO_2 emissions from the same energy vector. For Portugal and Belgium, the usage of electricity as the buildings' energy vector increases while the corresponding share of CO_2 emissions decreases.

The remaining EU-27 country summaries, for AS5, can be seen in Annex III.

Furthermore, some insights on the direct impacts of electrification adoption as it is considered in the KPI calculation tool methodology can be retrieved. Here, a comparison between AS3 and AS4 can illustrate how electrification can directly impact the carbon intensity.

On an aggregate EU-level outlook, the difference between AS4 and AS3 shows that the increase in the uptake of electrification of 0,4 can originate an absolute cumulative decrease of approximately 559 kilotons of CO_2 – representing 68% of the emissions avoided solely from the renovation of the building stock. This highlights the importance of fostering the building stock's electrification as one of the key pillars of the energy system's decarbonization. In Figure 18 and Figure 19 below, we can see the yearly percentage decrease in CO_2 emissions and the cumulative avoided CO_2 emissions for the timeframe analysis period, respectively.

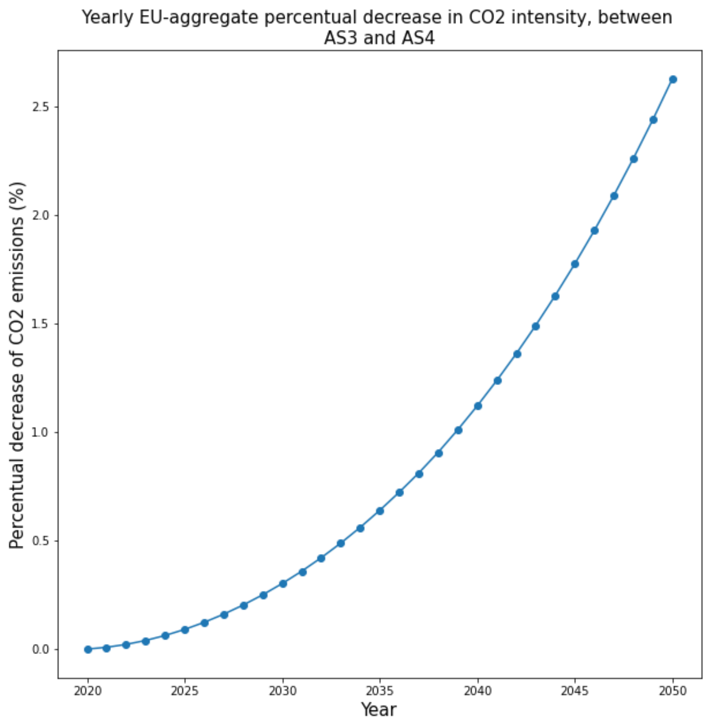


FIGURE 18: YEARLY EU-AGGREGATE PERCENTUAL DECREASE IN CO_2 EMISSIONS, BETWEEN AS3 AND AS4

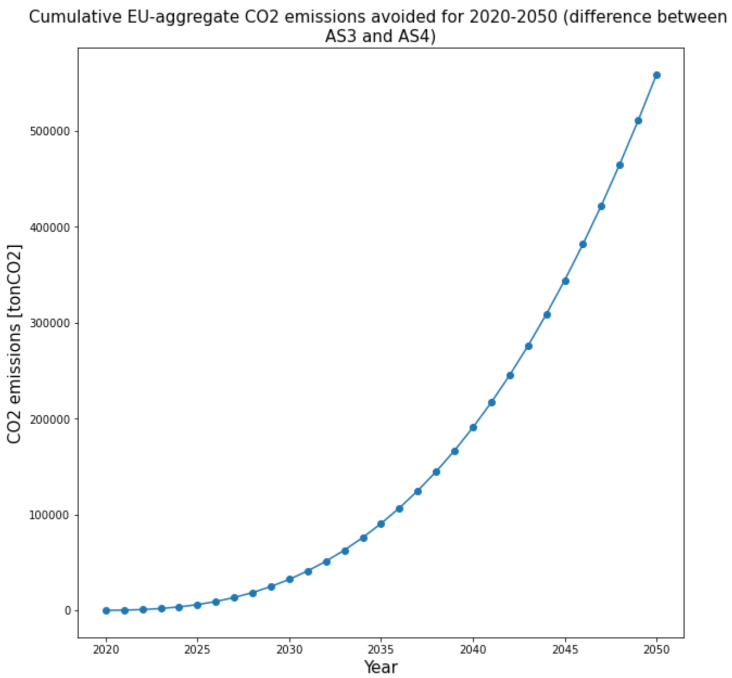


FIGURE 19: CUMULATIVE EVOLUTION OF AVOIDED CO_2 EMISSIONS FOR 2020-2050, BETWEEN AS3 AND AS4

The cumulative evolution of the avoided CO_2 emissions can be disaggregated for all EU-27 countries, as displayed in Figure 20.

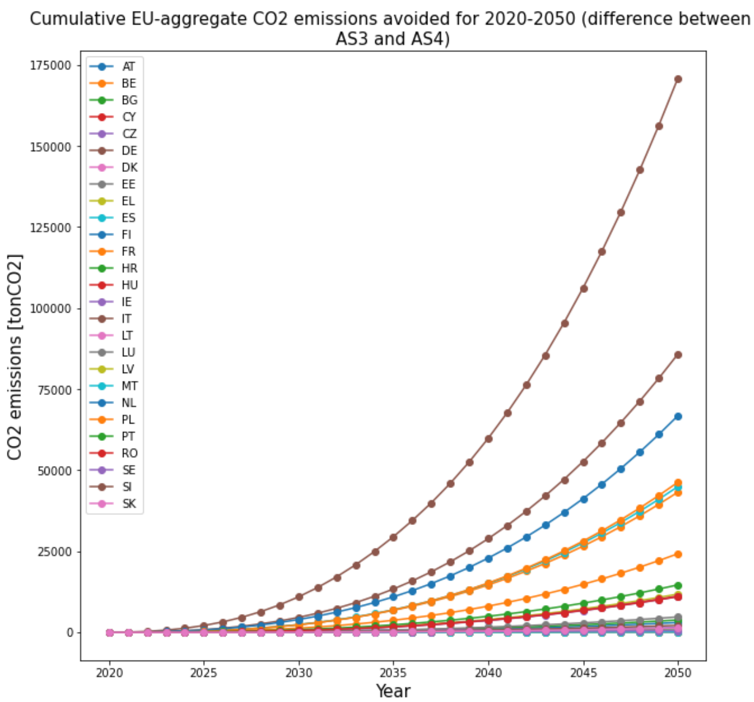


FIGURE 20: DISAGGREGATED CUMULATIVE CO_2 EMISSIONS AVOIDED FOR THE TIME FRAME ANALYSIS PERIOD FOR EACH EU-27 COUNTRY, DIFFERENCE BETWEEN AS4 AND AS3

A comparison for the consortium countries is shown in Figure 21 and Figure 22.

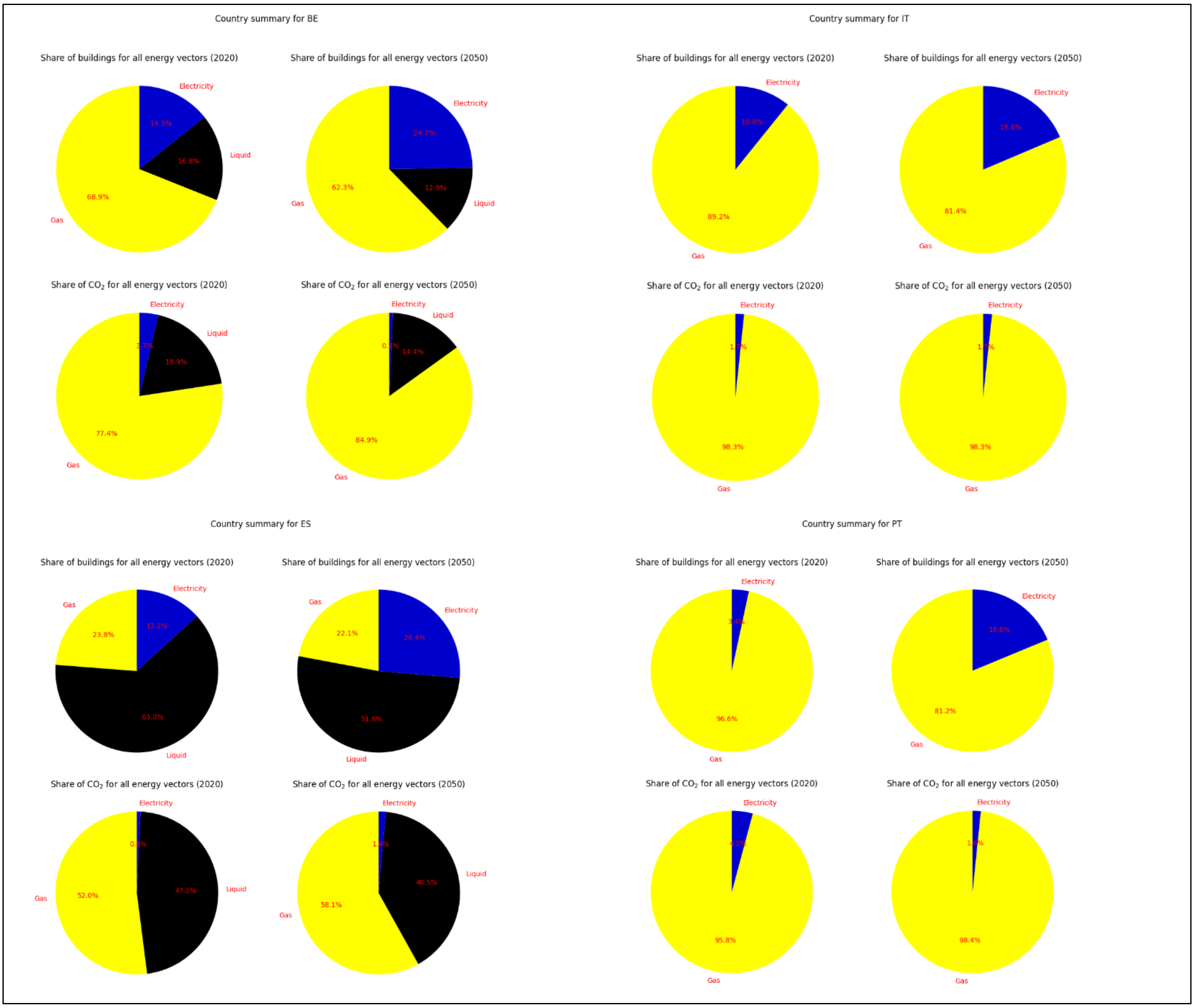


FIGURE 21: COUNTRY SUMMARY FOR AS3, FOR THE COUNTRIES REPRESENTED IN THE CONSORTIUM: BELGIUM (BE), ITALY (IT), SPAIN (ES) AND PORTUGAL (PT).

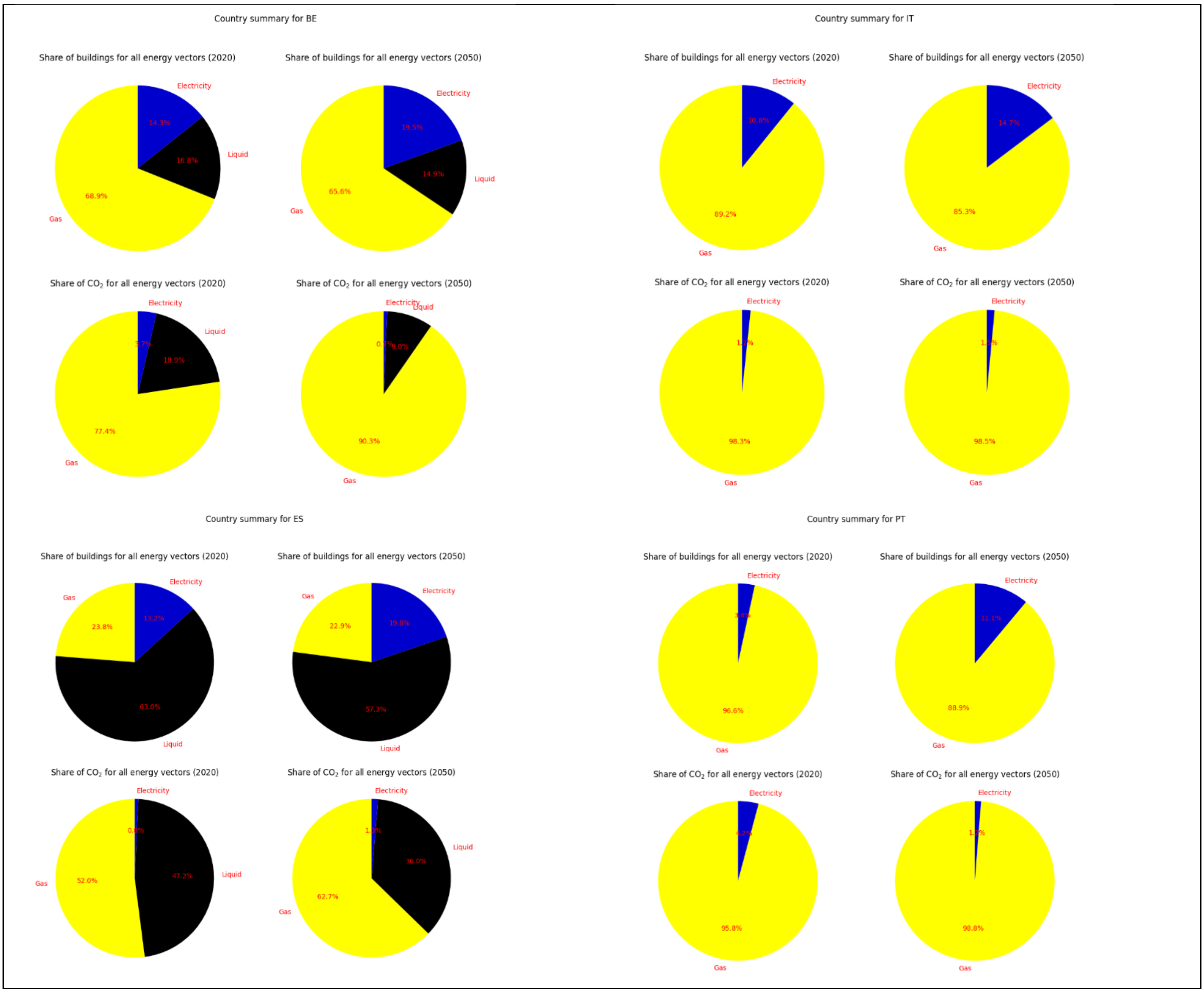


FIGURE 22: COUNTRY SUMMARY FOR AS4, FOR THE COUNTRIES REPRESENTED IN THE CONSORTIUM: BELGIUM (BE), ITALY (IT), SPAIN (ES) AND PORTUGAL (PT)

To achieve the building stock decarbonization, however, electrification is a crucial step: to create "space" for DR and/or flexibility services to be a reality in the future energy system, electrification must be pushed (market-oriented or otherwise).

Ultimately, the renovation of the building sector and its electrification are enablers to encourage the adoption of demand-side flexibility – vital for the transformation and decarbonization of the future energy system. Hence, a direct comparison between the ideal scenario (AS5) and AS3 illustrates how flexibility can further contribute to the decarbonization of the building stock and the energy system. Figure 23 shows the difference in emissions between AS5 and AS3 (the absolute cumulative CO_2 emissions avoided for the timeframe analysis period).

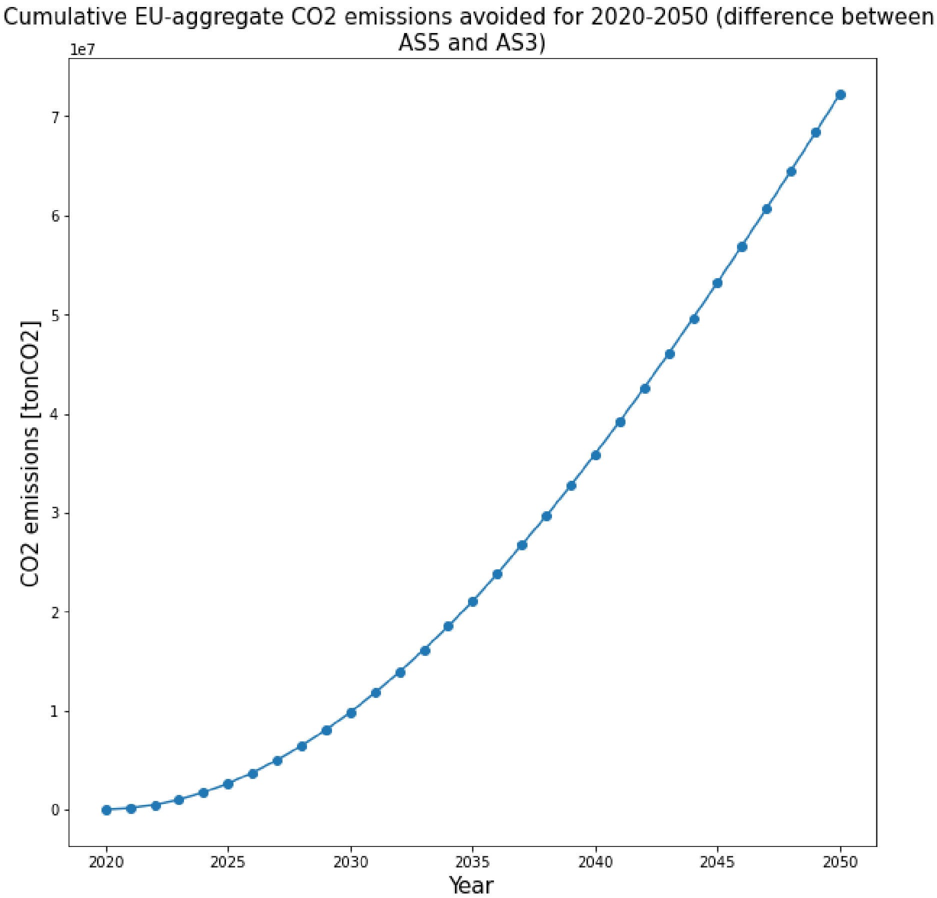


FIGURE 23: CUMULATIVE EU-AGGREGATE CO_2 EMISSIONS AVOIDED FOR 2020-2050, BETWEEN AS5-AS3

We can observe that the increase in the adoption of flexibility, as expected, originates a decrease of the aggregate EU CO_2 emissions – in absolute terms it translates to a cumulative decrease of 823 kiloton of CO_2 – aligned with the avoided emissions solely derived from the renovation wave, highlighting the importance of flexibility and active control adoption to shape and contribute to the decarbonization process. Below, the cumulative decrease of CO_2 emissions is disaggregated for each EU-27 country. The results are in accordance with the methodology: the MS with the highest share of CO_2 emissions contribute with a larger share of the emissions reductions.

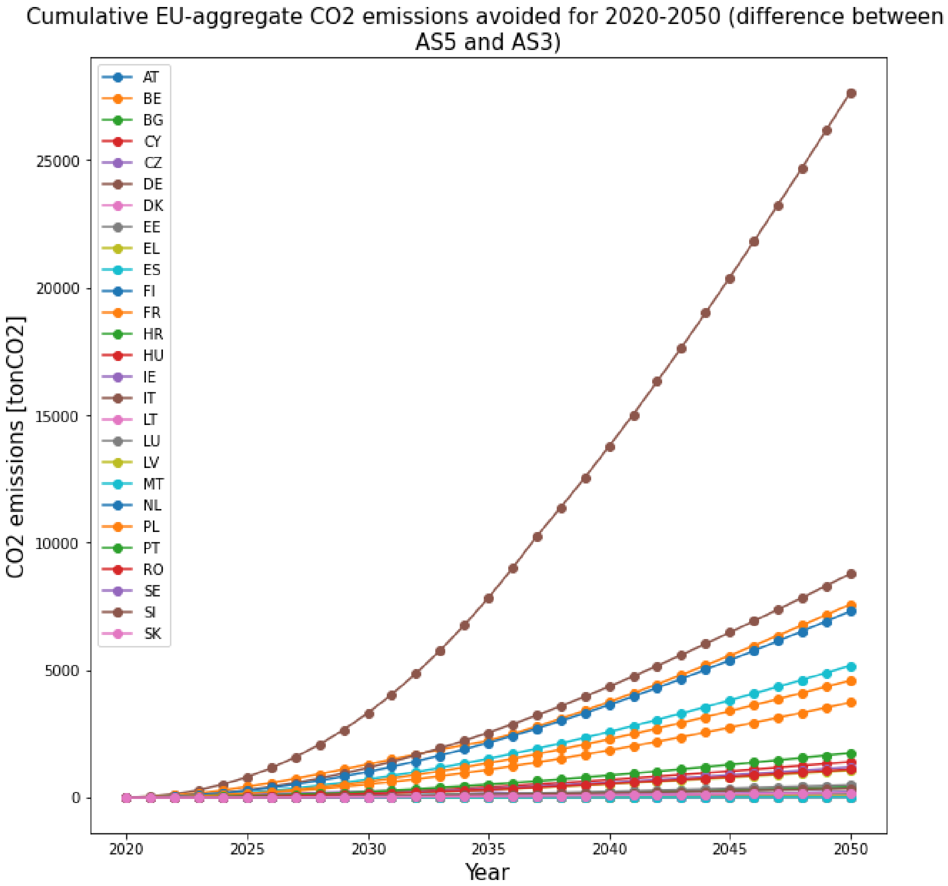


FIGURE 24: DISAGGREGATED CUMULATIVE CO_2 EMISSIONS AVOIDED FOR THE TIME FRAME ANALYSIS PERIOD FOR EACH EU-27 COUNTRY, DIFFERENCE BETWEEN AS3 AND AS1.

5. CONCLUSIONS AND RECOMMENDATIONS

Throughout this document a replicable methodology to characterize the state of the EU-27 building stock in the year of 2050 is developed. Coupled with grey-box models or any other simulation tool with the same purpose, the methodology approach and assumptions defined and developed enable dynamic calculations of the flexibility potential of the building stock for the time-frame analysis period, which in this case is 2050.

The different sections follow the required steps to, firstly, extend the scope of the database of grey-box models parameters to include the presence of technical systems in the EU-27 reference building stock, allowing to create and describe a baseline scenario which depicts the current state of such building stock. After which, energy-related scenarios focusing on the decarbonization of the energy sector for time-frame period are mapped out, providing insights on the possible paths through which the EU's climate and emission goals can be achieved. Through these scenarios, and considering the baseline case, we can then draw some forecasts on how the building stock renovation would take shape until 2050. The quantification of such renovation measures serves as inputs for the energy system impact assessment tool, ABEPeM, developed under the context of this project. It is important to highlight that the developed methodology and the set of assumptions are replicable to any other simulation tool or platform, for the same time-frame analysis horizon if the inputs are corrected accordingly. However, the KPI calculation tool enabled to study different scenarios which focus on the active control enablers and the energy system's impact of the decarbonization of the EU-27 building stock, providing quantifiable results for the energy system's impact of the adoption of active control within the building stock. Through the analysis it's estimated that by 2050 the European carbon emissions can decrease by 26% with the adoption of active control within the building stock. Successfully promoting and incentivizing the building stock renovation and its electrification are seen as two of the three pillars – flexibility proves to be as important as the effect of both renovation and electrification. The associated costs for renovating the building stock would amount to 2.74 trillion € – around 19% of the current European Union's GDP [29] –, representing approximately 60% of the EU-27 building stock which could be renovated, by 2050. Thus, to achieve the ambitious energetic and climate targets for 2050 it's key to enable the active control of the EU-27 building stock.

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ANNEX

ANNEX I.

In 2018 the recast of EPBD was developed to realize the saving potential in buildings, as they account for almost 40% of the consumption of energy in the EU. Thus, the EPBD plays a central role in achieving the EU's goal of energy savings and CO_2 emissions reduction. The EPBD defines the common basis for calculating building's energy performance and establishes minimum requirements for the energetic performance of both existing and new buildings, foreseeing that each Member State shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set achieving cost-optimal levels. One path to achieve the energetic performance and standards is through the improvement of the thermal behaviour of the building stock, which can be accomplished by focusing on the insulation of the building envelope elements and minimizing the heat losses through the building structure. In accordance with the work described in the deliverable D4.1 [3], the building envelope elements to be considered from this point forward are the windows, walls, roof and floor.

Thus, the methodology developments focus' on the building envelope renovations which tackles insulation requirements for the EU-27 building stock, in accordance with the EBPD standards [21]. These standards may focus either on the thermal transmittance, also known for U-value, after applying insulation in each building element or, alternatively, through the calculation of a primary energy performance indicator applied to the building. For simplification purposes, and since the quantification of this renovation category must be in line with the necessary inputs for the future integration of this data into the energy system impact assessment framework, any further developments concerning the building envelope renovations from this point forward will focus exclusively on the thermal transmittance of the building elements.

The first step of the methodology approach consists in the data collection of each country's EPBD transposition standards. In the attempt to collect the most accurate and up-to-date data on the standard requirements for the U-values, various data sources were used. The main data source was the Energy Performance of Buildings Concerted Action (EPBD CA) [4]. This joint initiative between each EU MS and the EC provides a web-based platform and database to enhance the sharing of information and experiences from national adoption and implementation of the EPBD. Either in the format of .html or .pdf, individual country reports are available to download, in which each of the EU-27 countries standard requirements and respective progresses towards the EPBD transposition are summarized. However, additional data sources were used to complement the information and data present in [33]: since some individuals reports are as old as 2016, in the attempt to gather the most up-to-date data for each country and for each individual building envelope element. These alternative and complimentary data sources include technical reports, scientific papers and national legislation documents from the appropriate respective national entities responsible for the EPBD transposition. The information and data gathered from these alternative data sources was then cross-checked, when possible, with the individual reports from the EPBD CA to ensure the veracity and of said complementary sources.

Some assumptions were necessary to standardize the information and data collected:

- Where the U-value is not available, the minimum requirement of thermal transmittance from a country within the EU-27 with similar climate type [31] is used. For example, Latvia's energy performance requirements are based on a primary energy performance indicator, not a U-value, therefor, for thermal insulation the U-values from Finland was considered." For example, in the case of Latvia the minimum requirements for thermal insulation were assumed and considered to be equal to those reported from Finland, which has clearly defined U-values requirements for all the considered building envelope elements and which possess the same climate type.
- From the data sources used for compiling U-value minimum requirements of the building envelope elements, only a few individual country reports make differentiation between residential and non-residential buildings, meaning that only a few individual country reports contain clearly defined different requirements for residential and non-residential sectors. In such cases both were taken into consideration. In cases where there is no mention to the requirements for the non-residential sector the minimum requirements are assumed to be equal to the ones defined for the residential sector.
- In some cases, individual countries define the minimum U-value standard requirements according to different climatic sub-regions present in such country. For simplification purposes and to be able to standardize the methodology applied to every EU-27 country, the considered U-value limitation for a country in which there are different U-value requirements depending on regions' climatic areas, only one limitation per building envelope element is considered and it is assumed to be equal to lowest identified U-value limitation per element in that country.
- In some of EPBD transpositions the U-value minimum requirements depend on the ratio of the renovated area versus the total area of a building, differentiating between two types of renovations: shallow and deep renovations, whether the renovated area is less than or greater then/equal than 25% of the total area of the building, respectively. To standardize the methodology applied to all EU-27 countries and to be able to identify a single U-value per building envelope element we assume the lowest identified U-value limitation in order to ensure that the proposed renovation complies with all energy performance requirements.

Thus, we can gather all the U-value minimum requirements for the considered building envelope elements for each EU-27 country. This data is presented Table 25 and Table 26 for the residential and non-residential sectors respectively. When complementary data sources were considered, in addition to [33], they are show in each table for the respective country.

TABLE 25: U-VALUE MINIMUM REQUIREMENTS FOR EU-27 COUNTRIES FOR THE RESIDENTIAL SECTOR

U-value (W/m2K)					Complementary References
	Window	Walls	Roof	Floor	
AT	1.4	0.35	0.24	0.4	[34], [35]
BE	1.5	0.24	0.24	0.24	[34], [35]
BG	-	-	-	-	[34], [35]
CY	2.9	0.4	0.4	0.4	[34], [35]
CZ	-	-	-	-	[34], [35]
DE	-	-	-	-	[34], [35]
DK	-	-	-	-	[34], [35]
EE	1.1	0.12	0.1	0.1	[34], [35]
EL	-	-	-	-	[34], [35]
ES	1.8-3.2	0.37-0.8	0.33-0.55	0.59-0.9	[34], [35]
FI	-	-	-	-	[34], [35]
FR	1.9	0,35	0.25-0.22	0.24	[34], [35]
HR	-	-	-	-	[34], [35], [36]
HU	1.4	0.24	0.17	0.26	[34], [35],
IE	3.3	0.7	0.35	0.7	[34], [35],
IT	3-1	0.4-0.26	0.32-0.22	0.42-0.28	[34], [35],
LT	-	-	-	-	[34], [35],
LU	1.5	0.32	0.4	0.32	[34], [35],
LV	-	-	-	-	[34], [35],
MT	4	1.57	0.59	1.57	[34], [35], [36]
NL	2.2	0.77	0.5	0.4	[34], [35]
PL	0.9-1.4	0.3-1	0.7-0.15	1-0.25	[34], [35]
PT	-	-	-	-	[34], [35]
RO	1.3	0.56	0.2	0.22	[34], [35]
SE	1.2	0.18	0.13	0.15	[34], [35]
SI	1.3	0.28	0.2	0.9	[34], [35]
SK	-	-	-	-	[34], [35]

TABLE 26: U-VALUE MINIMUM REQUIREMENTS FOR EU-27 COUNTRIES FOR THE NON-RESIDENTIAL SECTOR

	U-value (W/m2K)				Complementary References
	Window	Walls	Roof	Floor	
AT	1.4	0.35	0.2	0.4	-
BE	1.5	0.24	0.24	0.24	-
BG	1.4	0.35	0.28	0.4	-
CY	2.25	0.4	0.4	0.4	-
CZ	1.1	0.3	0.24	0.45	-
DE	-	-	-	-	-
DK	1.1	0.3	0.2	0.2	-
EE	-	-	-	-	-
EL	2.6	0.4	0.35	0.35	-
ES	1.8	0.37	0.33	0.59	-
FI	1	0.17	0.09	0.16	-
FR	1.9	0.35	0.22	0.24	-
HR	1.6	0.3	0.25	0.4	-
HU	1.15	0.24	0.17	0.26	-
IE	3.3	0.7	0.35	0.7	[37]
IT	3-1	0.4-0.26	0.32-0.22	0.42-0.28	-
LT	1.1	0.2	0.16	0.25	-
LU	1.5	0.32	0.4	0.32	-
LV	1	0.17	0.09	0.16	-
MT	4	1.57	0.4	1.57	[38]
NL	2.2	0.22	0.17	0.29	-
PL	1.1	0.2	0.15	0.25	-
PT	-	-	-	-	-
RO	-	-	-	-	-
SE	1.2	0.18	0.13	0.15	-
SI	1.3	0.28	0.2	0.9	-
SK	-	-	-	-	-

The minimum requirements are then compared with a standard renovation solution for all buildings, composed of renovation measures focused on the insulation of the considered building envelope elements, and which was collected from a reference search [39]. Below, in Table 27**TABLE 27**, the adopted standard renovation is described: both the insulation technologies and materials used and the respective U-values for each individual element.

TABLE 27: ADOPTED STANDARD SOLUTION, FOR RESIDENTIAL AND NON-RESIDENTIAL SECTORS

U-values (W/m2K)		
Window	Walls	Roof
1.5	0.3	0.15
Double glazed 4/16/4 with PVC frame	Mineral wool 10 cm	Rock wool 29.5 cm

The comparison between the adopted standard solution U-values and the U-value requirements for each individual country will allow the identification of which building elements, for each country, that will need further improvements on the insulation. If such case is identified the standard solution is adapted in order to comply with minimum U-value requirements for the respective country.

Below, in Table 28 and Table 29, are listed the final adopted solutions for each EU-27 country for the residential and non-residential sectors respectively.

TABLE 28: FINAL ADOPTED U-VALUE FOR EACH BUILDING ENVELOPE ELEMENT PER COUNTRY, FOR RESIDENTIAL SECTOR

	U-value (W/m2K)			
	Window	Walls	Roof	Floor
AT	1.4	0.3	0.15	0.34
BE	1.5	0.24	0.15	0.24
BG	1.4	0.3	0.15	0.34
CY	1.5	0.3	0.15	0.34
CZ	1.1	0.3	0.15	0.34
DE	1.3	0.24	0.15	0.34
DK	1.1	0.3	0.15	0.2
EE	1.1	0.12	0.1	0.1
EL	1.5	0.3	0.15	0.34
ES	1.5	0.3	0.15	0.34
FI	1	0.17	0.09	0.16
FR	1.5	0.3	0.15	0.24
HR	1.5	0.3	0.15	0.34
HU	1.15	0.3	0.15	0.34
IE	1.5	0.3	0.15	0.21
IT	1	0.26	0.15	0.28
LT	1.5	0.2	0.15	0.25
LU	1.5	0.3	0.15	0.32
LV	1	0.17	0.09	0.16
MT	1.5	0.3	0.15	0.34
NL	1.5	0.22	0.15	0.29
PL	1.1	0.2	0.15	0.25
PT	1.5	0.3	0.15	0.3
RO	1.5	0.3	0.15	0.34
SE	1.2	0.18	0.13	0.15
SI	1.5	0.3	0.15	0.34
SK	0.6	0.15	0.1	0.34

TABLE 29: FINAL ADOPTED U-VALUE FOR EACH BUILDING ENVELOPE ELEMENT PER COUNTRY, FOR NON-RESIDENTIAL SECTOR

U-value (W/m2K)				
	Window	Walls	Roof	Floor
AT	1.4	0.3	0.15	0.34
BE	1.5	0.24	0.15	0.24
BG	1.4	0.3	0.15	0.34
CY	1.5	0.3	0.15	0.34
CZ	1.1	0.3	0.15	0.34
DE	1.3	0.24	0.15	0.34
DK	1.1	0.3	0.15	0.2
EE	0.6	0.15	0.1	0.1
EL	1.5	0.3	0.15	0.34
ES	1.5	0.3	0.15	0.34
FI	1	0.17	0.09	0.16
FR	1.5	0.3	0.15	0.24
HR	1.5	0.3	0.15	0.34
HU	1.15	0.3	0.15	0.34
IE	1.5	0.27	0.15	0.25
IT	1	0.26	0.15	0.28
LT	1.1	0.2	0.15	0.25
LU	1.5	0.3	0.15	0.32
LV	1	0.17	0.09	0.16
MT	1.5	0.3	0.15	0.34
NL	1.5	0.22	0.15	0.29
PL	1.1	0.2	0.15	0.25
PT	1.5	0.3	0.15	0.3
RO	1.5	0.3	0.15	0.34
SE	1.2	0.18	0.13	0.15
SI	1.5	0.3	0.15	0.34
SK	0.6	0.15	0.1	0.34

The quantification of the proposed renovation measure, which will enable the energy impact assessment, is based on the modification of the relevant building stock parameters identified and included in the previous deliverable and database of grey-box models parameters (D4.1) [3]. The database fields which will require modification after the considered renovations are as follows:

- Floor: fields 19 – 24, concerning the reference building floor insulation material, reference building floor insulation material thickness (m), reference building floor insulation material thermal conductivity (W/m/K), reference building floor insulation material density (kg/m^3), reference building floor insulation material specific heat capacity (J/kg/K) and reference building floor U-value (W/m^2/K) respectively;

- Wall: fields 30 – 35, concerning the reference building wall insulation material, reference building wall insulation material thickness (m), reference building wall insulation material thermal conductivity (W/m/K), reference building wall insulation material density (kg/m^3), reference building wall insulation material specific heat capacity (J/kg/K) and reference building wall U-value (W/m^2/K) respectively;
- Window: fields 36 – 41, concerning the reference building window type, reference building window glazing type, reference building frame material, reference building window coated, reference building window filling gas, reference building window U-value (W/m^2/k), respectively;
- Roof: fields 47 – 52, concerning the reference building roof insulation material, reference building roof insulation material thickness (m), reference building roof insulation material thermal conductivity (W/m/K), reference building roof insulation material density (kg/m^3), reference building roof insulation material specific heat capacity (J/kg/K) and reference building roof U-value (W/m^2/K) respectively.

For all the building envelope elements the following is considered:

- After the renovations the reference building envelope U-value will be equivalent to the proposed U-values listed in the Table 10 and Table 11, complying with the EPBD requirements;
- The insulating materials properties considered for the renovations for all building envelope elements are presented below**:**

TABLE 30: INSULATING MATERIALS PROPERTIES

MATERIAL	THERMAL CONDUCTIVITY (W/m/K)	DENSITY (kg/m^3)	SPECIFIC HEAT CAPACITY (J/kg/K)
Rock wool	0.034	200	710
Mineral wool	0.042	12	1 030

ANNEX II.

One possible pathway to assist on unlocking the flexibility potential of the building stock is via price-driven DR, which uses electricity prices as control signals to motivate consumers to change or to shift their energy consumption from peak load into off-peak time periods [40].

Considering the time-frame period analysis, much uncertainty still exists on DR pricing schemes that could effectively be considered for 2050. A reference search [41] provided assumptions for this work, and two pricing schemes will be considered: a fixed pricing scheme, characterised by a fixed electricity price throughout the day, and a dynamic pricing scheme, characterised by electricity price variations throughout the day. For simplification purposes, since dynamic pricing schemes could take shape in a variety of options and in some cases very hard to predict (for example real time pricing schemes), the approach for the dynamic pricings will take shape as a Time-of-Use (ToU) tariff. In ToU tariffs, the electricity prices are already predefined, and change throughout a day according to if peak and off-peak demand periods, using this variation as a signal to encourage consumers to shift their energy consumption to off-peak periods. ToU tariff schemes are already widely implemented in energy markets of today and extensively documented.

Besides providing the mapping of the energy-related scenarios the EC Energy roadmap for 2050, [16], models the energy market evolution and outputs the forecasted average electricity prices for the timeframe period analysis, for both the residential and non-residential sector. Since we're considering five different scenarios, the forecasted average electricity prices for each scenario have been gathered from [16]. Necessary adjustments were necessary to update the values according to the inflation rate

since the calculations have been made – a cumulative inflation rate of 20.06% based on the Harmonised Index of Consumer Prices annual data for EU-27 must be considered since 2008 to 2021 [42]. Below, in Table 31 we can see the forecasted average electricity prices for both considered sectors per scenario for the considered time-frame period, the year of 2050.

TABLE 31: FORECASTED AVERAGE ELECTRICITY PRICE PER ENERGY SCENARIO FOR 2050, FOR RESIDENTIAL AND NON-RESIDENTIAL SECTOR

(€/MWh)	Scenario 1 Reference	Scenario 2 High Energy Efficiency	Scenario 3 Diversified supply	Scenario 4 High RES	Scenario 5 Low Nuclear
Residential	254.88	234.47	233.51	342.88	250.08
Non residential	207.34	193.89	191.85	268.69	206.02

From Eurostat [43] we gathered the current average EU-27 electricity prices for each considered sector, shown in Table 32, and assuming a stable and linear evolution we were able to draw the electricity prices relationship from 2021 until the year of 2050 for each considered sector, per scenario – shown in Figure 25.

TABLE 32: CURRENT AVERAGE ELECTRICITY PRICES FOR RESIDENTIAL AND NON-RESIDENTIAL SECTOR (2021).

(€/MWh)	2021
Residential	219.2
Non residential	128.3

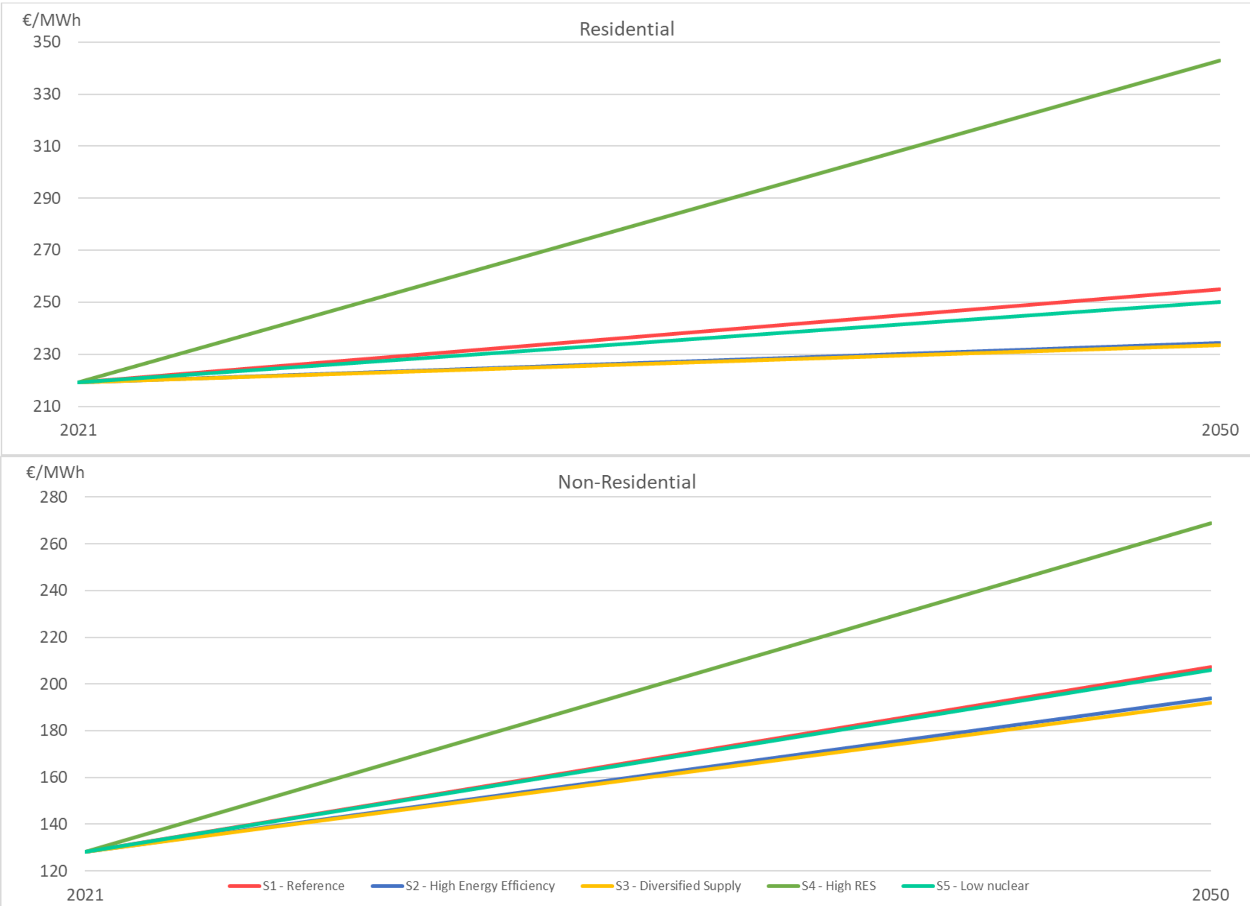


FIGURE 25: AVERAGE ELECTRICITY PRICE EVOLUTION PER SCENARIO FOR RESIDENTIAL AND NON-RESIDENTIAL SECTORS, ABOVE AND BELOW RESPECTIVELY.

However, across the whole EU-27 area electricity prices do not remain constant – the average electricity prices for both residential and non-residential sectors vary from country to country and consequently energy tariffs charged to both consumer types will also suffer variations accordingly. Thus, it is necessary to disaggregate the average prices per scenario and for each sector to be able to compute an average electricity price per country and per scenario for each sector. From Eurostat [43], the data on current average electricity prices per country and for each sector was collected and the linear relationship of the average electricity prices evolution from 2021–2050 of each scenario applied to each individual country, thus enabling the disaggregation of the average electricity prices for each individual country per scenario for both the residential and non-residential sector, for all EU-27 countries. Below, in Figure 26, we can see as an example the reference scenario disaggregated electricity prices for the residential and non-residential sector, per country.

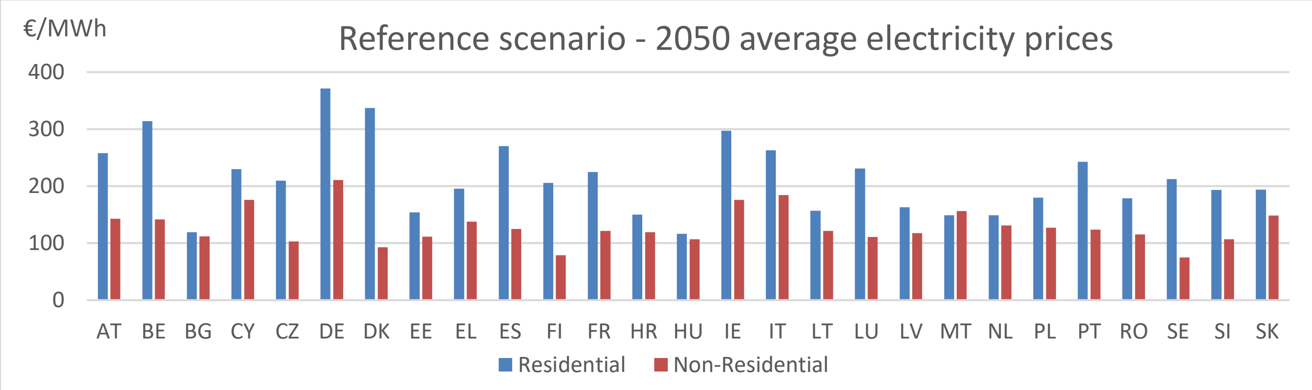


FIGURE 26: AVERAGE ELECTRICITY PRICES FOR TIME-FRAME ANALSYIS PERIOD FOR BOTH RESIDENTIAL AND NON-RESIDENTIAL SECTOR PER EU-27 COUNTRY, FOR REFERENCE SCENARIO

From this final data on the disaggregated average electricity prices per country and for each sector we can extract the fix tariff electricity prices. Concerning the ToU tariffs, [44] provides an overview on ToU tariffs implemented throughout all EU-27 countries. Using the forecasted average electricity prices for 2050, [44] will then serve as a basis to shape how each ToU will be constructed for each country.

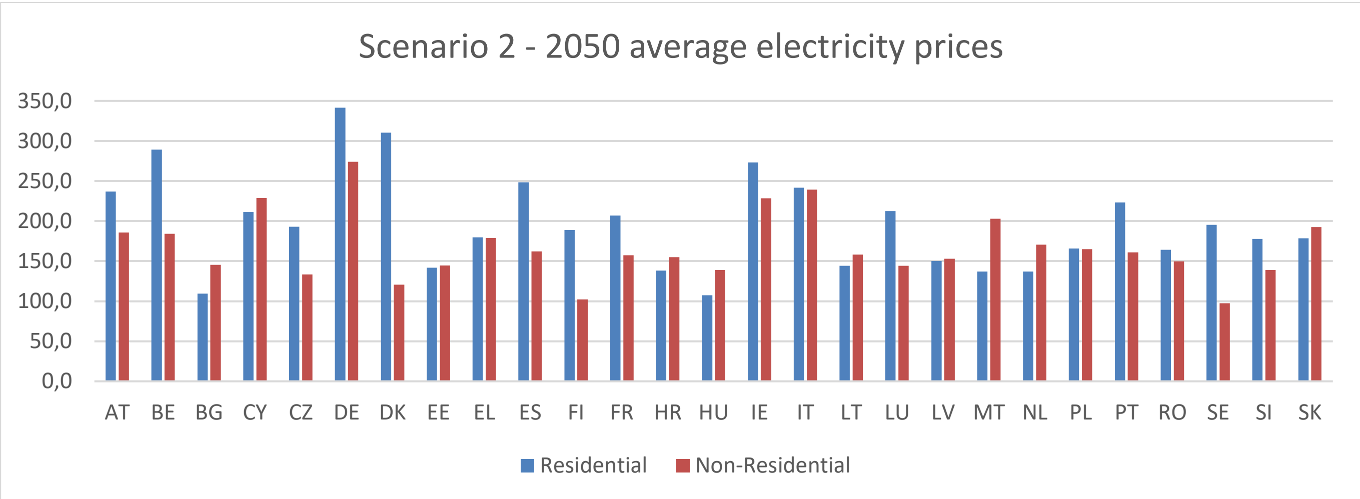


FIGURE 27: AVERAGE ELECTRICITY PRICES FOR TIME-FRAME ANALSYIS PERIOD FOR BOTH RESIDENTIAL AND NON-RESIDENTIAL SECTOR PER EU-27 COUNTRY, FOR HIGH ENERGY EFFICIENCY SCENARIO (SCENARIO 2)

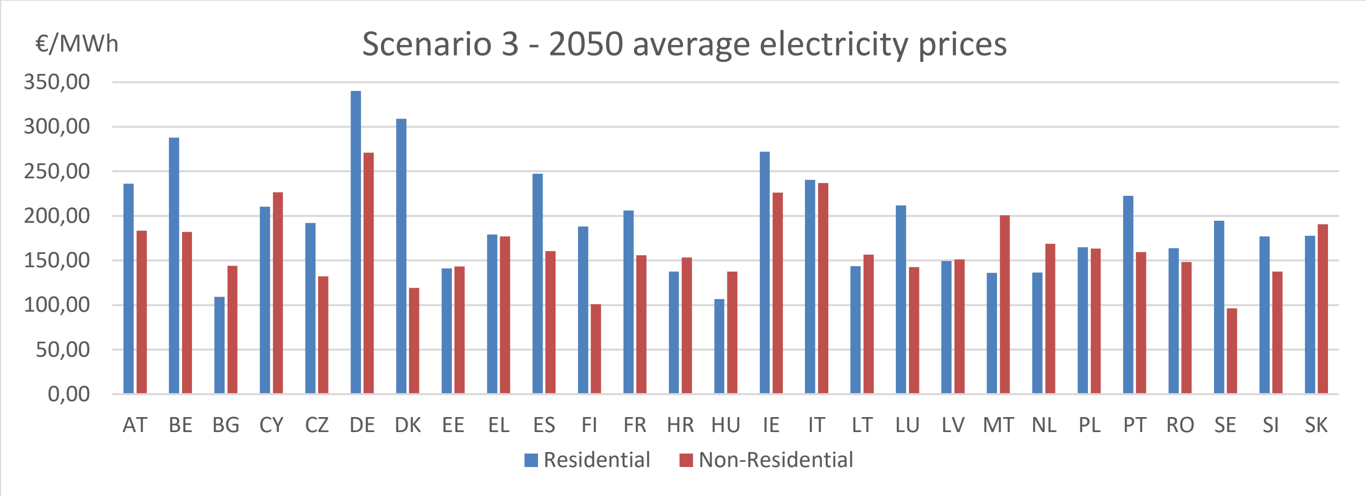


FIGURE 28: AVERAGE ELECTRICITY PRICES FOR TIME-FRAME ANALSYIS PERIOD FOR BOTH RESIDENTIAL AND NON-RESIDENTIAL SECTOR PER EU-27 COUNTRY, FOR DIVERSIFIED SUPPLY SCENARIO (SCENARIO 3)

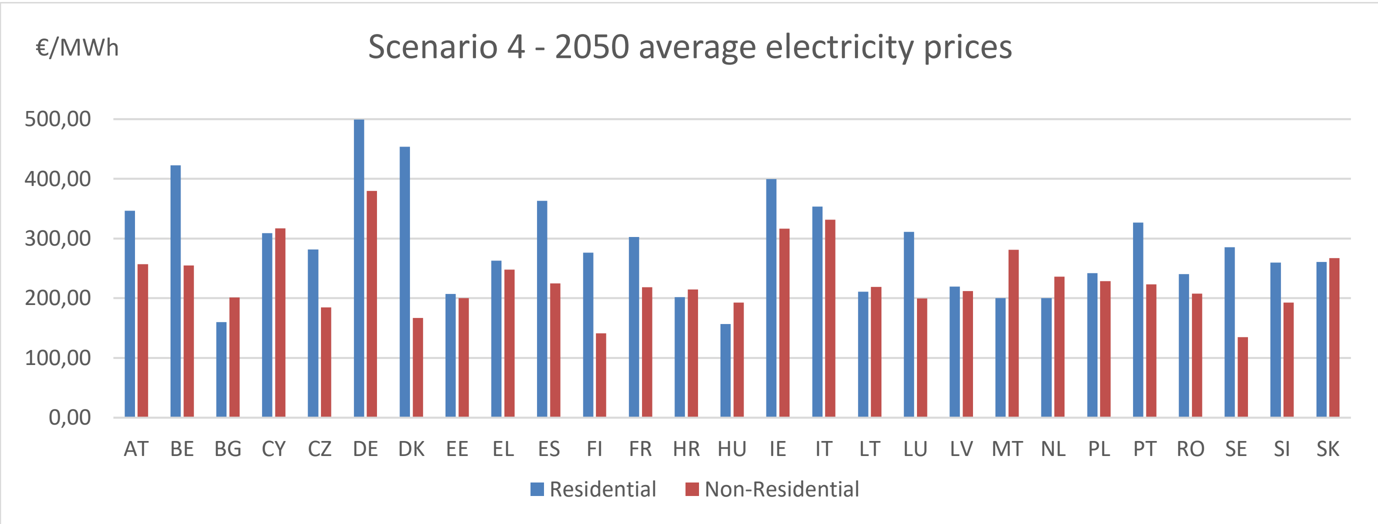


FIGURE 29: AVERAGE ELECTRICITY PRICES FOR TIME-FRAME ANALSYIS PERIOD FOR BOTH RESIDENTIAL AND NON-RESIDENTIAL SECTOR PER EU-27 COUNTRY, FOR HIGH RES SCENARIO (SCENARIO 4)

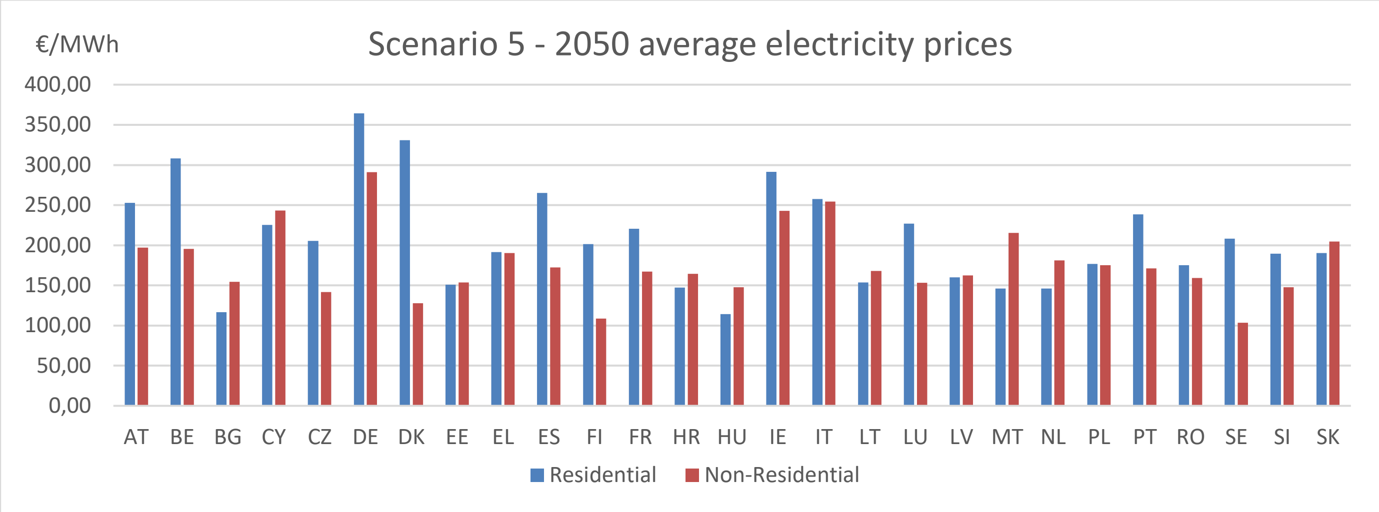


FIGURE 30: AVERAGE ELECTRICITY PRICES FOR TIME-FRAME ANALSYIS PERIOD FOR BOTH RESIDENTIAL AND NON-RESIDENTIAL SECTOR PER EU-27 COUNTRY, FOR LOW NUCLEAR SCENARIO (SCENARIO 5)

TABLE 33: DISCRIMINATED VALUES OF THE AVERAGE ELECTRICITY PRICES FORECASTED FOR THE TIME-FRAME ANALYSIS PERIOD, FOR EACH COUNTRY AND SECTOR PER SCENARIO

(€/MWh)	Scenario 1 Reference		Scenario 2 High EE		Scenario 3 Diversified Supply		Scenario 4 High RES		Scenario 5 Low nuclear	
	Residential	Non residential	Residential	Non residential	Residential	Non residential	Residential	Non residential	Residential	Non residential
AT	257.67	142.79	237.04	185.58	236.07	183.63	346.64	257.17	252.82	197.19
BE	314.18	141.63	289.03	184.07	287.84	182.13	422.66	255.08	308.26	195.58
BG	119.07	111.86	109.53	145.38	109.09	143.85	160.18	201.46	116.83	154.47
CY	229.77	176.16	211.37	228.95	210.50	226.54	309.10	317.27	225.44	243.27
CZ	209.53	102.67	192.75	133.44	191.97	132.04	281.88	184.92	205.59	141.79
DE	371.28	210.81	341.55	273.99	340.15	271.10	499.47	379.68	364.28	291.12
DK	337.21	92.67	310.20	120.45	308.93	119.18	453.63	166.91	330.85	127.98
EE	153.95	111.28	141.62	144.63	141.04	143.10	207.11	200.42	151.05	153.67
EL	195.35	137.67	179.70	178.93	178.97	177.05	262.79	247.96	191.67	190.12
ES	270.11	124.88	248.48	162.31	247.47	160.60	363.38	224.92	265.02	172.46
FI	205.46	78.60	189.01	102.16	188.24	101.08	276.40	141.57	201.59	108.55
FR	224.77	121.16	206.77	157.47	205.92	155.81	302.37	218.22	220.53	167.32
HR	150.12	119.19	138.09	154.90	137.53	153.27	201.94	214.66	147.29	164.59
HU	116.63	106.98	107.29	139.03	106.85	137.57	156.89	192.67	114.43	147.73
IE	297.09	175.81	273.30	228.50	272.18	226.09	399.67	316.65	291.49	242.79
IT	262.67	184.18	241.64	239.38	240.65	236.86	353.36	331.72	257.72	254.35
LT	156.74	121.63	144.19	158.08	143.60	156.41	210.86	219.06	153.79	167.96
LU	231.16	110.93	212.65	144.17	211.78	142.66	310.97	199.79	226.81	153.19
LV	163.14	117.67	150.07	152.94	149.46	151.33	219.46	211.94	160.06	162.50
MT	148.72	156.05	136.81	202.81	136.25	200.67	200.07	281.04	145.92	215.49
NL	148.95	131.16	137.02	170.47	136.46	168.67	200.38	236.23	146.15	181.13
PL	180.00	126.98	165.59	165.03	164.91	163.29	242.15	228.69	176.61	175.35
PT	242.91	123.95	223.45	161.10	222.54	159.40	326.77	223.24	238.33	171.17
RO	178.60	115.35	164.30	149.92	163.63	148.34	240.27	207.75	175.24	159.29
SE	212.32	75.00	195.32	97.48	194.52	96.45	285.63	135.08	208.32	103.57
SI	193.25	106.98	177.78	139.03	177.05	137.57	259.98	192.67	189.61	147.73
SK	193.95	148.25	178.42	192.68	177.69	190.66	260.92	267.01	190.30	204.73

ANNEX III.

Following the integration of each required input to assess the flexibility potential of the EU-27 building stock, it's key to outline how the assessment be quantified and evaluated. For this purpose, a reference search was conducted to gather the main key performance indicators (KPIs) which will enable the quantification of the energy system impact assessment.

Concerning the KPI tool analysis the main KPIs resourced to were costs and CO_2 emissions.

Concerning the simulations with ABEPeM For the framework methodology for the ABEPeM simulations, it is important to ensure that the KPIs reflect and measure the performance aspects which are relevant for the energy system analysis while ensuring an easy comparison between case-studies. Therefore, it is key to consider and employ a common assessment framework, widely used in literature. The data sources consist of an IEA report which performs literature review on energy flexibility indicators in the context of a building or building clusters [45] and a scientific paper which assesses energy flexibility in the context of residential building typologies [46].

A complete assessment of the building stock flexibility potential addresses not only the building's energy flexibility but should also address and consider grid interactions and load matching assessment since it's crucial to investigate the coupled performance among the building, the grid and RES generation. This complete assessment will enable the quantification and evaluation of grid control and operational strategies, sizing, and investment decisions.

In Table 35 each of the identified KPIs are shown, provided by the respective performance aspect and corresponding metric.

TABLE 34: IDENTIFIED KEY PERFORMANCE INDICATORS FOR DR ASSESSMENT

Performance Aspect	Definition	Metric
Power	Peak power reduction	$\Delta P = P_{peak\ ref} - P_{peak\ flexible}$
	Peak power reduction percentage	$\Delta P(\%) = 1 - (P_{peak\ flexible}/P_{peak\ ref})$
Emissions Cost Energy	Flexibility Factor (FF)	$FF = \frac{(Quantity_{low\ load} - Quantity_{high\ load})}{(Quantity_{low\ load} + Quantity_{high\ load})}$
Cost	Flexibility Index (FI)	$FI = \frac{Cost\ of\ flexible\ operation}{Cost\ of\ baseline\ operation}$
Energy	Self-Sufficiency (SS)	*SS = daily generation directly consumed / net daily load*
	Self-consumption (SC)	*SC = daily generation directly consumed / net daily generation*
	Capacity of Automated DR (ADR)	$C_{ADR} = \int_0^{length_{ADR}} (\text{QADR - Qref})dt$
	Efficiency of Automated DR (ADR)	$\eta_{ADR} = \frac{\int_0^{\infty} (\text{QADR - Qref})dt}{\int_0^{length_{ADR}} (\text{QADR - Qref})dt}$

The flexibility term is a relative quantity in contrast to "inflexibility", therefore in most cases the flexibility KPIs and its quantification requires a baseline or business-as-usual case to represent the "inflexible" scenario.

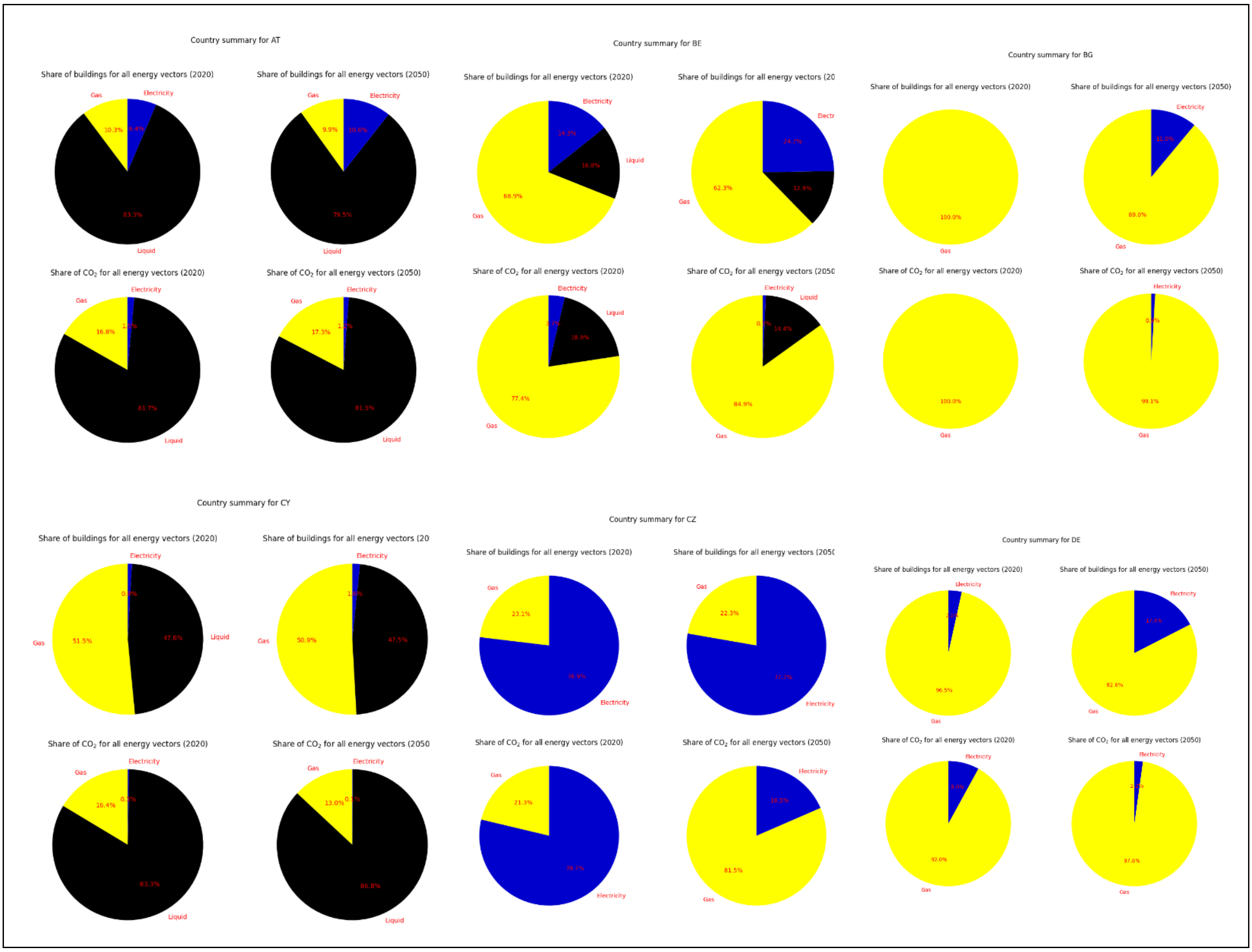
The first two identified KPIs concern and address power aspects of flexibility. Peak power reduction and peak power reduction percentage aim at assessing and monitor the power demand reduction during peak hours due to the flexible operation. These two KPIs are useful to evaluate controls and operational strategies to limit demand peaks. However, they do not provide any information neither on net energy exchange, consumption, or supply nor on the match between local load and generation.

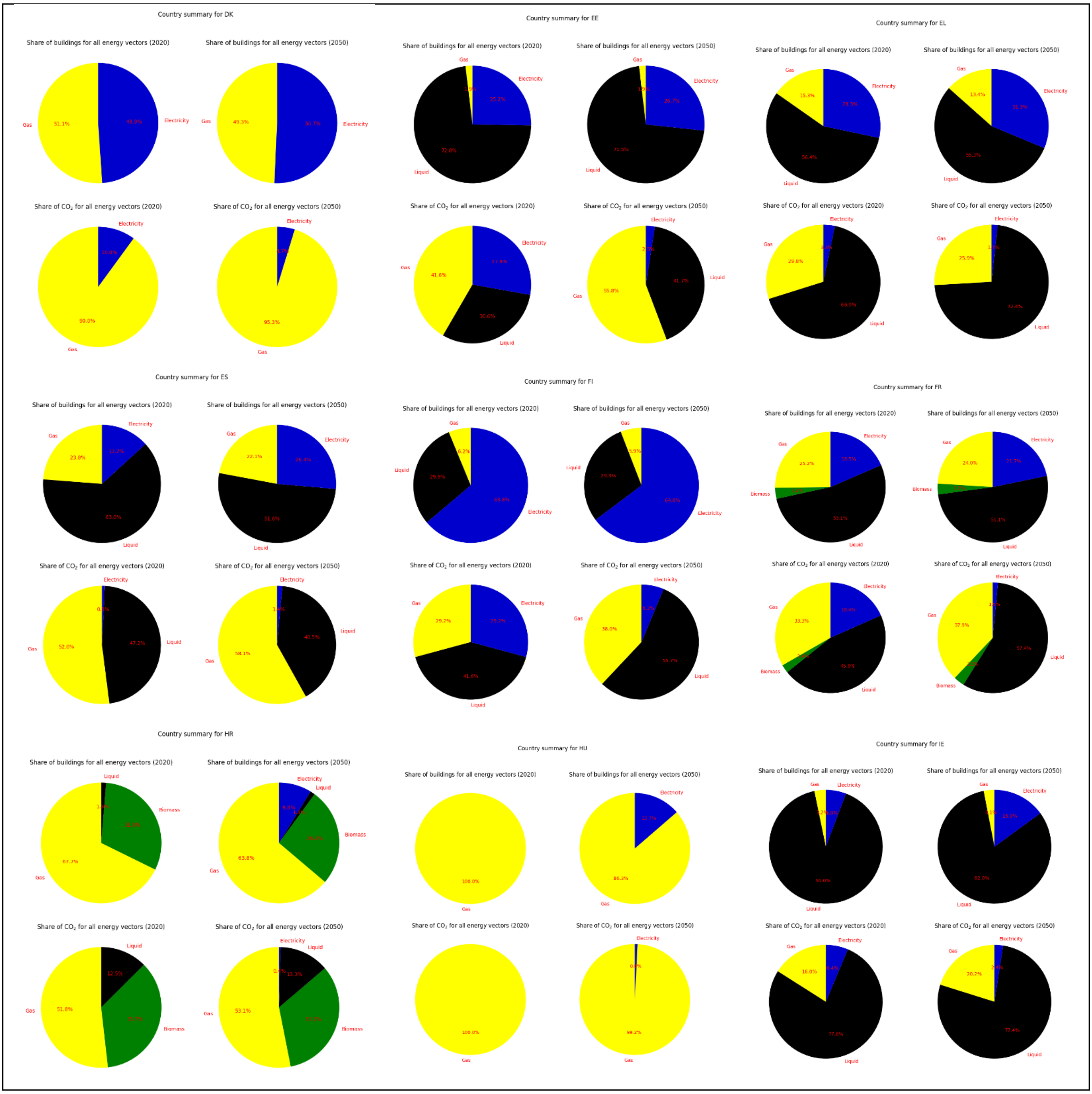
The flexibility factor (FF) can be considered and applied to different aspects – emissions, costs and energy – and establishes a comparison between the aspect/quantity during different load time periods, reflecting the emissions/cost/energy shifts from peak periods to non-peak periods. The flexibility factor ranges between −1, when emissions/cost/energy occur during peak periods, or 1, when emissions/cost/energy occur during non-peak periods. The FF factor is the only identified KPI, from Table 35, which does not need a baseline for its calculation. Additionally, in Annex IV the electricity carbon intensity for one kWh of electric energy produced for each country is presented, enabling to quantify the equivalent carbon emissions due to electricity usage.

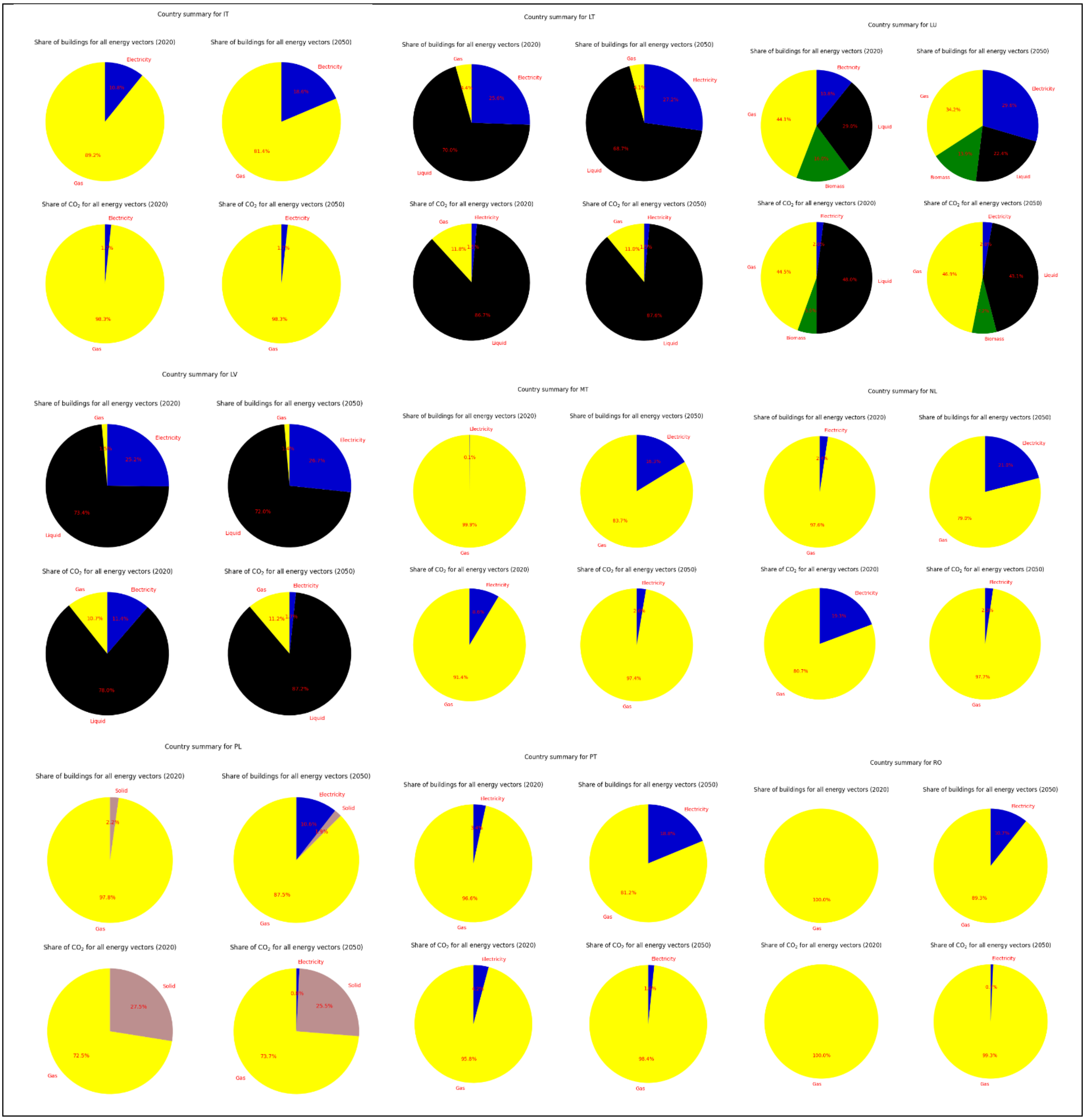
The Flexibility Index (FI) applies only to cost and reflects the fraction of saved costs from a penalty-aware

operational strategy (flexible) compared with a penalty-ignorant operation strategy (baseline).
Regarding energy related performance measures four different KPIs were identified. The Self-Sufficiency (SS) factor reflects the percentage of electrical demand which is covered by the local/on-site electricity generation. In periods with no on-site generation the SS factor value is zero, while the higher values are reached when there's an overlapping between the electricity load profile and self-generation profile. The Self-consumption (SC), complementary to the SS factor, reflects the percentage of the on-site generation that is used directly by the building. These two KPIs are widely used to evaluate control strategies aimed to decrease grid dependence and to study different types of energy systems used at the building and district level. The Capacity of Automated Demand Response (ADR) and the efficiency of ADR focus on the thermal performance of the building, considering the climate conditions, occupant behavior and HVAC systems. The Capacity of ADR key-performance indicator is defined as the amount of energy that can be added to building's thermal storage system without jeopardizing thermal comfort, reflecting the amount of heat which can be added to the building's thermal mass over the time of an ADR event and quantifying the reduced energy consumption during such event. The efficiency of ADR reflects the energy storage efficiency (not only applied to thermal, but every energy storage system) during an ADR event and which can later be used to reduce the heating power needed for maintaining the thermal comfort.

ANNEX IV.


Country summary for AT
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for BE
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (20
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050
Country summary for BG
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for CY
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (20
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050
Country summary for CZ
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for DE
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Gas
Electricity
Liquid


Country summary for DK
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO₂ for all energy vectors (2020)
Share of CO₂ for all energy vectors (2050)
Country summary for EE
Country summary for EL
Country summary for ES
Country summary for FI
Country summary for FR
Country summary for HR
Country summary for HU
Country summary for IE
Gas
Electricity
Liquid
Biomass



Country summary for IT
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for LT
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for LU
Share of buildings for all energy vectors (2020)
Share of buildings for all energy vectors (2050)
Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for LV
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Share of CO_2 for all energy vectors (2020)
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Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)
Country summary for RO
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Share of CO_2 for all energy vectors (2020)
Share of CO_2 for all energy vectors (2050)

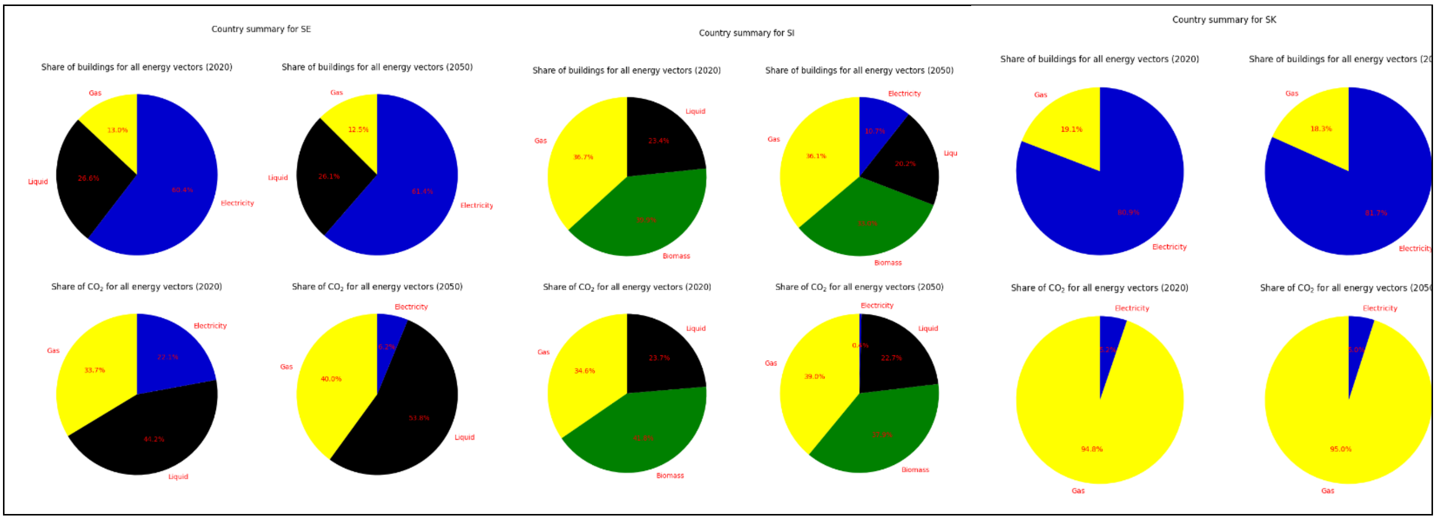

FIGURE 31: AMBIENCE SCENARIO 5 COUNTRY SUMMARIES.

ANNEX V.

The IEA [47] provides a forecast for the average CO_2 emissions intensity of hourly electricity supply in the European Union by scenario. In the work at hands the IEA's "Stated Policy Scenario" was considered since this scenario is in compliance with the EU's targets for CO2 emissions reductions and energy transition goals. Thus, the average carbon intensity per hour for the EU-27 energy system is provided in the table below.

TABLE 35: NET ELECTRICITY CARBON INTENSITY THROUGHOUT A DAY FOR EU -27'S ENERGY SYSTEM IN 2050. REMOVED FROM [47]

Hour of the day	Net Electricity carbon intensity (grams $eqC0_2$/kWh)
1	73.9
2	66.3
3	61.8
4	59.2
5	57.5
6	57.6
7	60.2
8	61.1
9	59.5
10	53.6
11	50.1
12	48.6
13	47.7
14	49.1
15	53.1
16	62.5
17	78.0
18	99.3
19	112.7
20	117.0
21	117.6
22	110.9
23	101.2
24	87.1

TABLE 36: NET ELECTRICITY CARBON INTENSITY PER COUNTRY FOR 2019. REMOVED FROM [56]

Country	Net Electricity carbon intensity (grams $eqC0_2$/kWh)
AT	170
BE	213
BG	504
CY	762
CZ	529
DE	410
DK	118
EE	659
EL	785
ES	262
FI	119
FR	237
HR	237
HU	286
IE	358
IT	371
LT	91
LU	108
LV	212
MT	462
NL	453
PL	807
PT	292
RO	400
SE	33
SI	281
SK	182

ANNEX VI. SAMPLE CONFIGURATION FILE

```
[GENERAL]
input = data/full_db_2.xlsx
output = scenario_analysis.xlsx
s_year = 2020
e_year = 2025

[CO2INT]
biomass = 230
natgas = 227
liquid = 314
solid = 414
electricity = data/co2_el_2018.csv
el_co2_decl_rate = 0.07
el_co2_decl_mode = 0
el_co2_min = 50

[RENOVATION]
renovation_rate.roof.s = 0.002666667
renovation_rate.roof.e = 0
renovation_rate.none.s = 0
renovation_rate.none.e = 0
renovation_rate.walls.s = 0.002666667
renovation_rate.walls.e = 0
renovation_rate.windows.s = 0.002666667
renovation_rate.windows.e = 0
renovation_rate.roofwalls.s = 0.0005
renovation_rate.roofwalls.e = 0.0007
renovation_rate.roofwindows.s = 0.0005
renovation_rate.roofwindows.e = 0.0007
renovation_rate.wallwindows.s = 0.0005
renovation_rate.wallwindows.e = 0.0007
renovation_rate.full.s = 0.0005
renovation_rate.full.e = 0.009
renovation_mode = 0
renovation_el_switch_rate = 0.8
cost_index_file = data/cost_index.csv
cost_file = data/cost_renovation.csv
cost_inflation = 0.025

[FLEXIBILITY]
```

flex_uptake.s = 0.02
flex_uptake.e = 0.20
flex_result = 0.8

ABBREVIATIONS AND ACRONYMS

ABEPeM	Active Building Energy Performance Modelling
ACER	Agency for the Cooperation of Energy Regulators
ADR	Automated Demand Response
AEPC	Active Building Energy Performance Contract
AS	AmBIENCe Scenario
ASHP	Air Source Heat Pumps
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CI	Carbon Intensity
COP	Coefficient of Performance
CSP	Concentrated Solar Power
DC	Direct Current
DHW	Domestic Hot Water
DR	Demand Response
EED	Energy Efficiency Directive
EMD	Electricity Market Directive
EPBD	Energy Performance Building Directive
EPBD CA	Energy Performance of Buildings Concerted Action
EPC	Energy Performance Contract
ESCO	Energy Service Company
ETS	Emission Trading System
EU	European Union
EV	Electric Vehicles
EV	Electric Vehicle
FF	Flexibility Factor
FI	Flexibility Index
GDP	Gross Domestic Product
GHG	Greenhouse gas
HVAC	Heating, Ventilation and Air-Conditioning
ICT	information and communication technologies
KPI	Key Performance Indicator
K-value	Thermal Conductivity
MS	Member State
PV	Photovoltaic
RES	Renewable Energy Sources
RES	Renewable Energy Sources
SC	Self-Consumption

SS	Self-Sufficiency
ToU	Time-of-Use
U-value	Thermal Transmittance