EUCALC

Explore sustainable European futures

Identification of levers and levels for the building stock

D2.5

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Short Description

This report summarises the levers and levels affecting changing energy use and consumption patterns in the building stock. The main drivers of greenhouse gas (GHG) emissions have been identified and defined. The calculation method is described for heating of residential and non-residential buildings, for district heating and for residential appliances.

The assumptions and definitions are explained. The respective ambition levels for each of the drivers are developed, from an ambition that follows the observed trend (level one) to a disruptive ambition (level four).

Quality check

Name of reviewer	Date
Luis Costa, Potsdam Institute for Climate Impact research (PIK)	27th of June 2019
Gino Baudry, Imperial College London	24th of June 2019

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This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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List of abbreviations

GHG – greenhouse gas

ITC – information and communications technology

SFH – single-family house

MFH – multi-family house

kWh_{therm} – thermal kilowatt-hour

kWh_{fuel} – kilowatt-hour in fuel

gCO_2e – grams of carbon dioxide-equivalents

MJ - Megajoule

€/m^2 – euro per meter square of area

CHP – combined heat and power

Glossary

Floor area – living space in residential buildings and used floor space in non-residential buildings

Conditioned space – floor area that is heated, cooled or ventilated

1 Executive Summary

The European Calculator (EUCalc) project which aims at developing a new state-of-the-art model, with origins in the modelling philosophy of the Global Calculator, will create an online tool for analysing trade-offs and pathways towards a sustainable and low-carbon future in Europe. With this tool, EUCalc aims to provide decision-makers with an accessible energy modelling solution to quantify the sectorial energy demand, greenhouse gas (GHG) emissions trajectories and social implications of lifestyles and energy technology choices in Europe. This deliverable specifically focuses on the building sector and its impact on energy and emissions.

What are the drivers of GHG emissions originating in buildings and what is their influence? To answer this question the building module is being developed that comprises residential and non-residential buildings and includes the main uses of energy and origins of GHG emissions in buildings and, therefore, it includes heating, cooling and household appliances.

To assess the impact of different switches in the tool interface, for example, renovation, energy quality in new construction, better heating systems and fuel, the user can select and change each driver and view the resulting change in delivered energy and GHG emissions instantly online. How these drivers – called 'levers'– are defined and what choices are offered to the user is described in this deliverable. Each lever has different levels of ambition defined for buildings.

2 Introduction

Greenhouse gas emissions (GHG) from buildings contribute one of the four biggest shares in Europe. Figure 1 (source: European Environment Agency (EEA), 2018) shows that the direct emissions from the residential and the commercial buildings make 13% of the GHG emissions. Most of these direct emissions stem from space and water heating which consumes 79.2% of the energy delivered to buildings (Eurostat, 2018). The indirect emissions from used electricity and district heating for buildings are still allocated to energy supply in figure 1. When considering them, buildings account for 36% (Directorate-General for Energy (European Commission), 2019) of the European GHG emissions.

The potential to save energy and GHG in buildings starts to take effect as the negative GHG emission growth rate begins as shown in figure 2 - (source: European Environment Agency (EEA), 2019). The potential has been assessed to be large (Kranzl *et al.*, 2014), however, numerous barriers need to be overcome (Bürger, 2012).

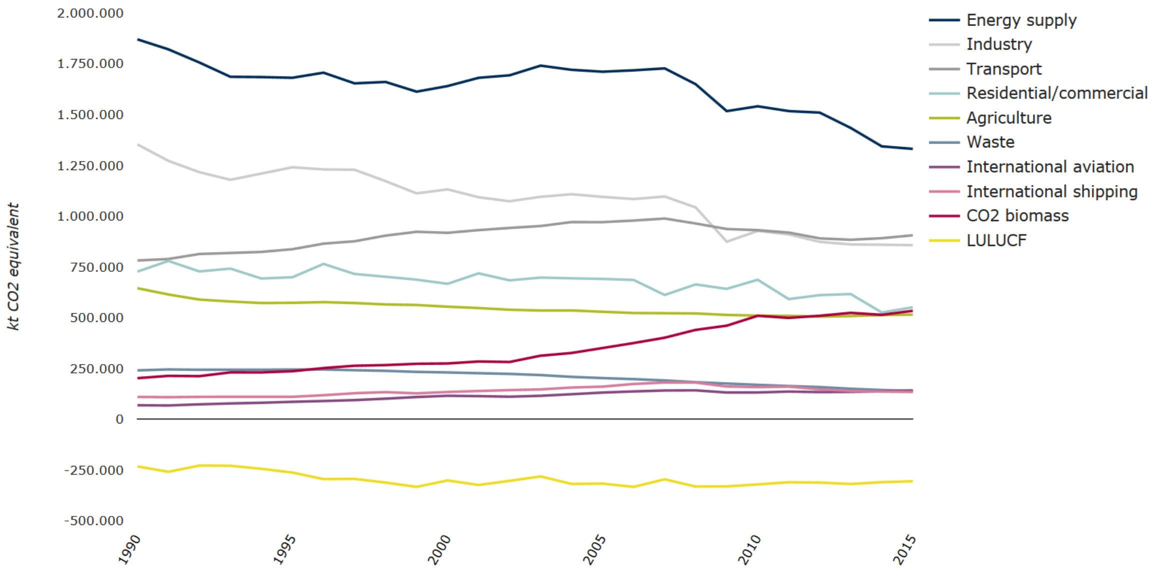

Figure 1 - GHG emissions by aggregated sector source

What do we mean by GHG emissions from buildings? Buildings host people and provide an environment that is liveable, healthy and comfortable. Heating, cooling, ventilation and lighting systems create this environment by burning fuel and by using electricity. The amount of energy consumed for creating a comfortable environment depends mostly on the design and the quality of the building. Hence, the GHG emissions related to conditioning the space and air in buildings are allocated to buildings.

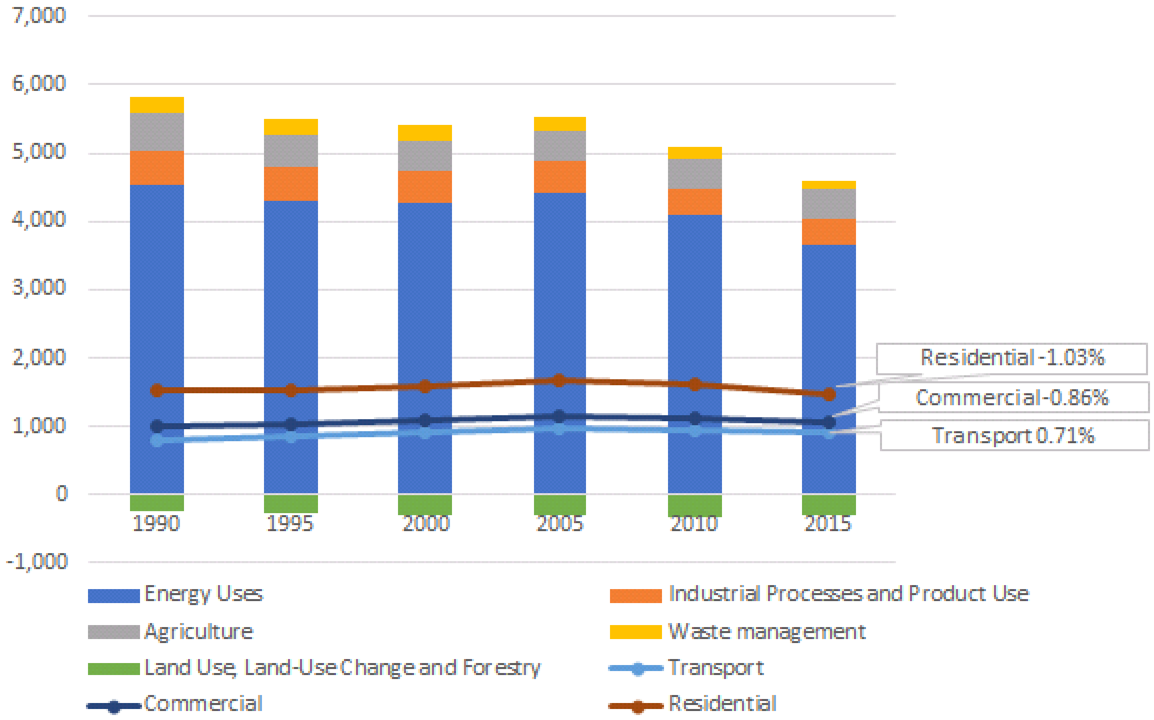

Figure 2 - Stacked GHG emissions by aggregated sector

Beyond providing a suitable environment, buildings are used by people to host many activities. Some of these activities may consume energy and cause GHG emissions, for example, working, cooking and entertainment.

As energy balances commonly aggregate sectors, the energy demand and GHG emissions of households and the service sector include not only indoor environment conditioning but also appliances (i.e. fridges, washing machines, dishwashers), and information and communications technology (ITC) equipment. Energy consumption of appliances, also referred to as plug-loads, depends on their efficiency and on users' behaviour. More about efficiency of appliances, their use, and how these are changed in their respective levers, can be found in the appliances submodule and lifestyle module documentation. However, for households, they are included in the buildings' module. If we talk about the service sector, this additional energy consumption is very dependent on the type of business. For example, a restaurant will have a much higher energy demand for cooking than an office, while an office will have a much lower heating demand than a swimming pool that will have a much lower electricity demand for ITC than a hospital. As a simplification, the building module includes service sector energy demand and GHG emissions for appliances, ITC, and cooking as an aggregate[1].

3 Drivers of the GHG emissions associated with buildings

Greenhouse gas emissions take place whenever fuels are burned, which can happen either directly in buildings or outside of them, for example, electricity used in buildings is generated in a local power plant. Fuels are usually burned for heating, and to a very small share for cooking. Depending on the location, electricity may also be used largely for heating. In general, electricity is consumed mostly for cooling (OECD/IEA, 2018), while appliances are responsible for approximately 17% of the final electricity used in buildings (International Energy Agency (IEA), 2018). The latter includes white appliances, such as fridge and washing machine, as well as black appliances including information and communications technology (ITC) equipment.

The heating and cooling drivers for GHG emissions, in general, encompass the building envelope on one hand and the technology and fuel choice combined with the system efficiency on the other hand. In specific, the living space demand per person also affects the space that needs to be heated and cooled, i.e. the conditioned space.

The drivers related to appliances cover the efficiency of the appliances and how much the appliances are used. While the use of a fridge or a washing machine may not vary a lot, the use of computers and phones has been increasing.

Parameters such as living space per person and use of appliances are covered in a lifestyle module and described in the respective documentation.

Additional way in which buildings are associated with GHG emissions is the composition and construction of the building itself, comprising grey energy needed to produce the materials for the construction and to perform the construction itself. In addition, we should note that biological and chemical processes needed for producing construction material may influence greenhouse gas emissions as well. To include the GHG emissions related to the construction

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[1] The energy use beyond heating is not implemented for the service sector. This will be done in an effort to map the energy balances.

and renovation of buildings, the building module interacts with the manufacturing module by providing constructed and renovated surface areas. In this sense, the composition and the production of the materials is calculated within the manufacturing module.

For the material calculation, the building envelope lever has a second effect. Aside from setting the fuel demand for heating (described above) it also sets the level of construction and insulation.

Finally, the material mix and the switch from concrete and steel to biomaterials rests with the material switch lever located in the manufacturing module. Following the inputs from the building module (WP2.1), the manufacturing module assesses the required amount of materials and estimates the future annual production of these industrial sectors. This describes the main material switches occurring in different products and is expressed as the percentage of material that is expected to be substituted by 2050 by a less carbon-intensive one, as described in the WP3 documentation.

The carbon emissions and energy inputs associated with products such as steel, wood or insulation can be reduced in 3 ways: (i) switching to less carbon-intensive materials, which is covered by the material switch lever; (ii) reducing the amount of required material during manufacturing, which can be done through improvements in the design, and (iii) using more recycled material to reduce energy & emissions. The last two ways are covered by the material efficiency lever.

lists all the levers associated with buildings. Please note that some of these levers are located and documented in other modules.

Table 1 - List of levers for heating, district heating, and appliances

Lever	Brief description
Living space demand per person [in lifestyle module]	This lever controls the average living space per person.
Building envelope	This lever controls the average heat loss which is reduced by insulation and affects the energy need per floor area.
Indoor temperature [in the lifestyle module]	This lever controls the average room temperature during warm and cold times of the year.
Material switch[2] [in the manufacturing module]	Percentage of material replaced by another in products.
Material efficiency	Percentage of decrease in material demand due to smart design, use of more efficient materials, smart manufacturing (e.g. 3D printing).
Heating and cooling (ventilation) system efficiency	This lever controls the average energy loss in heating, cooling and ventilation systems and district heating generation.

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[2] This lever also controls the material mix used to construct or insulate buildings.

District heating share	This lever controls the level of heating energy demand covered by district heating.
Technology and fuel share	This lever controls the mix of technologies used for space heating, space cooling, hot water, cooking and lighting, and district heating.
Appliances, cooking, lighting efficiency	This lever controls the average rate of energy use for appliances, cooking, and lighting.
Share of residential floor cooled [%] [in lifestyle module]	Amount of floor space cooled.
Appliance ownership [#/household] [in lifestyle module]	Yearly hours of use of each appliance.
Appliance use [hours/app] [in lifestyle module]	How often appliances are replaced.

3.1 Lever specification

3.1.1 Living space demand per person

The living space demand per person affects energy consumption. The larger floor area is conditioned (heated or cooled), the higher is the energy demand. Reducing the average size of dwellings, for example by sharing kitchens and common areas, will impact emission levels.

3.1.2 Building envelope

Heating and cooling account for around 30% of all the energy demand of buildings. The amount of energy needed to heat or cool buildings can be reduced significantly by improving external walls, floors, roofs, ceilings, windows and doors so that the building is better insulated. This means that less heat can escape from the inside of the building during cold weather, and less heat from outside can get in if when it is cooled.

3.1.3 Indoor temperature

Heating and cooling represent a big proportion of the energy demand of buildings. The energy demand will increase when maintained indoor temperatures significantly deviate from the outdoor temperatures.

3.1.4 Material switch

The material switch lever describes the main material switches occurring in products (e.g. in cars, buildings, etc.). It is expressed as the percentage of material in a product that is expected to be substituted by 2050 by a less carbon-intensive material, over the product lifecycle.

3.1.5 Material efficiency

This lever represents the percentage of decrease of material used in products due to certain factors, including designs that require less material, use of better materials, improvement of manufacturing yields, and reuse after disposal among others.

3.1.6 Heating and cooling (ventilation) system efficiency

HVAC systems have recently become more energy efficient. Increase in the energy efficiency lowers the emissions impact.

3.1.7 District heating share

District heating can facilitate decarbonisation buildings in dense urban areas, even with decreasing heat density. It is particularly difficult to reduce energy consumption of the protected buildings located in dense urban area, partly due to historic or special restrictions.

3.1.8 Technology and fuel share

A variety of different technologies are used in buildings for space heating, water heating, and cooking. These technologies can have very different efficiencies and emissions associated with them. Today, the most common forms of heating in urban areas are combined heat and power (CHP), district heating, and gas boilers. In rural areas, solid fuel boilers are most common.

In the future, new technologies with much lower emissions could be used, for example, heat pumps (that use electricity to move heat from the outside of the building to the inside) and solar hot water systems. This lever allows users to change the portion of buildings using these new technologies and reduce emissions. Similarly, this lever addresses the share of cooling systems that use more efficient and lower carbon technology. The technologies for space cooling within the model are air conditioning, chillers, and solar cooling.

3.1.9 Appliances, cooking, lighting efficiency

A variety of different technologies are used in buildings for cooking, lighting, and appliances. This lever allows a higher use of electricity in cooking (rather than gas, oil or traditional biomass), and to introduce more efficient lighting options like LED bulbs.

3.1.10 Share of residential floor cooled [%]

This lever determines the fraction of the residential floor space per person subjected to cooling. The rationale for the lever is that for large parts of Europe, increase in cooling energy demand due to global warming, are said to outweigh the expected reductions in energy for heating.

3.1.11 Appliance ownership [#/household]

This lever describes the amount of white and black appliances found in each household, and is expressed as appliance/cap. A reduction in the average number of appliances found in households, all other things kept constant, leads to a reduction in carbon emissions.

3.1.12 Appliance use [hours/app]

This lever controls the number of hours an appliance is used per year. In combination with the lever that sets the number of appliances owned, it will allow the user to additionally evaluate the energy implications of a moderate use of appliances.

4 Definition of the ambition levels

Table 2 describes four ambition levels used for the EUCalc model. Being one of the EUCalc components, the building module uses the same set of ambition levels.

Table 2 – Definition of ambition levels

Level 1 This level contains projections that are aligned and coherent with the observed trends.	**Level 2** This level is an intermediate scenario, more ambitious than observed trends but not reaching the full potential of available solutions.
Level 3 This level is considered very ambitious but realistic, given the current technology evolutions and the best practices observed in some geographical areas.	**Level 4** This level is considered as transformational and requires large additional efforts such as strong changes in the way society is organized, very fast market uptake of deep measures, an extended deployment of infrastructures, major technological advances and breakthroughs (but without relying on new fundamental research), etc.

5 Calculation logic of the building's module

5.1 Overall calculation logic for heating in the buildings' module

The buildings module is based on an approach of medium complexity[3] to compute energy consumption and GHG emissions from buildings in the household and service sector[4]. This calculation is based on historical data[5] and projections until 2050 considering the ambition level choices made by the user and described in the lever specifications sections in this document.

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[3] The Energy demand is performed on a bottom-up approach with a simplified single zone model for the assessment of climate impact on the energy demand for space heating and space cooling.

[4] Buildings from the industry sector are excluded.

[5] Historical data are described in deliverable D2.1.

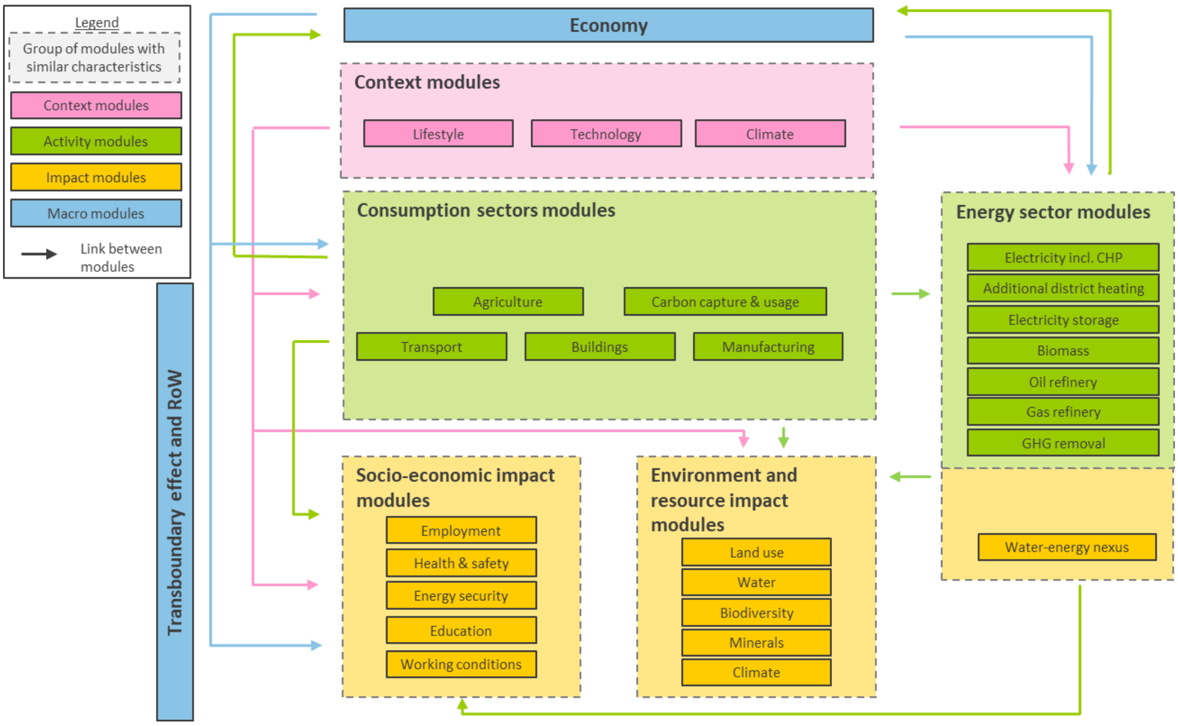

Figure 3 - Overview of the model architecture

Indirect emissions from buildings and appliances are addressed in other WPs. For example, Power module assesses the emissions related to the electricity production and the upstream emissions of fossil fuels, while the Manufacturing module assesses the emissions related to the manufacturing of the buildings, appliances, and infrastructures[6].

The interaction of the buildings' module with other modules in the EUCalc architecture can be found in Figure 3.

The calculation logic for heating consists of the following steps:

- the building stocks' energy performance with respect to its envelope quality is measured in energy need (also called useful energy) in kWh/m^2
- the heating behaviour of the occupant (in °C);
- the technology share for each heating system and fuel (in %);
- the energy efficiency of each technology for each heating system (in kWh_{therm}/kWh_{fuel});
- the emission intensity of each type of fuel used in the various technologies (gCO_2e/MJ);
- the costs for the renovation and new construction of buildings (€/m^2).

The calculation logic for heating that is described in the following sections is applied to both residential and non-residential buildings.

Heating energy delivered to buildings depends on three sets of factors:

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[6] WP5: Electricity and Fossil Fuels, WP3: Production and Manufacturing http://www.european-calculator.eu/research-approach-wps/

- The population development and the floor space demand per person (one part of the activity level).
- The mixes of different ages and geometries of buildings existing in the countries as well as the climate, behaviour and insulation-based heat losses. This forms a second part of the activity level and contains the passive technologies in the buildings.
- The heating technologies that are part of the active elements in a building encompassing the fuel type (e.g. biomass, gas), the technology mix (e.g. heat pump), and the efficiency of the systems.
- The energy need that is to be covered by district heating is determined via the district heating share-lever. This lever is described in the documentation of the district heating module in deliverable D2.6.

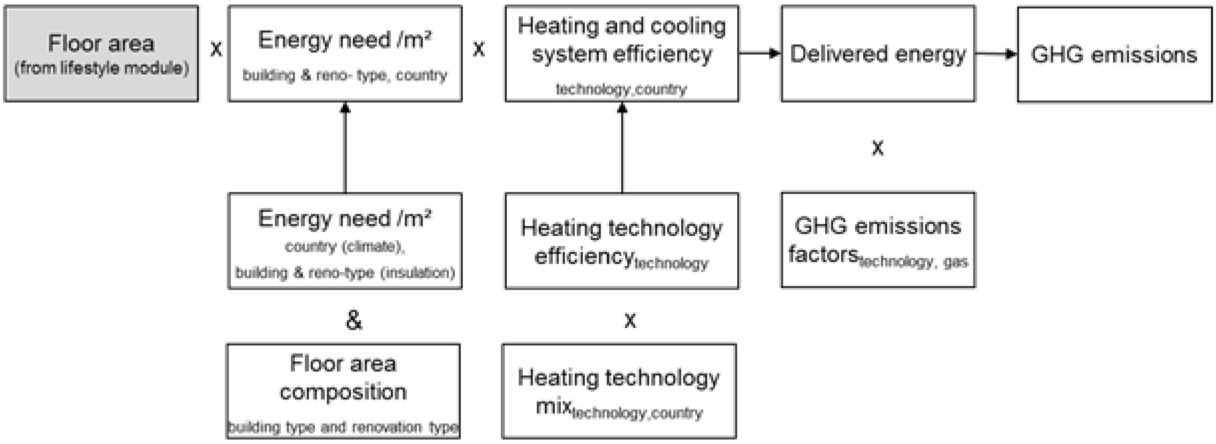

Figure 4 - Calculation logic of heating within the buildings' module

The following subsections describe the details of the three subsets.

5.2 Scope definition

The buildings' module comprises the calculation of energy demand for heating residential and non-residential buildings, household appliances, and additional district heating that supplements heat from combined heat and power and industry waste heat. Elements are to be added to calculate the energy demand for lighting, cooking, cooling and hot water.

GHG emissions are calculated whenever the energy transformation happens within the building or within additional district heating plants. This excludes GHG emissions from electricity generation and from combined heat and power plants. The reason behind is that district heating is mostly associated with supplying energy to buildings, while on the other hand, energy from electricity generation and CHP may be largely used for other purposes as well (industry, transport, etc.) and is, therefore, assessed in the other modules. GHG emissions from prior value chains, such as the production of cement or insulation material or steel for district heating pipelines, are calculated in other modules such as industry/manufacturing. Another example is the production of wood or biogas for heating which is calculated in agriculture and land-use.

The increasing integration of buildings into the energy system was covered regarding two aspects: the increasing electrification of the energy sources used in buildings and the potential for demand response. The second aspect is covered in the demand response module, while the first on is linked to the technology and fuel share lever described in section 6.2 on page 19.

Simultaneaously, the emission savings originating in buildings but taking effect only in the energy module where electricity is generated are integrated in the picture of emission savings from buildings. To be able to cover the complete CO_2 emissions in the buildings graphs and in the assessment, the factor for the CO_2 emissions from electricity generation and district heating combined heat and power (CHP) plants are received from the energy system module for electricity generation incl. CHP.

More information about interactions between different EUCalc modules can be found in table 3 and table 4 in the documentation[7] of the respective modules.

Table 3 – Input interfaces

Levers connected to inputs	**Inputs**	**Use of inputs**
From Climate • Global mitigation effort	• Average temperature outdoor air • wind speed • solar radiation	• Space cooling and space heating
From Lifestyle • Living space per person • Percentage of cooled living space • Space cooling and heating	• Total floor area demand • Space cooling factor	• Space heating, hot water and space cooling in buildings

Table 4 – Output interfaces

Outputs	**Levers affecting this output**	**Calculation of the output**
To Climate Emissions • emissions of CO2 and if available CH4 and N2O (both were not included in the building module)	Technology and fuel levers • Building envelope, • Technology and fuel share • Heating and cooling efficiency Key behaviours • Living space per person, • Percentage of cooled living space • Space cooling and heating All these levers are relevant for the demand for space heating, hot water and space cooling[8] and thus affect the output of GHG emissions.	• Space heating • Space cooling • Hot water
To District Heating (D2.6)		

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[7] http://www.european-calculator.eu/documentation/

[8] Levers relevant for heating and cooling in buildings are firstly on the technology side the levers for: (·) building envelope, (·) technology and fuel share as well as (·) heating and cooling efficiency. Secondly, on the side of key behaviours there are (·) living space per person, (·) percentage of cooled living space and (·)space cooling and heating [behaviour].

Outputs	Levers affecting this output	Calculation of the output
• Energy need for district heating	• District heating share lever And all the above mentioned levers for space heating, hot water and space cooling[8].	• Space heating • Space cooling • Hot water
To Agriculture		
• Energy demand for bioenergy split by gas, biodiesel, biogasoline and solid	• District heating share lever And all the above mentioned levers for space heating, hot water and space cooling[8].	• Space heating • Space cooling • Hot water • Cooking
To Manufacturing	Key behaviours	
• Constructed floor area	• Living space per person,	• Buildings’ production demand
• Number of new appliances needed	• Appliances owned and appliances used	• Appliances production demand
To Energy		
• Fossil fuel demand	• And all the above mentioned levers for space heating, hot water and space cooling[8].	• Space heating • Space cooling • Hot water • Cooking
• Electricity demand by demand response group: - appliances (incl. lighting and cooking) - space cooling - hotwater - space heating (residential and non-residential)	• Key Behaviour: Appliance use • Technology: Appliance efficiency	• Space heating • Space cooling • Hot water • Cooking • Lighting

5.3 Assumptions to estimate capital expenditures for renovation

The capital expenditures for renovations assumed to be the same for all countries and remain constant over time. The uncertainty about the future prices of labour, material and especially for the technology is very high, thus several sources, i.e. (Buildings Performance Institute Europe (BPIE), 2016; Moura and Fonseca, 2018, p. 1051; Toleikyte, Kranzl and Müller, 2018; Ipsos Belgium and Navigant, 2019) were compared and the following values for per-square meter capital expenditures were assumed to enable a rough estimate of the investment needs of the renovation activity for the different pathways.

Table 3: Capital expenditures for renovation in EUR per m²

	Single-family homes	Multi-family homes	Non-residential buildings
shallow renovation	150	120	150
medium renovation	250	200	250

	Single-family homes	Multi-family homes	Non-residential buildings
deep renovation	350	300	350

6 Levers and levels of ambition

The Levers and levels were discussed in the stakeholder workshop on June 4th 2018. The participants were explicitely asked about the design and approach regarding the choice of the levers and the definition of the ambition levels. The discussion results and the impulses from this workshop are collected in deliverable D2.7[9] and flow into the following lever and level definition.

6.1 Building Envelope

6.1.1 Lever description

This lever sets the thermal properties of building envelope (a physical separation between the exterior and interior environment of a building). When considering a building stock, building envelope quality can be changed through renovation and demolition, while portion of demolished buildings is replaced by newly constructed ones. Therefore, the demolition rate and renovation rate are set by this lever. In addition, new construction and renovation can be conducted at different quality levels. Regulations in this field include required level of achieved thermal performance, usually at each major renovation, or whenever a new building is constructed. Although these levels may differ across EU countries, their existence supports definition of three quality levels for new construction and renovation in this model: shallow, medium and deep. Number of buildings constructed and renovated at each quality level will influence the quality of the building stock. Therefore, the quality mix for construction and renovation are also included in this lever. When using the building envelope lever, it will be possible to change the ambition for the following drivers:

- renovation rate,
- renovation quality mix,
- demolition rate,
- new building quality mix[10].

6.1.2 The rationale for lever and level choices

The drivers above are combined to

- aggregate the drivers that influence the building envelope
- combine the measures that increase the energy efficiency in a building
- avoid overwhelming the user with too many choices.

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[9] http://www.european-calculator.eu/deliverables/

[10] The new building rate is a consequence of the demolition rate and of the evolution of the overall floor area needed. The floor area needed is an input from the lifestyle module and depends on the population growth and on required m²/person.

Recently observed renovation rate in member states lies between 0.5 – 2.5% (Endberichts *et al.*, 2005; Buildings Performance Institute Europe (BPIE), 2011; D'Agostino *et al.*, 2016; Dean *et al.*, 2016). Commonly used renovation rates peak at 3%, while the whole building stock would be renovated between today and 2050 (Buildings Performance Institute Europe (BPIE), 2011; Boermans *et al.*, 2012; Bettgenhäuser *et al.*, 2014; European Commission, 2018). On the other side, according to opinion of other experts, such a renovation rate is not likely to be achieved (Sandberg *et al.*, 2016).

The renovation and construction mix determine the energy needed after the measures. However, the categories shallow, medium and deep are adopted to aggregate different energy qualities that can be achieved. The representative energy need equals 100 kWh/m² in the shallow category, 75 kWh/m² in the medium category, and 50 kWh/m² in the deep category. The shallow, medium and deep categories are assigned an energy need value each, while their shares vary in the different pathways enabling a transparent representation of the distribution of different energy qualities.

The assumption that most of the renovations entail no measures that go beyond the minimum requirements, is reflected in the share of "shallow" and "medium" renovations (see table 3), as well as in the "minimum" and "near-zero" in newly built in Level 1 pathway that continues the observed trend (Umwelt *et al.*, 2018). As opposed to that, Level 4 scenario assumes that the majority of renovations will include very ambitious measures, and a small share of medium ambitious envelope renovations.

EU- ambition levels

Table 5 – EU-Levels

Name / Unit		1	2	3	4
annual renovation rate (%)		1	1.5	2	3
renovation mix (%)	shallow	80	20	10	0
	medium	15	60	70	30
	deep	5	20	20	70
annual demolition rate (%)		0.1	0.4	0.7	1
new construction mix (%)[11]	minimum	80	20	10	0
	near-zero	15	60	70	30
	plusenergy	5	20	20	70

Disaggregation by country

Table 6 – Disaggregation by country

Name / Unit	Disaggregation method	Exceptions/outliers
annual renovation rate (%) renovation mix (%) annual demolition rate (%) new construction mix (%)	same assumptions for the percentage rates and mixes but applied to the building stocks detailed by country.	No exceptions or outliers

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[11] shallow= minimum regulation; medium = nearly zero; deep = plus energy

6.2 Technology and fuel share for in-house heating and cooling technologies

For each country, the technology share shall be defined per pathway adopted in the EUCalc. Therefore, all technologies for one fuel type are simplified and aggregated. This also means that there will be a mixed efficiency and a mixed cost value for all technologies that are covered by an energy carrier.

6.2.1 Lever description

This lever controls the mix of technologies used to provide heating to the buildings. It is combined with the mix of technologies in district heating, see section 4.4.3.

6.2.2 The rationale for lever and level choices

The basis for the lever level definition is the initial fuel mix. For each fossil fuel the reduction share until 2050 is applied, as shown in the table 5 "EU-Levels" given below. The reduction in fossil fuels is balanced by the addition to any type of heat pumps (assuming that these need only one-fourth of the energy and including also geothermal and solar-thermal heat sources) and biomass.

The mix between heat pumps and biomass does not contribute to the ambition level for GHG savings as such. However, biomass is cheap to implement but may cause unhealthy emissions such as particulate matter. The implementation of heat pumps can serve the balancing of the electricity system and can be used for heating and cooling. From a social perspective, heat pumps are more expensive in their installation and depend on a valuable and high-priced electricity.

6.2.2.1 Disaggregation methodology rational

The basis for the fuel share at each lever level for the single countries is the initial fuel mix in the households[12] as provided by Eurostat (Eurostat, 2018).

To obtain the fuel share in 2050 the reduction defined in the table EU-Levels is applied to end up the value detailed in the table "Disaggregation by country" below.

6.2.3 Ambition levels & disaggregation method

This section presents the assumptions for setting the levels of different levers related to the possible future mix of technologies.

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[12] The assumptions of the heating fuel mix in households is also applied to non-residential buildings.

EU-Levels

Table 7 – Assumption for fuel phase out and substitution

Name / Unit	1	2	3	4
share of gas	- 5	- 50	- 65	- 95
share of electricity	- 5	- 50	- 68	- 93
share of coal	- 30	- 80	- 90	- 95
share of heating oil	- 10	- 50	- 65	- 95
substitution by heat pumps (including heat from the air, solar-thermal and geothermal sources)	30	40	50	70
substitution by biomass	65	60	50	30
substitution by geothermal	2	4	6	8
substitution by solarthermal	3	6	9	12

These assumptions suggest the fossil fuel phase out, that is currently being discussed in some of the EU member states such as Germany and Ireland. The above presented percentage reductions and the substitution pattern are assumed for all Member states and applied to their current individual energy mixes resulting in the energy mix in 2050, as shown in Table 8.

Fuel mix disaggregation by country

Table 8 – Fuel mix disaggregation by country

Country	energy carrier	%-share in 2015	%-share in 2050 Level 1	%-share in 2050 Level 2	%-share in 2050 Level 3	%-share in 2050 Level 4
Austria	electricity	9	9	12	14	17
	gas	30	28	15	9	1
	coal					
	oil	23	20	11	6	1
	bioenergy	36	39	50	50	46
	solarthermal			2	3	6
	ambient	2	3	10	16	24
	geothermal			1	2	4
	solid waste					
	renewables	38	42	62	71	81
Belgium	electricity	5	5	9	12	17
	gas	45	43	23	14	2
	coal	2	1			
	oil	40	36	20	10	2
	bioenergy	9	13	30	31	25
	solarthermal			3	6	10
	ambient		2	13	24	37
	geothermal			2	4	7
	solid waste					
	renewables	9	15	48	64	79
Bulgaria	electricity	11	12	13	13	14
	gas	4	4	2	1	
	coal	13	9	3	1	1
	oil					
	bioenergy	71	74	78	77	75
	solarthermal			1	1	2
	ambient		1	4	6	7
	geothermal			1	1	1
	solid waste					
	renewables	71	75	83	84	85

Country	energy carrier	%-share in 2015	%-share in 2050 Level 1	%-share in 2050 Level 2	%-share in 2050 Level 3	%-share in 2050 Level 4
Croatia	electricity	2	3	4	5	6
	gas	22	21	11	7	1
	coal					
	oil	5	5	3	1	
	bioenergy	70	71	77	77	75
	solarthermal			1	2	3
	ambient			4	7	12
	geothermal			1	1	2
	solid waste					
	renewables	70	71	82	87	92
Cyprus	electricity	16	17	20	23	27
	gas	10	9	5	3	
	coal					
	oil	67	60	33	17	3
	bioenergy	6	11	25	26	21
	solarthermal			2	5	9
	ambient		2	11	21	33
	geothermal	1	1	3	5	7
	solid waste					
	renewables	7	14	42	57	69
Czech Republic	electricity	6	7	9	11	14
	gas	33	32	17	10	2
	coal	19	13	4	2	1
	oil					
	bioenergy	40	45	56	55	50
	solarthermal			2	4	6
	ambient	1	3	10	16	23
	geothermal			1	2	4
	solid waste					
	renewables	41	48	70	77	84
Denmark	electricity	7	7	9	10	12
	gas	28	27	14	8	1
	coal					
	oil	11	10	6	3	1
	bioenergy	50	51	60	60	57
	solarthermal			1	3	5
	ambient	4	5	10	15	21
	geothermal			1	2	3
	solid waste					
	renewables	54	56	72	78	86
Estonia	electricity	3	3	4	4	5
	gas	10	10	5	3	1
	coal	1	1			
	oil	1	1			
	bioenergy	85	85	88	88	87
	solarthermal				1	1
	ambient			2	3	5
	geothermal				1	1
	solid waste					
	renewables	85	85	90	92	94
Finland	electricity	33	33	34	35	36
	gas	1	1	1		
	coal					
	oil	16	14	8	4	1
	bioenergy	50	51	54	54	53
	solarthermal			1	1	2
	ambient			3	5	7
	geothermal				1	1
	solid waste					
	renewables	50	51	58	61	63
France	electricity	14	14	16	19	22
	gas	37	35	18	11	2
	coal					
	oil	18	16	9	5	1
	bioenergy	28	30	41	41	38
	solarthermal			2	4	6
	ambient	4	5	12	19	27

Country	energy carrier	%-share in 2015	%-share in 2050 Level 1	%-share in 2050 Level 2	%-share in 2050 Level 3	%-share in 2050 Level 4
	geothermal			1	2	4
	solid waste					
	renewables	32	35	56	66	76
Germany	electricity	7	7	11	14	18
	gas	47	45	24	14	2
	coal	2	1			
	oil	29	26	15	7	1
	bioenergy	15	18	34	34	29
	solarthermal			2	5	9
	ambient		1	12	21	33
	geothermal			2	3	6
	solid waste					
	renewables	15	20	50	64	78
Greece	electricity	5	6	9	11	14
	gas	10	9	5	3	
	coal					
	oil	54	48	27	13	3
	bioenergy	31	35	47	48	43
	solarthermal			2	4	7
	ambient		1	10	18	27
	geothermal			1	3	5
	solid waste					
	renewables	31	37	60	72	82
Hungary	electricity	2	3	5	7	10
	gas	52	50	26	16	3
	coal	2	2			
	oil					
	bioenergy	43	45	57	57	53
	solarthermal			2	3	6
	ambient		1	8	15	23
	geothermal			1	2	4
	solid waste					
	renewables	43	46	68	77	87
Ireland	electricity	8	9	14	17	21
	gas	25	23	12	7	1
	coal	20	14	4	2	1
	oil	46	41	23	11	2
	bioenergy	2	9	27	26	19
	solarthermal			3	6	10
	ambient		3	15	26	38
	geothermal			2	4	7
	solid waste					
	renewables	2	12	47	62	74
Italy	electricity	2	2	6	8	12
	gas	65	61	32	19	3
	coal					
	oil	5	5	3	1	
	bioenergy	28	30	45	45	41
	solarthermal			2	4	8
	ambient		1	11	18	30
	geothermal			1	3	5
	solid waste					
	renewables	28	31	59	71	84
Latvia	electricity	1	2	3	3	5
	gas	15	14	8	5	1
	coal	2	1			
	oil	5	5	3	1	
	bioenergy	76	78	82	82	81
	solarthermal			1	1	3
	ambient			4	6	9
	geothermal				1	2
	solid waste					
	renewables	76	78	87	91	94
Lithuania	electricity	3	4	5	6	7
	gas	16	15	8	5	1
	coal	7	5	1	1	
	oil	1	1	1		

Country	energy carrier	%-share in 2015	%-share in 2050 Level 1	%-share in 2050 Level 2	%-share in 2050 Level 3	%-share in 2050 Level 4
	bioenergy	73	75	80	79	77
	solarthermal			1	2	3
	ambient		1	4	7	10
	geothermal			1	1	2
	solid waste					
	renewables	73	75	85	89	92
Luxembourg	electricity	5	5	9	13	18
	gas	49	46	24	15	2
	coal					
	oil	41	37	20	10	2
	bioenergy	5	9	28	28	22
	solarthermal			3	6	10
	ambient		2	14	25	39
	geothermal			2	4	7
	solid waste					
	renewables	6	12	46	62	78
Malta	electricity	25	25	28	31	35
	gas	56	53	28	17	3
	coal					
	oil	12	11	6	3	1
	bioenergy	7	10	24	24	20
	solarthermal			2	4	8
	ambient		1	10	18	29
	geothermal			1	3	5
	solid waste					
	renewables	7	11	38	49	62
Netherlands	electricity	5	6	10	13	18
	gas	87	83	44	26	4
	coal					
	oil					
	bioenergy	7	9	28	28	23
	solarthermal			3	6	10
	ambient		1	14	23	38
	geothermal			2	4	7
	solid waste					
	renewables	7	11	46	61	78
Poland	electricity	2	3	7	10	13
	gas	24	23	12	7	1
	coal	51	35	10	5	3
	oil	1	1			
	bioenergy	22	33	49	44	37
	solarthermal			3	6	9
	ambient		4	16	24	32
	geothermal		1	2	4	6
	solid waste					
	renewables	23	38	70	78	83
Portugal	electricity	3	3	5	5	7
	gas	18	17	9	5	1
	coal					
	oil	5	4	2	1	
	bioenergy	74	75	79	79	78
	solarthermal			1	1	3
	ambient			3	6	10
	geothermal				1	2
	solid waste					
	renewables	74	75	84	88	92
Romania	electricity	4	4	6	7	10
	gas	39	37	20	12	2
	coal	2	2			
	oil					
	bioenergy	55	56	65	65	63
	solarthermal			1	3	5
	ambient		1	6	11	18
	geothermal			1	2	3
	solid waste					
	renewables	55	57	74	81	88

Country	energy carrier	%-share in 2015	%-share in 2050 Level 1	%-share in 2050 Level 2	%-share in 2050 Level 3	%-share in 2050 Level 4
Slovakia	electricity	10	10	14	18	22
	gas	86	81	43	26	4
	coal	2	2			
	oil					
	bioenergy	2	6	25	24	19
	solarthermal			3	6	10
	ambient		1	13	23	38
	geothermal			2	4	7
	solid waste					
	renewables	2	7	42	57	73
Slovenia	electricity	7	7	9	10	11
	gas	13	12	6	4	1
	coal					
	oil	15	14	8	4	1
	bioenergy	60	62	67	67	66
	solarthermal			1	2	3
	ambient			4	8	12
	geothermal	5	5	5	6	7
	solid waste					
	renewables	65	67	77	83	87
Spain	electricity	15	15	17	20	22
	gas	31	29	15	9	2
	coal	1	1			
	oil	22	20	11	5	1
	bioenergy	31	33	44	44	41
	solarthermal			2	4	6
	ambient	1	2	9	15	24
	geothermal			1	3	4
	solid waste					
	renewables	31	35	56	66	75
Sweden	electricity	63	63	63	63	63
	gas	1	1	1		
	coal					
	oil	1	1	1		
	bioenergy	35	35	35	35	35
	solarthermal					
	ambient				1	1
	geothermal					
	solid waste					
	renewables	35	35	36	36	36
Switzerland	electricity	8	9	12	15	19
	gas	27	26	13	8	1
	coal					
	oil	47	42	23	12	2
	bioenergy	10	14	29	29	24
	solarthermal	3	3	5	7	11
	ambient	3	4	14	23	34
	geothermal	3	3	4	6	8
	solid waste					
	renewables	18	24	51	65	78
United Kingdom	electricity	12	12	16	19	24
	gas	72	69	36	22	4
	coal	2	1			
	oil	7	7	4	2	
	bioenergy	6	9	27	26	22
	solarthermal			2	5	9
	ambient		1	13	22	35
	geothermal			2	3	6
	solid waste					
	renewables	6	11	44	57	72

6.3 Heating and cooling efficiency

6.3.1 Lever description

This lever controls the average energy loss in heating, cooling and ventilation systems and district heating generation. HVAC systems are becoming more and more energy efficient. Increase in the energy efficiency lowers the emissions impact.

6.3.2 The rationale for lever and level choices

The efficiency of the systems within the building stock differ in age and technology, for example, low-temperature boilers versus condensing boilers. The efficiency of the whole system depends on the efficiency, insulation and configuration of several components of the heating system. How they are integrated into the individual building can be very different; the boiler, however, is most comparable. Therefore, the efficiency of the boiler is used to represent the improvement of the efficiency of the heating system.

Almost all boilers should be replaced at least once between 2015 and 2050 as the substitution rate based on the technical lifetime of a boiler is around 3.1%/a and the average lifetime approximately 25 years (Endberichts *et al.*, 2005). The efficiency of all the boilers in 2050 is dependent on the learning curve: if ambitious technologies are introduced quickly, then they will equip most of the buildings. The average efficiency will be higher compared to a slow market diffusion. The higher average efficiency associated with level 4 means a faster distribution of ambitious heating system compared to other ambition levels.

6.3.2.1 Disaggregation methodology rational

The efficiency values for the boilers are assumed to be the same within Europe, as these products can easily be traded across borders. As a starting point, the current efficiencies are used per country.

6.3.2.2 Ambition levels & disaggregation method

EU-Levels

Table 9 – EU-Levels

Efficiency improvement (%)	1	2	3	4
fossil	3	5	10	18
biomass	15	17	22	31

Disaggregation by country

Source for the table 8 is: Wenzel and Nitsch, 2010; Schramek, 2011; COWI, TI and DGC, 2012a, 2012b; Nitsch et al., 2012; Fleiter et al., 2016.

Table 10 – Disaggregation by country

Country	Fuel efficiency (%)	2015	1	2	3	4
Austria	Gas	83	86	87	91	98
	Coal	54	56	57	59	64

Country	Fuel efficiency (%)	2015	1	2	3	4
	Oil	86	89	91	95	98
	Renewables	55	63	64	67	72
Belgium	Gas	80	83	84	88	94
	Coal	56	57	59	61	65
	Oil	77	79	81	84	90
	Renewables	65	74	76	79	85
Bulgaria	Gas	83	85	87	91	97
	Coal	63	65	67	70	75
	Oil	72	75	76	80	85
	Renewables	59	68	69	72	77
Croatia	Gas	82	85	87	91	97
	Coal	59	61	62	65	69
	Oil	79	81	83	87	93
	Renewables	58	66	68	71	76
Cyprus	Gas	82	85	87	91	97
	Coal	60	62	63	66	71
	Oil	76	79	80	84	90
	Renewables	56	64	65	68	73
Czech Republic	Gas	85	88	89	93	98
	Coal	60	62	63	66	71
	Oil	79	81	83	87	93
	Renewables	64	73	75	78	84
Denmark	Gas	77	80	82	85	91
	Coal	60	62	63	66	71
	Oil	74	76	78	81	87
	Renewables	61	70	71	75	80
Estonia	Gas	83	86	88	92	98
	Coal	60	62	63	66	70
	Oil	75	78	79	83	89
	Renewables	64	73	75	78	84
Finland	Gas	82	85	87	91	97
	Coal	62	64	65	68	73
	Oil	81	83	85	89	95
	Renewables	56	64	65	68	73
France	Gas	83	86	87	91	98
	Coal	54	56	57	60	64
	Oil	87	90	91	95	98
	Renewables	55	63	64	67	72
Germany	Gas	83	86	87	91	98
	Coal	55	57	58	60	65
	Oil	85	87	89	93	98
	Renewables	55	63	64	67	72
Greece	Gas	81	83	85	89	95
	Coal	59	61	62	65	69
	Oil	76	79	80	84	90
	Renewables	55	63	64	67	72
Hungary	Gas	84	86	88	92	98
	Coal	60	62	63	66	71
	Oil	79	81	83	87	93
	Renewables	64	73	75	78	83
Ireland	Gas	82	85	86	90	97
	Coal	62	64	65	68	73
	Oil	79	81	83	87	93
	Renewables	53	61	63	65	70

Country	Fuel efficiency (%)	2015	1	2	3	4
Italy	Gas	79	81	83	87	93
	Coal	58	60	61	64	69
	Oil	75	77	79	83	88
	Renewables	56	65	66	69	74
Latvia	Gas	82	85	86	90	96
	Coal	58	60	61	64	68
	Oil	85	88	89	93	98
	Renewables	62	71	72	75	80
Lithuania	Gas	85	88	89	93	98
	Coal	61	63	64	67	72
	Oil	79	81	83	87	93
	Renewables	65	74	76	79	85
Luxembourg	Gas	84	86	88	92	98
	Coal	60	62	63	66	71
	Oil	79	82	83	87	93
	Renewables	68	77	79	83	88
Malta	Gas	82	85	87	91	97
	Coal	60	62	63	66	71
	Oil	76	79	80	84	90
	Renewables	67	77	79	82	88
Netherlands	Gas	82	84	86	90	96
	Coal	60	62	63	66	71
	Oil	80	82	84	88	94
	Renewables	60	68	70	73	78
Poland	Gas	86	89	90	94	98
	Coal	61	63	64	67	72
	Oil	77	79	81	84	90
	Renewables	70	80	82	85	91
Portugal	Gas	82	84	86	90	96
	Coal	60	62	63	66	71
	Oil	80	83	84	88	94
	Renewables	55	63	64	67	72
Romania	Gas	82	85	87	91	97
	Coal	63	64	66	69	74
	Oil	79	81	83	87	93
	Renewables	55	63	65	68	72
Slovakia	Gas	84	87	88	92	98
	Coal	60	62	63	66	71
	Oil	79	81	83	87	93
	Renewables	66	76	78	81	87
Slovenia	Gas	84	86	88	92	98
	Coal	60	62	63	66	71
	Oil	79	82	84	87	93
	Renewables	63	73	74	77	83
Spain	Gas	83	86	87	91	98
	Coal	67	69	70	74	79
	Oil	80	82	84	88	94
	Renewables	58	66	68	71	76
Sweden	Gas	85	87	89	93	98
	Coal	60	62	63	66	71
	Oil	81	83	85	88	95
	Renewables	56	64	65	68	73

Country	Fuel efficiency (%)	2015	1	2	3	4
Switzerland	Gas	82	85	87	91	97
	Coal	60	62	63	66	71
	Oil	76	78	80	84	89
	Renewables	56	64	65	68	73
United Kingdom	Gas	82	85	86	90	97
	Coal	61	63	64	67	72
	Oil	79	82	83	87	93
	Renewables	57	65	66	69	74

7 Conclusions

Greenhouse gas emissions (GHG) from buildings (both residential and commercial) make 13% of the total GHG emissions in Europe. In order to host people and provide a liveable environment, buildings use energy for different purposes including heating, cooling, ventilation, and lighting systems. The amount of energy consumed for creating a comfortable environment depends mostly on the design and the quality of the building. As energy balances aggregate sectors, the energy demand and GHG emissions for buildings include not only internal air conditioning, but also appliances and information and communications technology equipment.

Another way in which buildings are associated with GHG emissions is through the grey energy needed to produce the construction materials and perform the construction itself.

In order to assess the GHG emission originating from buildings, it is important to understand its drivers and effects that variations in the drivers would lead to. For this purpose, the report develops the logic applied in the building model and the calculation tool, by identifying and detailing the relevant drivers that influence buildings' GHG emissions in Europe.

The drivers refer to more than one area of interest included in the EUCalc project. Drivers will be related to different lifestyles of building occupants, to different trends in the construction industry, and finally, to the existing and foreseen building stock in Europe (including the embedded building and district heating energy systems).

A short list of the levers used in the EUCalc building module is presented in Table 1.

Table 11 – Short list of the levers

Lever	**Output**
Living space demand per person	Average living space per person
Building envelope	Average heat loss of a building
Indoor temperature	Average internal air temperature
Material switch	Percentage of material replaced
Material efficiency	Percentage of decrease in material demand
HVAC system efficiency	Average energy loss in HVAC and DH systems
District heating share	Level of energy demand covered by DH
Technology and fuel share	Technology mix linked to HVAC, DHW, cooking and lighting, and district heating.
Appliances, cooking, lighting efficiency	Average rate of energy use for appliances, cooking, and lighting
Share of residential floor cooled [%]	Amount of floor space cooled
Appliance ownership [#/household]	Yearly hours of use of each appliance
Appliance use [hours/app]	Replacement rate of the appliances

Each of the levers has four ambition levels attached to it. The ambition levels used in EUCalc are:

- Level 1: Observed trends continuation scenario
- Level 2: Intermediate scenario, more ambitious than Level 1
- Level 3: Very ambitious but realistic scenario
- Level 4: Transformational scenario requiring strong changes and advances

Building up on the definition of main levers, the buildings module is based on an approach of medium complexity[13]. The calculations is based on historical data for the energy demand and projections until 2050 considering the ambition level choices made by the user. Furthermore, the energy demand in buildings depends on:

- Framework assumptions, such as the population development and the Climate change depending mostly on the protection effort of the rest of the world
- Lifestyle/ behavioral choices, such as the floor space demand per person, the demand and use of applications and the heating and cooling behaviour
- Existing infrastructure and resources, such as the the mix of building ages and types and the current energy mix as well as the availability of renewable resources which are often bound to location

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[13] The Energy demand is performed on a bottom-up approach with a simplified single zone model for the assessment of climate impact on the energy demand for space heating and space cooling.

- Technology and fuel choises as defined and selected in the levers, such as the heating technologies, fuel type, technology mix, and system efficiencies.

8 References

Bettgenhäuser, K. *et al.* (2014) 'Deep renovation of buildings: an effective way to decrease Europe's energy import dependency', *ECOFYS Germany GmbH by order of Eurima, Germany, Project Number: BUIDE14901*.

Boermans, T. *et al.* (2012) 'Renovation tracks for Europe up to 2050', *Ecofys Germany: Köln, Germany*.

Buildings Performance Institute Europe (BPIE) (2011) *Europe's Buildings Under The Microscope*. doi: ISBN: 9789491143014.

Buildings Performance Institute Europe (BPIE) (2016) *Building Renovation Strategies Under the Spotlight Delivering the Energy Efficiency Directive Article 4* -. doi: http://dx.doi.org/10.1111/j.1468-1331.2006.01319.x.

Bürger, V. (2012) *Overview and assessment of new and innovative integrated policy sets that aim at the nZEB standard*. ENTRANZE. Available at: https://www.entranze.eu/files/downloads/D5_4/Entranze_D5.4_05-2012_final.pdf.

COWI, TI and DGC (2012a) *Technology data for energy plants - individual heating plants*. Available at: https://ens.dk/sites/ens.dk/files/Analyser/c_teknologikatalog_for_individuelle_varmeanlaeg_og_energitransport_2012.pdf.

COWI, TI and DGC (2012b) *Technology Data for Energy Plants Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion*. Available at: https://energiatalgud.ee/img_auth.php/4/42/Energinet.dk._Technology_Data_for_Energy_Plants._2012.pdf.

D'Agostino, D. *et al.* (2016) 'Synthesis report on the national plans for nearly zero energy buildings (NZEBs)', *Joint Research Center (JRC) publications*.

Dean, B. *et al.* (2016) 'Towards zero-emission efficient and resilient buildings.: Global Status Report'. Global Alliance for Buildings and Construction (GABC).

Directorate-General for Energy (European Commission) (2019) *Clean energy for all Europeans*. European Commission. Available at: https://publications.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1.

Endberichts, L. *et al.* (2005) 'Evaluierung der CO 2 -Minderungsmaßnahmen im Gebäudebereich'.

European Commission (2018) *A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competititve and climate neutral economy*.

Eurostat (2018) *Energy consumption in households*, *Statistics Explained*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households (Accessed: 29 May 2019).

Fleiter, T. *et al.* (2016) 'Mapping and analyses of the current and future (2020-2030) heating/cooling fuel deployment (fossil/renewables). Work package 2: Assessment of the technologies for the year 2012', *Hg. v. EUROPEAN COMMISSION: DIRECTORATE-GENERAL FOR ENERGY. Online verfügbar unter* *https://ec. europa. eu/energy/en/studies/mapping-and-analyses-current-and-future-2020-2030-heatingcooling-fuel-deployment, zuletzt geprüft am*, 11, p. 2017.

International Energy Agency (IEA) (2018) *Tracking Clean Energy Progress, Buildings*.

Ipsos Belgium and Navigant (2019) *Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report*. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/1.final_report.pdf.

Kranzl, L. *et al.* (2014) *Policies to enforce the transition to nZEB : Synthesis report and policy recommendations from the project*. Available at: https://www.entranze.eu/files/downloads/D5_7/D5_7_ENTRANZE_synthesisrecommendations_v14.pdf.

Moura, P. S. and Fonseca, P. (2018) 'Cost-effective options for nearly zero energy renovation of municipal buildings', pp. 1043–1053.

Nitsch, J. *et al.* (2012) 'Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global', *Schlussbericht im Auftrag des BMU, bearbeitet von DLR (Stuttgart), Fraunhofer IWES (Kassel) und IfNE (Teltow)*, 345. Available at: https://www.researchgate.net/profile/Michael_Sterner/publication/259895385_Langfristszenarien_und_Strategien_fur_den_Ausbau_der_erneuerbaren_Energien_in_Deutschland_bei_Berucksichtigung_der_Entwicklung_in_Europa_und_global/links/570c089e08aee0660351aa71.p.

OECD/IEA (2018) *The Future of Cooling Opportunities for energy-efficient air conditioning Together Secure Sustainable*.

Sandberg, N. H. *et al.* (2016) 'Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU', *Energy and Buildings*. Elsevier, 132, pp. 26–38. doi: 10.1016/j.enbuild.2016.05.100.

Schramek, E.-R. (2011) *Taschenbuch für Heizung und Klimatechnik. einschließlich Warmwasser- und Kältetechnik*. München: Oldenbourg Industrieverlag GmbH,.

Toleikyte, A., Kranzl, L. and Müller, A. (2018) 'Cost curves of energy efficiency investments in buildings – Methodologies and a case study of Lithuania', *Energy Policy*. Elsevier Ltd, 115(December 2017), pp. 148–157. doi: 10.1016/j.enpol.2017.12.043.

Umwelt, I. W. und *et al.* (2018) *Monitoring der KfW-Programme „ Energieeffizient Sanieren " und „ Energieeffizient Bauen " 2017*. Available at: https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-alle-Evaluationen/Monitoring-der-KfW-Programme-EBS-2017.pdf.

Wenzel, B. and Nitsch, J. (2010) 'Langfristszenarien und Strategien für den Ausbau der Erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global', *Deutsches Zentrum für Luft-und Raumfahrt (DLR), Stuttgart*. Available at: http://www.ifne.de/download/EEG-Kostenentwicklung_12_2010.pdf.