Energy-Efficient Retrofits on an Existing Home in Coimbra, Portugal

A dynamic assessment of environmental performance for future climate and energy mix scenarios.

JORDAN BERMAN
Abstract

This work introduces a method, called the dynamic building life cycle, to evaluate the environmental performance for residential renovation products. The method goes beyond a full-building life cycle by accounting for the changing dry bulb temperature and greenhouse gas (GHG) intensity over a 30-year period between 2020 and 2050. This method is a combination of using (1) life cycle assessment and environmental product declarations to determine environmental impact from renovation products, (2) climate projections and the morphing algorithm to determine future dry bulb temperature, (3) GHG intensity projections based on five different e-Highway2050 (eHW) project scenarios to predict the future state of national energy mix and (4) whole building energy simulations to calculate final energy demand. The work focuses on a case-study comparing renovation products applied to a single-family home located in Coimbra, Portugal. Renovations include replacing existing windows with double-glazed and triple-glazed windows along with three different insulation materials for Exterior Thermal Insulation Composite Systems (ETICS).

The results show that all renovation products reduced the overall emissions over the dynamic building life cycle compared to base model, however, improving the thermal insulation was significantly more effective than upgrading the windows across all eHW scenarios. From the insulation materials, XPS provided the best combination of low environmental impact and thermal properties to reduce the total GHG emissions, although EPS and mineral wool insulation performed similarly well. Despite having a low overall effect compared to the ETICS, triple-glazed windows outperformed double-glazed windows with 26% more reduction in GHG emissions on average across all eHW scenarios. The impact of using a dynamic building life cycle was compared to simplified methods. For instance, depending on the eHW scenario a comparison where the GHG intensity were to remain constant over the building life cycle could lead to a 5% under estimation or 30% over estimation for final GHG emissions compared to the dynamic method. Whereas if the climate were to remain constant the final emissions would be about 5% overestimation compared to the dynamic method.
Terms

Exterior Thermal Insulation Composite Systems (ETICS)
Greenhouse gas (GHG)
Global Warming Potential (GWP)
Intergovernmental Panel on Climate Change (IPCC)
5th Version of the Coupled Model Intercomparison Project (CMIP5)
Global Climate Model (GMC)
Regional Climate Model (RCM)
Typical Meteorological Year (TMY)
Representative Concentration Pathways (RCP)
eHighway 2050 Project (eHW)
Shared Socioeconomic Pathway (SSP)
Global Climate Model (GCM)
Regional Climate Model (RCM)
Typical Meteorological Year (TMY)
Lifecycle Assessment (LCA)
Environmental Product Declaration (EPD)
Exterior Thermal Insulation Systems (ETICS)
Predicted Mean Vote (PMV)
IDA Indoor Climate and Energy (IDA ICE)
Environmental Performance (EP)
Table of Contents

Abstract .................................................................................................................................................. 1

Terms.................................................................................................................................................. 2

1.0 Introduction ..................................................................................................................................... 4

1.1 Research Questions ...................................................................................................................... 5

2.0 Theory ............................................................................................................................................... 6

2.1 Present situation in Portugal .......................................................... 6

2.2 Energy-efficient renovations ................................................................. 7

2.3 The four-step method .................................................................................................................. 9

2.3.1 Product Life Cycle Assessment ........................................................... 9

2.3.2 Climate Projections ....................................................................................... 10

2.3.3 Greenhouse gas emission intensity ..................................................... 14

2.3.4 Energy simulations ..................................................................................... 17

3.0 Methods.......................................................................................................................................... 19

3.1 Product lifecycle assessment ................................................................. 20

3.2 Climate projections ......................................................................................... 21

3.2.1 Morphing algorithm in Python ............................................................ 24

3.3 Greenhouse gas intensity projections ..................................................... 25

3.4 Energy simulations ......................................................................................... 26

3.4.1 Reference building ................................................................................ 26

3.4.2 Tuning the base parameters ................................................................. 28

3.4.5 Renovation schedule ............................................................................ 30

3.5 Environmental performance ................................................................. 32

3.6 Limitations ............................................................................................................................... 33

4.0 Results ............................................................................................................................................ 34

5.0 Conclusion and Discussion .............................................................................................................. 39

6.0 References ...................................................................................................................................... 41
1.0 Introduction

Anthropogenic climate change is one of the most important global issues to address in this century. In the coming decades countries around the world will be directly affected by changing climate variables such as increasing dry bulb temperature, drought and wildfires, scarcity of fresh water, floods, and rising sea levels (Directorate-General for Climate Action, 2022). Although many counties have agreed to mitigate the effects of climate change to maintain a relatively low global temperature (Unfccc, 2015) there are sectors that will inevitably feel these effects. One area that receives a lot of attention is the building and construction sector which accounts for nearly 39% of carbon dioxide ($\text{CO}_2$) emissions when upstream power generation is included (Abergel et al., n.d.). The energy performance of many buildings is inadequate with approximately 37% of the housing stock in southern European countries, such as Portugal, consisting of homes built before 1960 (BPIE, 2011).

The changing climate poses a significant challenge for these buildings reduce energy consumption. On a similar note, the rising temperature could also alter the country’s energy demand patterns to maintain thermal comfort, with less heating demand in the winter and more cooling demand in the summer (IEA, 2021). At the same time, climate change mitigation strategies are reducing the reliance on fossil fuels for electricity generation, leading to more clean energy sources buildings (EEA, 2021). All this to say that buildings have lifecycles which span many decades and therefore, the performance assessments should be based on the future climate and socio-economic landscape that a building will operate within and not the present or historical data as traditional methods suggest.

The economics of renovations especially interested in the cost-optimal method and cost-effectiveness for renovations in Portugal has been extensively researched in the literature (Almeida et al., 2015; Ferrara et al., 2014; Ferreira et al., 2016; Tadeu et al., 2018). But while climate change and carbon intensity are observed, they are not necessarily considered as a foundation for the analysis over the building life cycle. On the other hand, many researchers have studied the effects of climate change on buildings using energy simulations (Farah et al., 2019; Jiang et al., 2019; Pulkkinen & Louis, 2021; Roux et al., 2016). Roux et al. even included a methodology which accounts for different climate and emissions scenarios in building life cycle assessment. However, the combination of this research has not been thoroughly studied. Therefore, the aim of this work is to account for the effects of climate change and energy mix scenarios on the choice of renovations using whole building energy simulations. I have chosen to compare the environmental performance of different types of insulation materials and windows using a case study for a single-family home located in Coimbra Portugal.
1.1 Research Questions

This research introduces a method called the dynamic building life cycle. It is a combination of four methods, namely, using (1) life cycle assessment (LCA) and environmental product declarations (EPDs) to determine environmental impact from renovation products, (2) climate projections and the morphing algorithm to determine future dry bulb temperatures, (3) GHG intensity projections to predict the future state of national energy mix for electricity generation and (4) whole building energy simulations to calculate final energy demand. The combination of these methods creates a simulation environment which accounts for the physical and socio-economic effects of climate change. This will be discussed in more detail in section 2.3 The four-step method.

This study presents the results using a parameter called environmental performance. This is a comparison between the base energy model and a renovated model, calculating the percent reduction of emissions over a 30-year simulation period. In this regard, a large positive percentage is best, showing that the renovation makes a significant reduction of final $\text{CO}_2$ emissions.

The goal of this research is to provide a more accurate way of analyzing building performance into future scenarios. I am particularly interested in the context of environmentally conscious mass renovation plans for pre-1960 homes in Portugal and throughout the EU. It is estimated that only 11% of European buildings are renovated per year, however only 0.2% achieve a deep energy retrofit which reduces the energy consumption by at least 60% (Vandenbussche, 2021) With many researchers claiming that the largest available source of cost-effective energy saving, and greenhouse gas reduction potential is associated with the older building stock (Rodrigues et al., 2015)

The main research questions that I want to answer with the study are:

Q1: What are the effects of climate change on energy demand and the final GWP for the case study?

Q2: What are the effects of the changing GHG intensity on final GWP for the case study?

Q3: What impact do the selected energy-efficient renovations have over the 30-year dynamic building life cycle?

Q4: What is the impact of the dynamic method over the traditional method? For instance, assuming that climate is constant, GHG intensity is constant, or both are constant?
2.0 Theory

2.1 Present situation in Portugal

The focus of the study is on anticipating the future climate and socio-economic landscape for Portugal in the context of building energy simulations for energy-efficient renovations, however it is worth taking note of the present time as well. First, the decision to focus this case study on Coimbra, Portugal is arbitrary because this kind of study could have taken place anywhere in the EU. However, I was inspired by a family member who has recently moved to Coimbra and is exploring options to build a sustainable and resilient home.

Coimbra spans across the warm-summer and hot-summer Mediterranean Köppen climate zones. As mentioned in previous section Portugal, like many EU countries has a large percentage of low energy efficient homes which can lead to poor thermal comfort for occupants and higher than necessary energy consumption (BPIE, 2011).

According to statistics from the Climate ADAPT, the climate in mainland Portugal near Coimbra is primarily affected by vicinity to the Atlantic Ocean and is responsible for high precipitation and the reduction of the effects of dry and cold winds from the Iberian Peninsula’s interior (Climate-ADAPT, 2021). An increase in the number of days with high temperatures and a decrease in the number of days with low temperatures has been observed as well as the intensity and duration of heat waves (WBG, 2021).

Another reason why this research is important, is to address the situation for environmentally effective renovation plans for older homes in regions where people may soon be returning. Portugal has experience steady decline of the population in rural areas since the midcentury and saw an even larger spike the years following the financial crisis in 2008 (MacroTrends, n.d.). Urban areas along the coast continue to grow, however, the extreme events of climate change pose many risks especially along the coastal strip between the two main metropolitan areas where sea level rise threatens the tourism business and the livelihoods of 40% of the population who reside there (Climate-ADAPT, 2021). This may give rise to a return to the mainland where there is already a sense of artisan revival (Oliver Balch, 2019). However, people moving back to these regions will likely find old homes which are not ready to meet the demands of the changing climate.
2.2 Energy-efficient renovations

In Europe the most significant parameter to consider for an energy-efficient renovation is the heating of indoor spaces, accounting for 76% of final energy demand (Tobias et al., 2016). The fundamental theory for this study is that the energy-efficient renovations will reduce the final energy demand of the home by improving the building envelope. The building envelope refers to components of the construction such as the walls, floors, roof, and windows. By improving the performance of these elements, a building can reduce the amount of energy needed to maintain the indoor climate. Indoor climate has many factors, but the two most important factors for this study are the indoor thermal comfort and the concentration of carbon dioxide in the air. Indoor air temperature is also part of a broader term called thermal comfort. Thermal comfort is a combination of environmental and personal parameters which influence an occupant’s experience of an indoor space. The four environmental factors are air temperature, radiant temperature, air velocity, and humidity, while the two personal factors are the occupant’s metabolic rate and amount of clothing. Adequate indoor air temperature varies between 20 and 25 degrees Celsius and values of concentration of carbon dioxide vary between 600 and 800 ppm (REHVA Journal 01/2021 - CO₂ Monitoring and Indoor Air Quality, n.d.; REHVA Journal 02/2013 - Thermal and Acoustic Comfort Requirements in European Standard and National Regulations, n.d.).

While the metabolic rate and amount of clothing that the occupant wears can influence their experience, the environmental factors of thermal comfort can be adjusted through active or passive design strategies to help maintain acceptable ranges. Active strategies require energy to move air or change the air temperature. For example, an electric radiator, wood-burning stove, air-conditioning unit, heat pump and fan are all active systems. Passive systems optimize the buildings heat transport and airflows without using any fuel. Passive systems rely on the design and orientation of the building as well as natural phenomena, such as natural ventilation from pressure differentials. Passive designs include improvements to the building envelope such as installing high performance windows or increasing the thermal insulation of walls, roofs, and floors.

The focus of this study is to compare environmental performance of renovations for passive systems, such as the insulation and windows. However, many homes from this era lack a central heating and cooling system (Tadeu et al., 2018) and will generally have poor thermal comfort despite passive system improvements. Therefore, there will be an active systems renovation made to the home but as described in section 3.4.2 Tuning the base parameters, it will be present in all energy simulations and therefore become a background variable. I would like to note that the introduction of the active system is a vital part of the study because it is used to maintain thermal comfort and indoor air quality by heating, cooling, and ventilating the indoor air. On that note, I also assume that the active system uses electricity as opposed to solid or liquid fuels. This means that the associated GHG emissions from the energy demand are dependent on the energy mix of the region. And this is what makes the GHG intensity projections, described in section 2.3.3 Greenhouse gas emission intensity, important for the methodology.

---

1 This assumption is ambitious considering that as of now the energy mix in residential building in the southern European countries is approximately only 18% (BPIE, 2011). However, considering that homes in this era will likely have systems with poor efficiency (>60%) the need for renovations will be desired. Also, the EU is expecting to see an increase in electrification in space heating, mainly from heat pumps, rising to 50 - 70% share by 2050 (Vandenbussche, 2021).
An increasingly common practice for improving the thermal insulation of walls is to use an Exterior Thermal Insulation System (ETICS). ETICS were first introduced in Germany in the 1957 and have become more common place solution for new construction and renovations since the 1970 (Michalak, 2021). ETICS are a multi-layer system which is applied to the exterior façade to reduce thermal bridges and improve the overall performance of the envelope while maintaining the indoor livable area. The layers of a typical ETICS system are shown in Figure 2. The main difference between ETICS is type of thermal insulation. The product that I investigate in this report uses EPS, XPS or Mineral Wool. All three of these options are all commonly used in the construction industry and have varying degrees of the thermal performance and environmental impact.

![Figure 2 ETICS Layers (Berger, 2020a)](image)

Windows are also a large source for undesired heat gains and losses. Typical Portuguese windows for pre-1960s houses were single pain windows with wood or aluminum framing (Tadeu et al., 2018). These types of windows do a poor job of maintaining the indoor climate for the home because they have low thermal resistance and are often leaky, which can lead to air drafts in the home. An airtight installation of a double-glazed or triple-glazed window will improve the thermal resistance and minimize heat losses by air flows. Figure 3 shows sections of a double-glazed and triple-glazed window from STURGAL manufacturing company who produces windows in Spain and Portugal. This company has also provided an Environmental Product Declaration (EPD) which will be discussed more in the section 2.3.1 Product Life Cycle Assessment.

![Figure 3 Double-glazed (left) and triple-glazed (right) window sections (STRUGAL, 2022)](image)
2.3 The four-step method

2.3.1 Product Life Cycle Assessment

One Click LCA, an automated life cycle assessment software company, says that to develop a low-carbon economy, it is imperative that buyers have access to reliable environmental impact information so that they can assess and select low-carbon products (OneClickLCA, 2022a). Life cycle assessment (LCA) is a framework for assessing the environmental impacts of a product over its life cycle. Below is a summary of the four stages of the LCA from ISO 14040 guidelines (Muralikrishna & Manickam, 2017) and Error! Reference source not found. shows a visualization of the different LCA stages.

**Stage 1**: Goal and scope define how much of the life cycle will be considered in the assessment and the purpose of the assessment. Some common scopes include the cradle-to-gate, cradle-to-grave and cradle-to-cradle assessments. It is also important to define the functional unit for the assessment. For example, the EPD for thermal insulation may present GWP per square meter.

**Stage 2**: Inventory analysis describes the material and energy flows in the system of the product.

**Stage 3**: Impact assessment is served by the inventory analysis, where the importance of each impact category is assessed, normalized, and weighted.

**Stage 4**: The last step is the critical review and interpretation of the results and data sensitivity.

![Figure 4 Example Life Cycle Assessment (LCA) stages diagram (By MtW17 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=97566700)](image)

The information obtained during an LCA for a product can be summarized in an Environmental Product Declaration (EPD). EPDs present many different types of environmental impact properties, however, the most important one for this research is the global-warming potential (GWP).

If all things are the same between two products, it is safe to say that the one with the lower environmental impact is the better option. However, oftentimes other parameters, such as cost, durability and the mechanical or thermal properties influence the decision for one product over another. In the case for thermal insulation and windows for building construction there are three
main parameters to consider (1) total GWP, (2) thermal resistance and (3) the durability. Ideally, the product has a low GWP, high thermal resistance and is durable enough to last the entire life cycle of the building with minimal maintenance or replacement.

There are few more important parameters to consider from an EPD. (1) It is advisable to use EPDs where the geographic scope is the same as the building location. This is because the EPD usually contain an estimated value for the transportation to building site parameter based on the average distance that the manufacturer transports goods and the fuel used for different kinds of freight. (2) The declared unit defines the unit per which the results are provided. When considering construction materials, the declared unit is often one square meter, one cubic meter, or one product unit. For example, the EPDs for thermal insulation provide $1m^2$ as the declared unit. Therefore, the sum of GWP from each stage must be multiplied by the total surface area of product applied to the building. Finally, (3) the life cycle stages define from which part of the product life the data is collected from.

Figure 5 shows the standard stages provided in all EPDs. As to which product stages are included in the EPD depends on the provider and can vary between products. However, at a minimum the EPD should provide data for the cradle-to-gate (A1 – A3) analysis. But oftentimes, the EPD will also contain data for the use-stage (B), end-of-life stage (C) and the benefits for reuse, recycling, and recovery (D).

<table>
<thead>
<tr>
<th>Product Stage</th>
<th>Construction Process Stage</th>
<th>Use Stage</th>
<th>End-of-life stage</th>
<th>Benefits and loads beyond the system boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Material Supply</td>
<td>Transport</td>
<td>Manufacturing</td>
<td>Transport to building site</td>
<td>Installation into building</td>
</tr>
<tr>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>A5</td>
</tr>
</tbody>
</table>

*Figure 5 Life cycle assessment (LCA) included in the environmental product declarations (EPDs)*

### 2.3.2 Climate Projections

Climate projections help designers and policy makers understand the potential futures for the global climate. The fifth phase of the Coupled Intercomparison Project (CMIP5) is a report which provides simulated climate futures characterized by the global socio-economic landscape of the next few decades and centuries (Taylor et al., 2012).

Global Climate Models (GMCs) are the foundation for climate projections. These models are based on the numerical equations which describe the physical processes of the climate system. GMCs are also forced by representative concentration pathways (RCPs) which represent the emissions scenarios that are influenced by socio-economic behavior. RCPs represents various assumptions about technological developments and provides a large range of possible future scenarios. For instance, RCP8.5 (radiative forcing of 8.5 W/m²) is a high-emissions scenario, with concentrations of greenhouse gases by the end of the century that are almost four times preindustrial levels. And RCP4.5 (radiative forcing of 4.5 W/m²) is a low to moderate scenario, in which emissions decline
beyond the middle of the century (Taylor et al., 2012). Figure 6 shows all the various RCPs that are commonly used in climate projections, however in study I only focus on RCP4.5.

My primary source for climate projection data was the Copernicus Climate Change Service (C3S) and the tool called The European Climate Energy Mixes (ECEM) Demonstrator. ECEM provides both data on two different geometric scopes (1) for the country and (2) for more local clusters. The clusters are defined in the e-Highway2050 project (e-Highway2050, 2015) and provide a more local climate region. Figure 7 is a screenshot from ECEM which shows the difference between the countries and clusters. For climate projections, I used the 12PT cluster because it contains the city of Coimbra. However, for the GHG emission projections, in the next section, use countries because of resolution of energy data.

---

2 I also use ECEM for energy projection data as part of the method to estimate greenhouse gas emission intensity as described in the following section.
Figure 8 shows the annual mean dry bulb temperature projections for the northern region of Portugal based on an RCP4.5 forcing scenario (http://ecem.wemcouncil.org/). The highlighted area corresponds to the simulation period for the building life cycle for this case study. While the temperature differential is quite dramatic during the latter half of the century, the temperature projections for RCP4.5 and RCP8.5 during the selected time period are quite similar. Due to this I did not pursue simulations for both scenarios because the results would have been insignificant.

The purpose of climate projections for this research is to produce future climate variables to be used in energy simulations in the climate region of Coimbra, Portugal. However, the spatial resolution for GMC models is typically too coarse compared to the scale which is important for the simulations. To address this, GMC are typically refined to a regional resolution through dynamic and statistical downscaling. Dynamic downscaling refers to the application of high-resolution regional simulations to extrapolate the effects of climate processes from large to local scales. Statistical downscaling refers to the use of statistics-based techniques to determine the relationship between large-scale climate patterns and observed local climate response (GFDL, n.d.). However, RCM data only provides data for average daily temperature, which is not sufficient for building energy simulations.

Typical meteorological year (TMY) data, on the other hand, is often presented at an hourly resolution and can be used as a base climate file for an energy simulation tool. A TMY file is created using a set of representative observed data over a significant temporal period, varying between 5 and 30 years. Each month of the year is represented by actual observed data for the most representative month from the set of selected years. Figure 9 shows an example from the TMY file obtained for this research spanning 2004 until 2018, where the selected year for each month has been color coordinated. These files include variables such as dry bulb temperature, dew point temperature, relative humidity, solar radiation, and wind speed. The TMY data for this research was obtained from an open-source repository of free climate data for building performance simulation called Climate.OneBuilding.org managed by the creators of the EPW file format, a common and standard format used for energy simulations.

3 There are several settings used on the ECEM Demonstrator tool which are described in more detail in Section 3.2.
Figure 9 Example of a TMY (One.Building, TMY_2004-2018) file where each month of the year is represented by actual observed data for the most representative month from a set of selected years.

While TMY data are based on historical climate they can also be used as a baseline for climate projections. Belcher et al. first introduced a method called morphing that uses a present TMY file and future an RCM to create a future TMY file (2005). The output from the morphing algorithm has the same shape as the present TMY data and can be used for energy simulations. The morphing algorithm has been widely used in the literature and accepted as a simple yet reliable method for generating future climate data for building energy simulations (Jiang et al., 2019). More details on the application of the morphing method used in this research is described in section
3.2.1 Morphing algorithm in Python.

Morphing encapsulates average weather conditions of future climate scenarios by combining present-day observed weather data with results from climate models. In this morphing downscapes the coarse resolution from global circulation models (GMCs) and regional climate models (RCMs) to the fine spatial and temporal resolution required for energy simulations (Belcher et al., 2005).

Equation 1 is used to morph dry bulb temperature, where $p$ is the morphed temperature [°C], $x_o$ is the present hourly temperature [°C], $x_m$ is the mean monthly temperature [°C] of the present data, $\Delta x_m$ is the change in monthly mean temperature between the present and future scenario [°C], and $\alpha_m$ [-] is fractional change in monthly mean temperature.

$$ p = x_o + \Delta x_m + \alpha_m \times (x_o - x_m) $$

Equation 1

The fractional change parameter $\alpha_m$ is used to assess the daily temperature variation and it has different forms depending on the available data (Pulkkinen & Louis, 2021). The first method is to use the changes in daily maximum and minimum temperatures and is the original form given by Belcher et al. (2005). The formula is given in Equation 2 where $\Delta$ refers to the change between the projected and the baseline climate, $\Delta T_{\text{max},m}$ is the change in average daily maximum temperature in the month $m$, $\Delta T_{\text{min},m}$ is the change in average daily minimum temperature in the month $m$, and $< T_{\text{max}} >$ is the average daily maximum temperature [°C] of the baseline climate for month $m$, and $< T_{\text{min}} >$ is the average daily minimum temperature [°C] of the baseline climate for month $m$.

$$ \alpha_m = \frac{\Delta T_{\text{max},m} - \Delta T_{\text{min},m}}{< T_{\text{max}} > - < T_{\text{min}} >} $$

Equation 2

The second method is used in the case when there is no data on daily maximum and minimum temperature (Pulkkinen & Louis, 2021). Here it is assumed that daily temperature variation is relative to the daily mean temperature variation on a certain month and is calculated using the M2 method given by Räisänen & Räty (2013). The formula is provided in Equation 3 were $S_p$ and $S_o$ refer to the standard deviation of the projected scenario and the baseline climate respectively.

$$ \alpha_m = \frac{S_p}{S_o} - 1 $$

Equation 3

2.3.3 Greenhouse gas emission intensity

The greenhouse gas emission (GHG) intensity of power generation in the EU has been continuously decreasing over the last three decades, see Figure 10 (EEA, 2021). The GHG intensity is dependent on the energy mix of country where less carbon-intensive energy sources, such as renewable energy systems, help to reduce the intensity. This reduction in GHG intensity will impact the GHG emissions
associated with the final energy demand from the residential sector. The main research objective associated with this trend is to accurately model this reduction into the dynamic building life cycle.

Figure 10 Greenhouse gas emissions intensity of electricity generation (EEA, 2021)

I will now introduce the eHighway2050 project which plays important role in the development of the methods for predicting GHG intensity. As described on the eHighway2050 website, “the overarching objective of e-Highway2050 is to develop a top-down planning methodology to provide a first version of a modular and robust expansion plan for the Pan-European Transmission Network from 2020 to 2050, in line with the pillars of European energy policy (e-Highway2050, 2013).” In the e-Highway2050 booklet several scenarios are presented to “explore a wide scope of plausible and predictable challenges to be faced by the power system (e-Highway2050, 2015).” The scenarios differ within the following categories (1) Economy: GDP, population growth, fuel costs, (2) Technology: maturity of carbon capture storage, (3) Policies: incentives towards renewable energy systems, energy efficiency, energy independency, and (4) Social behavior: nuclear acceptance, preference towards decentralized generation (e-Highway2050, 2015).” Figure 11 shows a visual representation of the differences between the five scenarios. The booklet clearly states that these scenarios are neither prediction nor forecasts and there are no underlying assumptions that any scenario is more likely than others (e-Highway2050, 2015).

For this reason, I chose to present the results based on the various scenarios to compare the impact of alternative futures. Figure 11 shows the descriptions for each scenario along with a pie chart which shows the corresponding European energy mix. C3S ECEM Demonstrator, which was introduced in the previous selection, uses the data from the e-Highway2050 (eHW) Project to determine energy demand and percentage of renewable energy generation for each country. The eHW Project has energy data from three points in 2014, 2040 and 2050. And then daily data between 2014 and 2050 are computed by linear interpolation (http://ecem.wemcouncil.org/).
Figure 11 Reproduced from Table 1 from the e-Highway2050 project results (e-Highway2050, 2015).
2.3.4 Energy simulations

This research uses energy simulations to estimate the final energy demand for a reference house in Coimbra, Portugal based on the dynamic building life cycle. The energy modeling tool that I chose is IDA Indoor Climate and Energy. Equa, the company that creates and distributes the IDA software environment says that IDA ICE “is a program for study of the indoor climate of individual zones within a building, as well as energy consumption for the entire building (2013).”

Typically, the simulation consists of a building with one or more zones. IDA ICE accounts for climate region, architectural design, building orientation, construction materials, heating and cooling systems, mechanical and natural ventilation, on-site energy generation, occupants, equipment and much more. Weather data is supplied with weather files, such as using the EPW file format, to create the environment and the context for the energy simulation (Equa, 2013). The simulation returns several important results such as the final energy demand from heating, cooling, lighting, and ventilation as well as the indoor air temperature and air quality.

Each zone is given controller setpoints for various parameters in for form of maximum and minimum values. Figure 12 shows an example from one of the zones of the energy model used in this research. Note that the temperature setpoints have a lower limit of 20 and an upper limit of 25 degrees, while the $CO_2$ has a lower limit of 700 and an upper limit of 1100 ppm in agreement with the recommended levels. Active systems such as heating, cooling, and ventilation systems are generally equipped with default control systems which moderate the signal by comparing the indoor climate to the set points. For instance, in the case of a heating system, there is a default proportional-integral (PI) controller which is activated once the room temperature drops below the minimum, 20 degrees. However, if the heating system is under sized and the capacity is not able to meet the required power output to maintain the setpoint temperature, the zone will drop below the desired temperature and lead to poor thermal comfort. In the winter this undersized unit may also run the risk of a continuous signal which will consume more power than intended and could lead to early retirement of the equipment. Therefore, is it important to properly size the room units to meet heating and cooling loads.
Figure 12 Screen shot from IDA ICE Control Setpoints for the Living Room zone in the energy model.
3.0 Methods

For this study, I defined environmental performance (EP) as the net GWP over the life cycle of the building. Four main methods were used to develop the EP: (1) product life-cycle assessments (LCA), (2) climate projections, (3) greenhouse gas (GHG) intensity projections, and (4) energy model simulations. I calculated the EP over a dynamic 30-year life cycle spanning 2020 to 2050. The period is dynamic because the dry bulb temperature and GHG intensity change over time. However, this dynamic period becomes a background variable when comparing renovation products to each other. To reduce computational demand, I divided the entire life cycle into six five-year-long simulation periods. Table 1 shows the breakdown for the simulation periods. I acknowledge that this also reduces the accuracy of results and affects the external validity. However, since all simulation sets have the same structure, the study is internally valid. Figure 13 shows an overview of the concept for the dynamic building life cycle, including the energy mix projections and climate as parameters which influence the cumulative emissions. Note the difference between the base model and renovated model will be used to determine the environmental performance.

Table 1 Simulation Periods and Representative Years

<table>
<thead>
<tr>
<th>Simulation Period</th>
<th>Representative years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2020 - 2024</td>
</tr>
<tr>
<td>2</td>
<td>2025 - 2029</td>
</tr>
<tr>
<td>3</td>
<td>2030 - 2034</td>
</tr>
<tr>
<td>4</td>
<td>2035 - 2040</td>
</tr>
<tr>
<td>5</td>
<td>2040 - 2044</td>
</tr>
<tr>
<td>6</td>
<td>2045 - 2049</td>
</tr>
</tbody>
</table>

Figure 13 Graphic displaying the general concept of the dynamic building life cycle.
3.1 Product lifecycle assessment

The product life assessment accounts for the emissions associated with each renovation product. Once these renovations are complete, the emissions should be added to the building. One way to determine the total emissions from a particular product is to review the Environmental Product Declaration provided by the company or manufacturer in collaboration with common reporting standards as described in 2.3.1 Product Life Cycle Assessment. As mentioned before, the geographic scope of EPDs is an important factor in the final whole building life cycle. Unfortunately, at the time of writing this report, there are no EPDs available for ETICS products available in Portugal or in the European geographic scope. Therefore, I decided to use the EPD from Berger Paints India Ltd Group.

Berger Paints India Ltd Group is an Indian owned multinational company with exports to over 25 countries, however the geographic scope is India. This EPD was published in 2020 and is valid until 2025 and adheres to following reference standards S0 14020:2001, ISO 14025:2006, ISO 14040/44, EN 15804:2012, EN 16783:2017 (Berger, 2020b). It includes several ETICS products with varying types of insulation materials presented for 50mm, 75mm, 100mm and 120mm (Berger, 2020a). While the insulation material varies, the other layers of the composition remain constant between products. The declared unit for the EPD is 1 $m^2$ (Berger, 2020b).

Since the products are all contained in the same EPD, comparisons between products are internally valid since the procedure is essentially identical. However, the issue is that this Berger EPD has a geographic scope of India (Berger, 2020a), whereas the building that I am studying is in Portugal. While One Click LCA, uses a “BRE-approved data regionalization methodology according to CEN/TR 15941:2010 to adjust the emissions to match with local manufacturing conditions,” the method is part of One Click LCA’s intellectual property and is not disclosed on their website (OneClickLCA, 2022b). Therefore, I considered two options to reconcile this issue. (1) Account for additional emission associated with the transportation of the finished product to an estimated site location or (2) compare the production fuel mix factors for the manufacturing between the two countries to represent a similar company who manufactures ETICS in Portugal. For simplicity, I chose the second option to compare carbon intensities of the two countries. Table 2 shows the production fuel mix factors for India and Portugal. Note that the factor for India is much higher than that for Portugal, leading to the final emissions for the ETICS to be less when produced in Portugal than in India. As for the double-glazed and triple-glazed windows, I found an EPD from STURGAL. This company has production plants and distribution centers in both Spain and Portugal and therefore the energy mix was not converted from Spain to Portugal, because this is already accounted for in the EPD.

<table>
<thead>
<tr>
<th>Country</th>
<th>Production fuel mix factor (kgCO2e per kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>0.7082</td>
</tr>
<tr>
<td>Portugal</td>
<td>0.20155</td>
</tr>
</tbody>
</table>

Next, I will explain the process for calculating the effective GPW for the EPD by considering the amount of material used in the renovation and the conversion of production fuel mixes. Since the declared unit for this EPD is 1 $m^2$ (Berger, 2020a), the total amount of GHG emissions is the sum of emissions from all stages multiplied by the surface area of the application. Equation 4 gives the
The method described above produces an effective GWP for the ETICS which is less than the original EPD. This decision causes trouble for external validity of the results for the final GHG emissions and somewhat for the calculation of environmental performance. However, the internal validity for this is maintained since the objective is to compare the performance for each insulation material to each other. Other methods for comparing EPDs for individual insulation materials would have yielded similar issues with internal and external validity since life cycle stages, geographic scope, and other processes for each EPD can vary significantly between companies. Therefore, since the Berger EPD contained GWP for all three insulation materials, it was the best option for consistent and unbiased results.

The EPD for the windows from STUGEL also provided several products including the selected double-glazed and triple-glazed window. This also helps to maintain internal validity for the comparison of each window. However, I chose not to grade or compare the performance of the windows to the insulation. Both with issues regarding the inconsistency in the EPDs as well as issues in the energy simulations, which is described in more detail in the results.

### 3.2 Climate projections

The purpose of climate projections for this research was to develop future climate files for energy simulations to account for the changing dry bulb temperature over the dynamic building life cycle. I considered two alternatives for this method. The first was to use a weather generator to create future EPW files and the second was to write my own Python script to apply the algorithm.

Jiang et al. developed an open-source tool called *Weather Morph: Climate Change Weather File Generator* which was able to, “generate the future weather data for more than 2100 locations throughout the world for all four IPCC (Intergovernmental Panel of Climate Change) emission scenarios in the three future time slices of the 2020s, 2050s and 2080s (2019).” However, even though it was claimed to be accessible to the public, the link provided in the article was broken and I was unable to find it elsewhere on the internet. However, in the report they also compared their tool to *CCWorldWeatherGen Software*. This excel-based tool was developed at the University of South Hampton and applies Belcher’s morphing algorithm to generate climate change weather files in the EPW file format (SOTON, 2020). I was able to download and install this tool, however the climate projections are based coarse General Circulation Model (GCM) data from Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. Therefore, the geographic resolution and relevance of the report, compared to more recent versions, was less than ideal for this project. Therefore, I
decided to pursue the second option to write a simple Python program to apply the algorithm and generate EPW files. This option also allowed me to define my own simulation periods and to use climate data from my source of choice.

To apply the morphing algorithm, I needed a data set for projected climate data for mean daily temperatures that cover the span of simulation periods defined in Table 1 and historical data with an hourly time series to be used as the baseline climate. My primary source for climate projection data was the Copernicus Climate Change Service (C3S) and the tool called The European Climate Energy Mixes (ECEM) Demonstrator. My primary source for present climate data was obtained from a database called Climate.OneBuilding and is based on the most recent data from Portugal’s Climatology from 2004 to 2018 (https://climate.onebuilding.org/).

ECEM is an online data and visualization tool which helps the user to understand the relationship between climate and energy data (http://ecem.wemcouncil.org/). Figure 14 is a screen shot from the ECEM Demonstrator showing the possible configuration for the selected variable, temporal resolution, climate scenarios, and emissions scenarios. ECEM Demonstrator uses CMIP5-forced global and regional climate simulations undertaken as part of Coordinated Regional Downscaling Experiment (CORDEX) (Troccoli et al., 2018). Troccoli also says that “it was decided to base the projections on RCM output for our European domain, EUROCORDEX, rather than global climate projections (2018).” This is because of three main reasons (1) EUROCORDEX provided a higher spatial and temporal resolution, (2) bias-adjustment of energy-related climate variables were already available through the Impact2C/C3S CLIM4ENERGY (C4E) and (3) consistency in output relative to climate change projections from the two Energy Sectoral Information Systems (SISs, namely C3S ECEM and C4E) was considered a desirable outcome (Troccoli et al., 2018). The data is made available with a 7-member sub-ensemble of GMC-RCM pairs, shown in Table 3, with two RCPs (4.5 and 8.5) from 1979 to 2100. The historical period from 1979 – 2016 is a bias-adjusted reanalysis using the ERA-interim data. Reanalysis is preferred to direct observation in this case because of the large domain covered by C3S ECEM, however observational data are used as reference in the bias-adjustment procedures (Troccoli et al., 2018).

Figure 15 shows an overview of the ECEM project and the information flow between the climate data and energy data. There are many climate variables which influence building performance such as wind speed and relative humidity. And while these variables are provided by the ECEM Demonstrator, I have only modeled the change in dry bulb temperature because the other variables were consistent over the building life cycle. Figure 15 is a screen shot from ECEM Demonstrator which shows the
difference between the countries and clusters. Clusters provide a more local geographical scale and are used for the climate projections. The countries however will be used in the 3.3 Greenhouse gas intensity projections to determine the national energy demand. Lastly, I would like to reiterate that while ECEM does provide historical reanalysis for the bed of 1970 – 2016, this data set cannot be used as the baseline climate in the morphing algorithm because it does not have an hourly temporal resolution.

Table 3 List of the RCM-GCM configurations provided by ECEM Demonstrator (http://ecem.wemcouncil.org/)

| RCM1: RCA4/Hadgem2 (ECEM code RCMO) |
| RCM2: RACMO/EC-Earth (ECEM code RAIC) |
| RCM3: ARPEGE/CNRM (ECEM code ARCN) |
| RCM4: WRF/IPSL (ECEM code WRIP) |
| RCM5: REMO/MPI (ECEM code REMP) |
| RCM6: HIRHAM/EC-Earth (ECEM code HIIC) |
| RCM7: RCA4/EC-Earth (ECEM code RCIC) |

Figure 15 Overview of the ECEM project (Troccoli et al., 2018). Note that air temperature is the main variable taken from the climate data while the energy data is used in method to develop GHG intensity projections in 3.3 Greenhouse gas intensity projections.
3.2.1 Morphing algorithm in Python

Python is an open-source programming language which can be downloaded and installed on Mac, PC and Linux machines. User-defined functions in Python help to automate repetitive tasks such as applying the morphing algorithm to a large data, like the EPW time series. Python also gives users the flexibility to install custom modules which further improve the functionality. I found an open-source module for reading, editing, and saving EPW files (https://github.com/building-energy/epw). This allowed me to create the future climate files in the EPW file format directly from Python to be used in IDA ICE. I also used a module called Pandas which is a “a fast, powerful, flexible, and easy to use open-source data analysis and manipulation tool built on top of the Python programming language (https://pandas.pydata.org/).” Pandas use a tool called a Data Frame which is similar to the way in which Microsoft Excel uses rows and columns to organize data.

Since ECEM provides climate projection data for dry bulb temperatures with mean daily temperatures and does not include the mean daily maximum or minimum temperature, I decided to use the alternative for calculating the stretching factor as discussed in section 2.3.2 Climate Projections. The Equations 1 & 2 from section 2.3.2 Climate Projections for the morphing algorithm have been copied below. Note that I selected to use the form for $\alpha_m$ from the M2 method (Räisänen & Räty, 2013).

\[ p = x_0 + \Delta x_m + \alpha_m \times (x_o - x_m); \alpha_m = \frac{5p}{x_o} - 1 \]

When applicable ECEM recommends using the Ensemble Mean to minimize the bias from any single climate model (http://ecem.wemcouncil.org/). The Ensemble Mean refers to an averaging of the of climate model configurations. Unfortunately, ECEM does not provide climate projections on a daily temporal resolution for the Ensemble Mean; only annual, monthly, or seasonal. And since this temporal resolution is required to determine the monthly variance, I had to find work around. Luckily, ECEM does provide daily temporal resolution for each individual RCM-GCM configuration. Therefore, I choose to use the RCM2 configuration for the morphing algorithm because it aligned best with the present-day data in the EPW that I obtained from One.building database.

I downloaded the RCM2 which provided daily temperature values from 1979 until 2098. The Python script uses portions of this data set in the morphing algorithm to create future EPW files for each simulation period defined in Table 1. For example, I created a function which isolates the RCM data for the selected simulation period (i.e., 2020 to 2024). Using that portion, the function calculates the average monthly mean and standard deviation every January of the period (5 in in total) and then averages those values once again. This process is iterated to calculate the average monthly mean and standard deviation for all 12 months to produce a single Pandas Data Frame of statistics for the simulation period. Using the EPW module, I loaded the present-day EPW file into a Pandas Data Frame. This data set contains 8760 data points for dry bulb temperature where the month, day, and hour are clearly designated. I defined another function which calculates the mean and standard deviation for every month of the year to produce Pandas Data Frame of statistics for the present-day climate.

Next, I defined a function to apply the morphing algorithm. Using a for loop I iterated through each data point from the present EPW Data Frame and applied Equation 1 and then saved the new values in a future EPW Data Frame where all other values remained the same. Here the value for $x_o$ is simply the Dry Bulb Temperature from the EPW file and I used the statistics, described above, to

---

4 Here I am referring to the other climate variables such as wet bulb temperature, relative humidity, atmospheric pressure, precipitation, etc. These variables remained the same as the present climate.
calculate the terms for $\Delta x_m$, $x_m$, $\alpha_m$, $S_p$ and $S_o$. This future EPW Data Frame was then exported in the EPW file format directly from Python. A new EPW file was created for each of the six simulation periods presented in Table 1.

### 3.3 Greenhouse gas intensity projections

Greenhouse gas (GHG) intensity projections are used to convert the final energy demand from each simulation period into total emissions. This is important for comparing the emissions associated with the electricity used in the home to the emissions from the EPDs. During my research, reliable projections for GHG intensity were not found in the literature for the building lifecycle (2020 to 2050) I was studying. Therefore, a simple method for developing these projections is presented in this section. The method requires data from ECEM along with historically measured GHG intensity for Portugal, specifically for the reference year 2020.

ECEM provides projections for electricity demand and the generation of electricity from renewable energy systems (RES) for five different energy scenarios from the e-Highway2050 (eHW) project. For this study, I chose to compare the performance of the various renovation products under all five of the eHW scenarios. The reason for choosing this scenario was to align with the relatively conservative selection of RCP4.5, however, the selection is somewhat arbitrary and any of the five scenarios could have been selected for this portion of the research. It is important to note the electricity demand in this context is referring to a theoretical national demand; not to be confused with the electricity demand simulated for the representative house.

Assuming that the electricity demand is always met with electricity generated by the national grid, the RES only represents a percentage of the electricity generated to meet the total demand. Therefore, I assumed that the rest of the demand is met with electricity generated from fossil fuels. With these assumptions, I made a calculation for the projected percent of fossil fuels in the energy mix for every year from 2020 until 2050. I concede that the percent of fossil fuels in the energy mix is undoubtedly vague since there are many sources of fossil fuels that are potentially present in different amounts for any given year (coal, natural gas, oil, etc.). However, to move forward, I assumed that the relative proportion of each fossil fuel will remain constant between 2020 and 2050. Meaning that the total percentage of fossil fuels compared to RES will change but the relative percentage of the coal and natural gas will remain the same.

With these assumptions, I was able to estimate the GHG intensity for every year from 2020 until 2050 by using Equation 6. Where the projected GHG intensity for the simulation period ($e_i$) is equal to the product of the GHG intensity for the reference year ($e_{2020}$) and the projected percentage of fossil fuels in the energy mix ($F_i$).

$$ e_i = e_{2020} \times F_i $$

Equation 6

Based on the methods described above, the GHG intensity projections until 2050 were calculated and are presented in Error! Reference source not found.. Note that each simulation period shows a decrease in the intensity leading to a final reduction of 50% for 2050 compared to 2020. Along with the reduced final energy demand brought on by increasing winter temperatures, this reduction in GHG intensity will also prove to reduce overall GHG emissions from home.

---

5 While I could calculate the GHG intensity for every year I used a rolling 5-year average of this data to make it compatible with the simulation periods defined in Table 2.1.
3.4 Energy simulations

This section has three parts. First, I will introduce the reference model used for all simulations. Then, I will describe the process I followed in IDA ICE to tune the main engineering parameters. And finally, I will discuss the renovation schedule.

3.4.1 Reference building

I chose to model the reference building based on the literature for a typical Portuguese single-family home as described by Tadeu et al. (2018). First, I created a 3D model in Autodesk Revit to visualize the building (Figure 17) and create a floor plan to export as a CAD drawing (Figure 18). Upon importing the CAD drawing into IDA ICE, I created zones based on the rooms. These types of homes typically have a ventilated roof where the roof insulation is placed on the ceiling and not along the rafters. Therefore, the geometry of the roof is excluded from the model in IDA ICE. I assume that the entire house is relying on electricity for heating and therefore all solid and gas fuels have been replaced with electric systems. Since the layout of rooms was not clearly defined, I chose to model the reference building with two bedrooms, a single bathroom, and an open concept living room, kitchen, and dining area. The construction materials and properties for the walls, floors, roof, and windows were modified to achieve similar thermal performance to those provided in Table 4 and Table 5.
Figure 17 Revit 3D Model (left) and floor plan (right)

Figure 18 IDA ICE 3D model (left) and floor plan (right)
### Table 4 Dimensions of the reference building (Tadeu et al., 2018)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living space floor area</td>
<td>80 m²</td>
</tr>
<tr>
<td>Height of ceilings</td>
<td>2.7 m²</td>
</tr>
<tr>
<td>Envelope area</td>
<td>85 m²</td>
</tr>
<tr>
<td>Windows area</td>
<td>12 m²</td>
</tr>
<tr>
<td>Roof area</td>
<td>80 m²</td>
</tr>
</tbody>
</table>

### Table 5 Thermal characteristics of the reference building (Tadeu et al., 2018)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{walls}}$</td>
<td>2.0 W/m²°C</td>
</tr>
<tr>
<td>$U_{\text{floor}}$</td>
<td>1.65 W/m²°C</td>
</tr>
<tr>
<td>$U_{\text{roof}}$</td>
<td>2.8 W/m²°C</td>
</tr>
<tr>
<td>$U_{\text{windows}}$</td>
<td>5.1 W/m²°C</td>
</tr>
<tr>
<td>$G_{\text{windows}}$</td>
<td>0.85</td>
</tr>
<tr>
<td>$R_{\text{ph}}$</td>
<td>0.4 h⁻¹</td>
</tr>
</tbody>
</table>

### 3.4.2 Tuning the base parameters

While there are many factors that are important to consider during an energy simulation, I chose to focus on three parameters. My goal was to tune the base model and systems to achieve acceptable ranges for (1) indoor air temperature, (2) concentration of $CO_2$, and (3) to monitor the energy demand from the active systems.

First, I ran heating and cooling load simulations for the climate year 2020. The heating load simulation used an ideal heater in every zone while the cooling load simulation used an ideal cooler. According to the IDA ICE manual, ideal heaters and coolers should be used when there is no specific information about the actual room unit, or the details are unmotivated (Equa, 2013). These units do not have a specific location within the zone and are not connected to the building plant. While they have a parameter for the maximum capacity, the parameter is typically set large enough to account for any foreseen needs (Equa, 2013). Along with the large capacity the efficiency of the ideal heater and cooler were set to 1.0. The heating load simulation yielded a specific energy consumption of 243 kW h/m² for the climate year 2020. This is 22% higher than the average heating consumption for single-family homes in Portugal before 1960 (BPIE, 2011). Based on an initial cooling load simulation, the base model had a cooling load of 45 kW h/m². Since the ideal heaters and coolers have a very large capacity, they will maintain the setpoint temperatures by expending the necessary amount of energy. However, these heating loads do not consider the indoor air quality to maintain comfortable levels of $CO_2$.

Since many of the homes in this construction year used natural ventilation to supply fresh air, I ran a simulation where the windows had a control to open based on concentration of $CO_2$. The control set points for all zones was set to a maximum value of 1100 ppm. To maintain the indoor air temperature, this simulation used 10% more energy compared to the initial heat load. However, it reduced the maximum concentration of $CO_2$ from 1300 to 800 ppm, which is within the acceptable

---

6 The discrepancy could come from several different sources. One reason may be the location of the home. The climate in Portugal can vary significantly depending on the region therefore the final energy demand will also vary.
range. I also simulated a version of the model with a constant air volume (CAV) ventilation system. The standard ventilation rate for indoor spaces is 7.0 l/s per person. However, according to a study published in the REHVA journal, to provide an acceptable level of *perceived air quality* it is estimated that one third of the ventilation rate is sufficient (Olesen, 2011). Therefore, I lowered the ventilation rate from 7.0 l/s to 2.3 l/s per person. Since my model accounts for three occupants, the total ventilation rate was set 7.0 l/s for each zone. A one-year simulation for the 2020 climate, showed improved indoor air quality by maintaining levels of $CO_2$ to about 400 ppm throughout the year, which is equivalent to the levels in the outdoor air. However, since the outdoor air temperature is often lower than the setpoint, the supply air requires heating from the ventilation system. This accounted for a significant amount of heating energy which was almost 3X more energy compared to the initial heating load. I also tested model variations with 1.0 and 0.5 l/s CAV systems. Table 6 contains a summary of the results.

<table>
<thead>
<tr>
<th>Model variant</th>
<th>Average Concentration of $CO_2$</th>
<th>Delivered Energy</th>
<th>Computation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAV 7.0 l/s</td>
<td>400 ppm</td>
<td>710.3 $kWh/m^2$</td>
<td>3 mins</td>
</tr>
<tr>
<td>CAV 1.0 l/s</td>
<td>600 ppm</td>
<td>316.7 $kWh/m^2$</td>
<td>3 mins</td>
</tr>
<tr>
<td>CAV 0.5 l/s</td>
<td>700 ppm</td>
<td>278.4 $kWh/m^2$</td>
<td>3 mins</td>
</tr>
<tr>
<td>Natural Ventilation</td>
<td>700 ppm</td>
<td>268.2 $kWh/m^2$</td>
<td>&gt;10 mins</td>
</tr>
</tbody>
</table>

After these initial tests, I created the final base model. Aside from the interventions on the wall construction and windows of the building made in the next section, all the assumptions made for the base model persist as background variables. Generally, my goal was to reduce the complexity of the model to save on computational demand while maintaining thermal comfort and indoor air quality. Since the results are intended to be a *comparison* between the renovation products some aspects of the design and reality are suspended.

1. I chose to use ideal heaters and coolers with a very large capacity (20 kW) instead of a specific air conditioning unit or heat pump. This was to ensure that thermal comfort would be maintained in every simulation for future climates and not suffer from an undersized room unit.
2. I chose to use the CAV with 0.5 l/s. Although this is much less than the recommended amount of fresh air to supply (Olesen, 2011), this still achieves the recommended levels of concentration of $CO_2$ of 700 ppm. Air is supplied in the bedrooms and equal amount of air is exhausted from the living room and bathroom. This variation is also simpler than the natural ventilation variant and requires less computation time.
3. I chose not to model any equipment in the reference house. For instance, there are no appliances, personal computers, or televisions. This is because, first, the renovations do not consider any changes to the equipment and, second, I wanted to simply the model and reduce computational demand.
4. There are three occupants. The presence of occupants is managed by schedules which move them between the bedrooms, living room, and out of the home. I use typical residential schedules to model the amount of time that people occupy each room. For simplicity the same schedule is used for everyday of the year including weekends and holidays.
5. Exterior door is set to *never open* and interior doors are set to *always open*. This was also to simply the model and reduce computational demand.
3.4.5 Renovation schedule

I chose to compare the performance of different insulation materials and a double-glazed versus triple-glazed window. Regarding energy performance, these renovations aim to improve the thermal resistance of the building envelope and minimize the heat losses. The renovation schedule is provided in Table 7. Note that each of these simulation models will be simulated for all six simulation periods between 2020 and 2050 for a total of 36 simulations. Also, note that there are no simulation models which combine the insulation materials with the windows. This is an intentional decision to study the impact that each individual product has on the building; as well as issues with the compatibility of the EPDs as described in section

![Figure 13 Graphic displaying the general concept of the dynamic building life cycle.](image)

### Table 7 Renovation schedule

<table>
<thead>
<tr>
<th>Simulation model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>The reference building</td>
</tr>
<tr>
<td>EPS-100</td>
<td>100 mm of EPS insulation added to the entire building envelope</td>
</tr>
<tr>
<td>XPS-100</td>
<td>100 mm of XPS insulation added to the entire building envelope</td>
</tr>
<tr>
<td>MN-100</td>
<td>100 mm of MN insulation added to the entire building envelope</td>
</tr>
<tr>
<td>WN2</td>
<td>STRUGEL double-glazed window to replace all windows</td>
</tr>
<tr>
<td>WN3</td>
<td>STRUGEL triple-glazed window replace all windows</td>
</tr>
</tbody>
</table>
The application of thermal insulation is assumed to be applied to all surfaces of the building envelope including the floor, roof, and walls. The wall insulation is assumed to be added as an exterior thermal insulation composite system (ETICS) with either EPS, XPS or mineral wool (MN) insulation. For simplicity, I did not model all the layers of the ETICS. The insulation layer is placed on the outside of the stone wall and then a final render layer on top of that. The roof insulation is assumed to be added above the ceiling in the attic space. And the floor insulation is added on top of the existing slab and then a thin floor coating is applied. As for the windows, I upgraded the single-pain window with a double-glazed or triple-glazed insulating glass unit (IGU) with improved window frame based on data from the EPD. The thermal properties of the renovations are included in Table 8.

Table 8 Thermal Properties of renovations

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>0.04 W/m(^\circ)C</td>
</tr>
<tr>
<td>Mineral Wool (MN)</td>
<td>0.035 W/m(^\circ)C</td>
</tr>
<tr>
<td>XPS</td>
<td>0.0289 W/m(^\circ)C</td>
</tr>
<tr>
<td>Double-glazed window IGU(^7)</td>
<td>1.1 W/m(^\circ)C</td>
</tr>
<tr>
<td>Double-glazed window frame</td>
<td>1.6 W/m(^\circ)C</td>
</tr>
<tr>
<td>Triple-glazed window IGU(^8)</td>
<td>0.6 W/m(^\circ)C</td>
</tr>
<tr>
<td>Triple-glazed window frame</td>
<td>1.4 W/m(^\circ)C</td>
</tr>
</tbody>
</table>

I have included a heat balance diagram for the living room zone from the reference model in climate year 2020. A heat balance diagram shows the heat transfer between indoors and outdoors through the surfaces of the building envelope. Values which are less than zero are considered losses while those above zero are considered gains. Ideally, the building envelope is supposed to minimize undesired losses and gains to maintain a value close to zero. Figure 19 shows heat balance for the walls and floors compared to the windows and illustrates the potential for improvements to the building envelope. In this case the walls and floors, there are significant losses and gains; and therefore, a lot of potential for improvement. However, on the other hand, the windows only account for about 5% of the entire building envelope by area, and therefore the losses and gains are not as significant. This means that the improvements made to the windows will have less of an impact on the final energy demand compared to the walls and floors. The comparison between windows will still provide an answer in terms of performance, however, the magnitude is not justly comparable to the insulation materials.

\(^7\) The thermal resistance of the IGU unit was not provided in the EPD. Therefore, this value was estimated based on default double-glazed IGU unit from IDA ICE.

\(^8\) This value was estimated based on default triple-glazed IGU unit from IDA ICE.
3.5 Environmental performance

The environmental performance (EP) is used to compare the impact that the renovation products have on final emissions using the dynamic building life cycle. I have defined the EP as the percent reduction of GHG emissions of the renovated model compared to base model, see Equation 7. By this definition, a large percentage is best, showing a more significant reduction in GHG emissions.

Equation 8 calculates $GWP_{REN} [kg \text{CO}_2e]$ for the renovated model, where $GWP_{EPD}$ is the amount of GHG emissions given in the EPD, $ED_i [kWh]$ is the final electricity demand for each simulation period and $e_i [kg \text{CO}_2e/kWh]$ is the GHG intensity for each simulation period. Since the simulation periods are based on rolling 5-year averages, the inside of the summation is multiplied by 5 to obtain the GWP for the actual number of years. Finally, Equation 9 shows a similar form to calculate $GWP_{REF}$, however, since there was no renovation applied to the reference model $GWP_{EPD} = 0$.

$$EP = 1 - \frac{GWP_{REN}}{GWP_{REF}}$$  \hspace{1cm} \text{Equation 7}

$$GWP_{REN} = GWP_{EPD} + \sum_{i=1}^{n} (5 \times ED_i \times e_i)$$  \hspace{1cm} \text{Equation 8}

$$GWP_{REF} = \sum_{i=1}^{n} (5 \times ED_i \times e_i)$$  \hspace{1cm} \text{Equation 9}
3.6 Limitations

- This report does not include an economic assessment in the dynamic building life cycle.
- I am not considering the effects of proper installation or craftsmanship for renovations. However, the proper installation of renovations is paramount.
- The data used for climate projections come from ECEM Demonstrator; several limitations are outlined on the tool in the *Methods and Assumptions* section (http://ecem.wemcouncil.org/).
- This work introduces a simple method for estimating GHG intensity projections for this study because I did not find the required data during the research period; see section 3.3 Greenhouse gas intensity projections.
- There are several combinations of climate models, emission scenarios, and energy scenarios that can produce widely varying projections for climate variables and GHG intensity. This report focuses on one combination, however, the method applies to any combination.
- The case study is for a statistically typical reference house see 3.4.1 Reference building. And the climate region chosen to be Coimbra, Portugal. However, this study could have been performed in for any climate region with a relevant reference house.
4.0 Results

In this section, I will report the findings for environmental performance (EP) over the dynamic period. I will also present the supporting results from the climate projects and environmental product declarations (EPDs) and finish with an impact analysis. Figure 20 shows the climate projections for monthly mean temperatures based on RCP4.5, the data is presented using 5-year rolling average.

Figure 20 Mean monthly dry bulb temperature based on 5-year rolling averages
The selection of RCP4.5 and the RCM2 from the ECEM Demonstrator, the region of Coimbra is projected to experience increasing average temperatures. Between 2020 and 2090 the annual average temperature is projected to increase by about 4 degrees\(^9\). The increasing in monthly mean temperatures will manifest in warmer summer months and warmer winter months. Especially for the period between 2020 and 2045, this average increase is expected to reduce the annual final energy demand from the home because heating demand is much more prominent than cooling demand.

The results for GWP and Environmental Performance are presented on the following pages. Note that the results for the windows and insulation materials are included on different figures and have different scales for the environmental performance. This is intentional because the comparison between windows and insulation materials is not justified in terms of their EPDs or heat balance as described before.

The total GWP for the three Berger ETICS and two STURGAL windows are included in Error! Reference source not found.(a) and Error! Reference source not found.(a) respectively. While the Environmental Performance for the three Berger ETICS and two STURGAL windows are included in Figure 21(b) and Figure 22(b). The results for GWP are based on the methods described in 3.1 Product lifecycle assessment where the main data is collected from Environmental Product Declarations for each renovation product. The results for environmental performance (EP) are based on the electricity demand from the energy simulations, life cycle assessment from the renovation products, and the changing GHG intensity over the dynamic period. The final electricity demand from the house is simplified to only account for the energy required for heating, cooling, and ventilation\(^10\).

All three insulation materials perform similarly over the entire dynamic building life cycle with EP well above 70% for all e-Highway2050 Project scenarios. However, the renovation which applied 100 mm of XPS insulation to the building envelope achieved the highest environmental performance; meaning that this renovation accounts for the most significant reduction in GHG emissions over the dynamic building life cycle. Note here that EPS has the least variation in across the different scenarios, probably due to the lower initial emissions from the LCA.

As expected, based on the heat balance analysis, the EP for the windows were significantly less than the ETICS renovations with an average EP of 3.3%. However, the results show that on average over the various e-Highway2050 Project scenarios, the triple glazed window outperformed the double-glazed window by 27% over the dynamic building life cycle. Both window options show a similar amount of variation when compared to the ETICS across the possible energy mix futures.

Despite XPS insulation having more GWP from the EPD stage compared to EPS insulation, the thermal properties, and resulting reduction of final energy demand, significantly improved the environmental performance. The same effect can be observed with the STURGAL windows. The GWP from the EPD of the triple-glazed window was higher than that for the double-glazed window, however, the environmental performance is still higher for the former. It important to note that the percentage of total GHG emissions from the EPDs were small (1% - 5%) compared to the emissions from final energy demand in all cases.

\(^9\) Note that the portion of this projection that is selected for the dynamic building life cycle is from 2020 to 2050, which is only has an average annual temperature increase of 0.717 degrees.

\(^10\) Since the energy from equipment, lighting and domestic hot water have been removed from the analysis the results for final energy will be lower than for the actual house.
Figure 21 (a) GWP for window upgrades based on methods presented in Section 3.1 (b) Environmental Performance for window upgrades based on methods presented in Section 3.5
Figure 22 (a) GWP for window upgrades based on methods presented in Section 3.1 (b) Environmental Performance for window upgrades based on methods presented in Section 3.5
Finally, I was interested in the impact that the dynamic building life cycle had on the whole process. Therefore, I set up a comparison where the GHG emissions were calculated by assuming some other common simplified methods: (1) **Constant ED**, where a single climate year is used for the entire building life cycle with final energy demand for a one-year simulation multiplied by the number of years (2) **Constant GHGi**, where the GHG intensity projections are assumed to be constant, using the most recent value from 2020, and (3) **Constant both**, where both assumptions are held constant. The results are summarized in Figure 23.

With the results from the analysis for a dynamic period set equal to 100%, the other methods could be over or under estimation depending on the e-highway2050 energy mix scenario. If electricity demand would remain constant during the analysis, using a final energy demand from a single simulation with current climate of 2020 multiplied by the number of years, the results would be about 5% over estimation. However, for the case of Constant GHG Intensity, in the most extreme case with the eHW5 scenario the results would be about 31% over estimation. Like the findings from the environmental performance presented above, the influence of the energy mix scenario plays a significant role in the impact on the study. With cases that rely more on fossil fuels, like eHW2 and eHW4, being under estimations while those that rely on renewable energy systems will be overestimations.

*Figure 23 Summary of the impact of using the dynamic period compared to other boundary conditions and assumptions such as constant electricity demand (ED) or constant greenhouse gas intensity projections (GHGi) or by assuming a constant value for both during the building life cycle.*
5.0 Conclusion and Discussion

I have introduced a method for evaluating the environmental performance for renovation products for a residential home over a dynamic building life cycle. The goal was to frame this research in the context of environmentally conscious mass renovation plans for pre-1960 homes in Portugal and throughout the EU. The method goes beyond a full-building life cycle for renovations on an existing home by not only accounting for the environmental impact of the products and final energy demand of the home, but also considering projections for climate change and greenhouse gas (GHG) intensity.

The method introduced in this report is a combination of other methods (1) life cycle assessment (LCA) and environmental product declarations to determine environmental impact from renovation products, (2) climate projections using morphing algorithm to determine future dry bulb temperature, (3) GHG intensity projections to predict the future state of national energy mix for electricity generation and (4) whole building energy simulations to calculate final energy demand.

While I believe that considerations for the environmental impact are of the upmost importance for making design decisions for renovations, I am aware that the economics of the renovations is an important aspect for both for the individual home buyer and for mass renovation plans. Further research could include a cost-analysis components borrowing methods from cost-optimal renovation research and accounting for the cost projections of final electricity demand for the region where the home is being studied. By including the cost analysis there could be two performance factors to consider, using weighting factors to decide whether the cost or environmental impact was more important for the final decision.

This report relies on the morphing algorithm, defined by Belcher et al., to produce future climate files for building energy simulations. While some studies have introduced more sophisticated methods (Farah et al., 2019) or critique the morphing algorithm (Herrera et al., 2017), I have chosen to use this method for its simplicity like other researchers (Jiang et al., 2019).

There are many more types of energy-efficient renovations that have not been studied in this research. For instance, the installation of energy-efficient heating and cooling systems such as a ductless reversible air-to-air heat pump, which are very common improvements for homes like the one studied in this report. Also, the addition of solar panels for on-site energy generation were not included nor exterior shading systems. This is not a limitation of the energy modeling software but more so due to the availability of EPDs. I found that this was one of the most limiting factors for conducting a study like this.

This report only studies the effects of a renovation over a 30-year building life cycle ending around the year 2050. However, much of the significant warming will occur in the latter half of the century. Which is one of the reasons I did not provide an analysis on the RCP8.5, because the climate projections for RCP4.5 were very similar. The constraints of this study, namely the extent of the e-Highway2050 Project data, fix the length of the chosen period, but further research can pursue a longer time frame.

I would argue that a method like the dynamic building life cycle can provide a more accurate representation of the actual final emissions, however there could some destructive take aways. For instance, one might reason for using materials with more embodied energy by claiming that the reduction in emissions will be reduced from other means such as the reducing GHG intensity or noting that in this study climate change is helping to reduce the heating demand in buildings. Obviously, this is not the intention of the study. More so I believe that this emphasizes how connected our energy is;
especially considering the electrification of so many sectors and industries. As can be seen from the results in from Error! Reference source not found. and Error! Reference source not found. the environmental performance depends heavily on the future GHG intensity of the delivered electricity. The reduction of fossil-based primary energy is essential for meeting climate goals along with other strategies such as mass renovation schedules to make energy efficient renovations for existing buildings. My results show that the scenarios for eHW2 and eHW4, which rely more on fossil fuels, will see renovations with higher environmental performance, making it more important to make renovations to the building stock. And on the other hand, the scenarios which rely more on renewable energy systems will lead to comparatively lower environmental performance.

However, the main takeaway is that under all scenarios the environmental performance is a positive value meaning that over the 30-year time frame there a net reduction of GHG emissions compared to the unrenovated building while maintaining acceptable levels of indoor climate. Making renovations, especially in terms of thermal insulation, improved the case study to have a nearly zero-energy levels with final specific energy between 60 and 70 (kWh/m²) (Tadeu et al., 2018). It is important to reiterate that the case study was testing the performance of building envelope, however, there was still an ideal active system which provided heating, cooling, and ventilation. While passive systems do well to minimize energy losses, active system are almost certainly a requirement to achieve the required levels of indoor climate. I believe that in most cases, the current state of energy performance of homes built before 1960s will benefit a great deal from energy-efficient renovations, helping to bring these homes into the future to provide comfortable indoor spaces that reduce final emissions.
6.0 References


OneClickLCA. (2022a). *EPDs Comparability: when and how to use EPDs for sustainable design.* https://www.oneclicklca.com/epds-comparability/


STRUGAL. (2022, January 10). *The International EPD® System | Environmental Product Declaration | STRUGAL*. The International EPD® System. https://portal.environdec.com/api/api/v1/EPDLibrary/Files/1112f09e-60a7-40ec-ab0d-08d9c4927501/Data


