# An Evaluation Method of the Building Decarbonization Process at the International Level

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**Abstract.** The anthropogenic greenhouse effect results from human activity that causes greenhouse gas (GHG) emissions, the effects of which are now directly observable in terms of pollution and global warming. Among the negative consequences of rising global temperatures are the advancing processes of desertification, rising water levels, and biodiversity loss. The seriousness of the problem is underlined by the many plans and policies being implemented by governments internationally. The paper analyses the real estate sector's responsibility for GHG emissions. The existing building stock, built before introducing energy efficiency measures, needs to be energetically renovated to meet the current requirements and performance standards that governments now demand.

The paper presents an analysis of forecast data from the Carbon Risk Real Estate Monitor (CRREM) project, an EU-funded initiative to provide information on the decarbonization path to be followed by the existing building stock in 30 European countries. The study's contribution is the construction of a Building Decarbonisation Performance Index ($I_{BDP}$). The index was constructed using forecast data provided by the CRREM project, which were processed by implementing the operational logic of multi-criteria techniques. $I_{BDP}$ was designed with the objective of monitoring and assessing the degree of alignment between European countries and the decarbonization paths set by EU policies.

**Keywords:** Decarbonization pathway · CRREM · Real Estate

## 1 Introduction

Climate change is one of the most pressing issues that humanity has ever faced. The current uncontrolled use of natural land, the appropriation and consequent degradation of ecosystem services, and the progressive loss of biodiversity are issues of global magnitude and unprecedented in human history [1]. The impacts on ecosystems, economic sectors, health, and human well-being are severe. Climate change is closely linked to GHG emissions, which are produced and emitted by human activities. The consequences

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and risks associated with GHG emissions can now be seen in the desertification phenomena affecting the globe, acidification of the oceans, loss of vitality and resilience of ecosystems, and the progressive rise in temperatures [2]. The relevance and urgency of this issue is demonstrated by the introduction of climate change mitigation and adaptation laws and policies that have been adopted in worldwide countries [3–5].

In September 2015, 193 Member States of the United Nations (UN) signed the 2030 Agenda [6], a program of action comprising 17 Sustainable Development Goals (SDGs) to be achieved by 2030. The SDGs cover a range of common issues of global concern, including the fight against climate change[1].

In December 2015, during the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC)[2] [7], a legally binding international treaty on climate change was adopted: the Paris Agreement. The goal of the agreement is to keep the global average temperature increase well below 2 °C above pre-industrial levels (1850) and to limit the increase to 1.5 °C. The Paris Agreement is based on a five-year cycle of climate action to be taken by countries. Specifically, from 2020 onwards, each country will submit its national climate action plans, called National Determining Contributions (NDCs), in which it will communicate the strategies it intends to implement to reduce GHG emissions. In this context of global legislation and policies, the European Commission presented the 'Green Deal', a package of policy initiatives aimed at making Europe a climate-neutral continent by 2050 [8]. With the passing of the EU Climate Change Act[3], the Green Deal commitment has become a binding obligation; specifically, the legislation requires EU countries to reduce their GHG emissions by 55% (compared to 1990 levels) by 2030 to achieve climate neutrality by 2050.

In this context, an analysis of the sectors that contribute the most to GHG emissions is required. This study focuses on the building and construction sector, which is a significant contributor to energy consumption and GHG emissions [9]. According to the European Environment Agency[4] [10], the building sector accounts for 40% of EU energy consumption and 36% of annual GHG emissions from the EU energy sector. Similarly, the 2022 Global Status Report for Buildings and Construction[5] (Buildings-GSR) [11] shows a negative trend in the sector's decarbonization process, with construction activity returning to pre-pandemic levels in 2021 (Covid-19, 2020). This means that the gap between the required decarbonization path and the actual energy consumed and emissions generated becomes increasingly large [12].

[1] Goal 13 of Agenda 2030 is to "Promote action, at all levels, to combat climate change.".

[2] The UN organization is charged with supporting the global response to the threat of climate change.

[3] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing a framework for achieving climate neutrality and amending Regulation (EC) N. 401/2009 and Regulation (EU) 2018/1999 ('European Climate Regulation').

[4] The European Environment Agency (EEA) is an agency of the European Union that delivers knowledge and data to support Europe's environmental and climate goals.

[5] The Global Status Report for Buildings and Construction (Buildings-GSR) is a publication of the Global Alliance for Buildings and Construction (Global ABC), the leading global platform for all building stakeholders committed to the vision of a zero-emission system.

The criticality of the building stock in terms of GHG emissions forces a reflection on the existing building stock [13]. Buildings have a long lifecycle, and it is important to remember that focusing on energy efficiency in the design of new buildings will have an effect that is not immediately visible.

Approximately 80–90% of the existing building stock, for which no sustainability certification guidelines have been established, will still be in existence in 2050 [9], which is why it is necessary to accelerate energy renovation.

Consumers and investors are increasingly interested in sustainable products, and governments are moving toward stricter policies on the energy efficiency of building stock. From this perspective, a building that does not meet regulatory requirements and market expectations gradually loses value [14]. In this context, several certifications that monitor and certify the sustainability of building stock (GRESB[6], LEED[7], BREEAM[8]) have become widespread [15–17].

Among the various monitoring projects active at the international level, the EU-funded CRREM project [18] occupies a prominent position. The main objectives of the CREEM project are to reduce the risk factors associated with premature obsolescence and potential depreciation of the existing building stock, issues that will arise because of legislation and market demand for more sustainable products. CREEM is a support tool for companies operating in the real estate sector to face these risks and promote energy efficiency to avoid the 'stranding' of the many assets that will not meet future energy performance standards.

This paper addresses the issues previously outlined. The European Union has set forth stringent parameters to be met by all member states. These include the European Commission's goal to reduce GHG emissions by 55% by the year 2030 with the ultimate objective of achieving climate neutrality by the year 2050. All economic sectors must contribute to the reduction of GHG emissions. Achieving climate neutrality entails reducing GHG emissions to the greatest extent possible and offsetting any remaining emissions. In this context, the European Union introduced the CRREM project, which provides forecasting data to guide the decarbonization path that the real estate sector must take, to meet the targets set by the EU. The CRREM project provides indications of the rate of GHG emissions expressed in kgCO2e/m$^2$/yr for each year from 2020 to 2050. These indications are intended to guide 10 classes of real estate use in their efforts to achieve climate neutrality in 2050.

This paper contributes to the construction of the $I_{BDP}$, which was developed from the processing of forecast data contained in the CRREM project. The data provided by CRREM was processed using the logic of multi-criteria techniques to structure an index that would synthesize the CRREM data and provide an overview of the energy performance of the building stock in 30 European countries. The index developed is intended to identify which European countries are furthest from and closest to the net zero emissions target to be reached by 2050. The development of this index is a valuable support for government decision-making. It allows for the identification of countries

[6] Global Real Estate Sustainability Benchmark (GRESB).

[7] Leadership in Energy and Environmental Design (LEED).

[8] Building Research Establishment Environmental Assessment Method (BREEAM).

where more stringent policies are needed to facilitate the decarbonization of the real estate sector, thereby incentivizing renovation activities.

The second phase of the research involved structuring an etiological analysis. Specifically, the authors identified a set of synthetic indicators, which were derived from statistics portals that were active at the European level (Eurostat). The indicators, such as national population numbers and population density, were correlated with $I_{BDP}$ values. The objective of this correlation process was to determine whether there was a relationship between the indicators and the $I_{BDP}$. In conclusion, the necessary path of decarbonization of the real estate sector to be undertaken and realized by European nations can be influenced by different parameters and aspects that this paper attempts to identify through etiological analysis.

## 2 Material and Method

The decarbonization trajectory of fossil fuel-reliant economic systems is being meticulously monitored by analytical systems designed to track the advancement of distinct sectors. This attention is necessary not only to limit pollution rates but also because of the expected economic impacts. The current GHG emission rates of most economic sectors, if continued over their lifetimes, would be incompatible with the 1.5–2 °C degree temperature rise limit. Failing to adhere to the decarbonization trajectory prescribed by international law would result in a loss of asset value, a phenomenon commonly referred to as a "stranding asset". The phenomenon of stranding assets can manifest itself in many ways [19]. These include:

i) the premature decommissioning of assets,
ii) a progressively reduced utilization of assets, and
iii) ever-increasing costs of asset efficiency.

In the forthcoming period, properties with suboptimal energy performance will be subjected to a process of depreciation, thereby increasing the risk of premature economic obsolescence. The increasing development of European regulations on sustainable finance will encourage economic actors to invest their resources in assets that comply with regulations and market demands. In this context, the importance of energy certification is becoming increasingly apparent. Although certified buildings are more expensive to construct, they have a higher return on investment. The majority of certifications to date have been for new buildings. However, what about existing buildings?

The CRREM project offers a comprehensive understanding of the future of real estate portfolios and the decarbonization trajectory that must be pursued, enabling investors to evaluate not only the current emissions of their assets but also the prospective risk of stranded assets [20].

### 2.1 Carbon Risk Real Estate Monitor (CRREM)

The CRREM initiative represents the most significant global initiative to date in the field of operational decarbonization of real estate assets. The initiative provides incentives and

accelerates energy retrofit initiatives in real estate portfolios by communicating the financial risks associated with poor building energy performance. The primary objective is to reduce the downside risk of properties that will not meet future energy performance standards and for which energy upgrades will become financially unaffordable. The CRREM toolkit generated a decarbonization pathway forecast for 10 asset classes (office, retail high street, retail shopping center, retail warehouse, industrial distribution warehouse cooled, hotel, healthcare, lodging leisure & recreation, residential multi-family) across 30[9] European countries.

In particular, the CRREM tool translated the aspiration to limit global temperature rise by 2050 into different country- and property-specific trajectories. The project employed a scientific approach to allocate the remaining global anthropogenic emissions budget, following the Paris Agreement targets, by country. The CRREM tool is presented in XLS format and requires the input of a set of information that defines the energy efficiency status of an individual asset or portfolio of assets. This enables the identification of assets that are at risk of stranding. Furthermore, the tool enables the measurement of the impact of asset refurbishment on the entire property portfolio, including the progress resulting from the refurbishment of a single asset.

However, in the absence of precise data on individual buildings, the project provides the "*Decarbonization Target Tool"*, which enables the assessment of decarbonization and energy reduction pathways without the need to enter precise data on building portfolios. The initial baseline year is 2020, at which point the tool provides data on GHG emissions (in kgCO2e/$m^2$/yr) and energy use intensity (in kWh/$m^2$/yr) derived from market averages. Having established the baseline and the target of a global temperature rise of no more than 1.5 °C, the tool presents annual emission and energy use reduction targets from 2020 to 2050, building a pathway to near-zero emissions.

### 2.2 Method

The objective of this paper is to carry out a comparative analysis of the decarbonization pathways of the building stock of 30 European countries, the same as those considered by the CRREM project. The objective of this comparative analysis is to identify which countries are furthest away from the climate neutrality targets set by European legislation and which countries are most aligned with European targets in terms of GHG emissions. In particular, this analysis is necessary to identify which countries require the implementation of more stringent and meticulous policies that will incentivize and accelerate the renovation of the nation's housing stock.

It should be noted that data made available through the CRREM project, and in particular within the worksheet designated as the "Decarbonisation Target Tool", are disaggregated. This means that they do not provide an overview of the overall situation in terms of GHG emissions for the Country in question. The CRREM dataset provides the GHG emission figure for each year from 2020 to 2050 (thus 31 GHG emission rates in

[9] Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

kgCO2e/m$^2$/yr) for 10 classes of real estate use *(office, retail high street, retail shopping center, retail warehouse, industrial distribution cooled warehouse, hotel, healthcare, lodging leisure & recreation, residential multi-family)* for each of the 30 European nations examined. The data presented in this way offers insights that can inform the decarbonization strategy to be pursued for each class of real estate use within each nation. The decarbonization pathway was developed by CRREM through an analytical approach, utilizing 2020 GHG emissions data as the foundation. Nevertheless, the disaggregated presentation of the data precludes certain considerations, such as: i) Which real estate use class is the most responsible in terms of GHG emissions? ii) Which European nation is furthest from the targets set by the European Commission in EU policies?

In order to address these questions an analysis of the data made available by the CRREM toolkit was conducted. In particular, the data available in the Decarbonization Target Tool worksheet were extracted and processed using the operational logic of the pairwise comparison. The logic of the pairwise comparison constitutes the basis for the implementation of several multicriteria techniques, among which the Analytic Hierarchy Process (AHP) represents one of the most widely applied. By combining qualitative and quantitative analysis [21, 22], the AHP is a multicriteria technique used by researchers and decision-makers in many fields to select the best alternative, guide resource allocation decisions, and optimize decision-making processes [23–25]. The versatility of the technique allows it to be applied to different topics, and there is a growing body of literature on using AHP to evaluate decarbonization processes in economic systems [21, 26, 27].

In this study, the logic of pairwise comparison was employed and applied to the dataset extracted from the CRREM toolkit. In particular, the initial database is formed by 310 data points on GHG emissions expressed in kgCO2e/m$^2$/year for each of the 30 Nations. The operational logic of the pairwise comparison has permitted the evaluation of the 10 classes of real estate use within each nation.

The objective of this initial operation was to identify which class of real estate use was more responsible in terms of GHG emissions within each nation. This process has also allowed for the development of a hierarchization of the classes of real estate use, enabling the creation of a ranking of the sectors from the most to the least energy-efficient.

The initial phase of the research involved the pairwise comparison of the different sectors of real estate use. This was followed by a further phase of aggregation of the data, which enabled the researchers to obtain an overall indicator of the energy performance of each nation. The ultimate objective of this research was to construct $I_{BDP}$, a descriptive index of the performance of the 30 European nations in terms of GHG emissions.

The operational methodology that has led to the construction of the $I_{BDP}$ consists of 3 steps, as described below.

## 3 Operational Methodology and Results

### 3.1 Pairwise Comparison

The first phase of the methodology involved the construction of pairwise comparison matrices. The operational logic of the pairwise comparison is to compare the GHG emissions of each of the 10 real estate use classes within the same nation. As described

above, CRREM provides an indication of GHG emissions for each real estate use sector for each year from 2020 to 2050. Therefore, the dataset considered contains 31 data (one for each year) for each of the use sectors. To compare the sectors, 31 matrices (one for each year from 2020 to 2050) of order 10 × 10 (since 10 are the classes of use to be compared) were constructed for each of the 30 European countries included in the CRREM. This operation resulted in the construction of a total of 930 comparison matrices.

Figure 1 below shows a randomly selected example of a constructed comparison matrix. Specifically, the matrix below in Fig. 1 contains data (GHG emissions) extracted from the CRREM related to Belgium for the year 2020 for all 10 sectors of real estate use. The logic used to construct the matrix is the same as that used for all the other Nations.

| 2020 Belgium | Office | Retail, High Street | Retail, Shopping Centre | Retail, Warehouse | Industrial, Distribution Warehouse Cooled | Industrial, Distribution Warehouse | Hotel | Healthcare | Lodging, Leisure & Recreation | Residential Multi-Family |
|---|---|---|---|---|---|---|---|---|---|---|
| Office | 1 | 0,807554835 | 0,965025874 | 1,183854261 | 1,345678676 | 3,523231442 | 0,954653394 | 0,755344068 | 0,756300058 | 1,191205851 |
| Retail, High Street | 1,238306003 | 1 | 1,194997332 | 1,465973838 | 1,666361982 | 4,362838644 | 1,182153029 | 0,935347094 | 0,936530902 | 1,475077356 |
| Retail, Shopping Centre | 1,036241646 | 0,836821952 | 1 | 1,226759088 | 1,394448286 | 3,65091915 | 0,989251605 | 0,782718981 | 0,783709617 | 1,234377113 |
| Retail, Warehouse | 0,844698569 | 0,682140414 | 0,815155974 | 1 | 1,136692852 | 2,976068557 | 0,806394356 | 0,638038053 | 0,638845577 | 1,006209878 |
| Industrial, Distribution Warehouse Cooled | 0,743119452 | 0,600109707 | 0,717129498 | 0,87974513 | 1 | 2,618181818 | 0,709421507 | 0,56131087 | 0,562021285 | 0,88520824 |
| Industrial, Distribution Warehouse | 0,283830346 | 0,229208568 | 0,273903628 | 0,336013765 | 0,381944444 | 1 | 0,270959603 | 0,214389568 | 0,214660907 | 0,338100369 |
| Hotel | 1,047500597 | 0,845914172 | 1,010865178 | 1,240088044 | 1,409599216 | 3,690587037 | 1 | 0,791223362 | 0,792224762 | 1,24778884 |
| Healthcare | 1,323899984 | 1,069121834 | 1,277597739 | 1,567304637 | 1,781543978 | 4,664406051 | 1,263865614 | 1 | 1,001265635 | 1,577037408 |
| Lodging, Leisure & Recreation | 1,322226528 | 1,067770426 | 1,27598281 | 1,565323509 | 1,779292043 | 4,658510077 | 1,262268043 | 0,998735965 | 1 | 1,575043977 |
| Residential Multi-Family | 0,839485467 | 0,677930548 | 0,810125196 | 0,993828447 | 1,129677691 | 2,957701591 | 0,80141765 | 0,634100367 | 0,634902907 | 1 |

**Fig. 1.** Pairwise comparison matrix of real estate sectors for the year 2020 for the country Belgium

The ratio of GHG emissions of the two sectors being compared is displayed in each cell of the pair comparison matrix (see Fig. 1). The values obtained within each row have been added together, resulting in the generation of 10 scores (one for each row) associated with the sectors of real estate use (see Table 1). These scores are intended to describe the energy performance in terms of GHG of the real estate class for the specific year considered in the matrix.

The illustrative example provided concerning the processing of data for the year 2020 in Belgium offers a preliminary insight. In Belgium in 2020, the sector with the greatest responsibility for GHG emissions is Healthcare. Conversely, the most efficient sector is Industrial distribution warehouses.

### 3.2 Identifying the Real Estate Sector Class Most Responsible for GHG Emissions for Each Nation

The second step aims to understand, for each of the 30 countries, which real estate sector class is most responsible for GHG emissions. This was done by adding together

**Table 1.** Index Belgium, describing GHG emissions performance by real estate class sector.

| Belgium (2020) | |
|---|---|
| Real Estate sector classes | Score of the sector |
| Industrial distribution warehouse | 3,543011 |
| Industrial distribution warehouse cooled | 9,276247 |
| Residential multi-family | 10,479169 |
| Retail warehouse | 10,544244 |
| Office | 12,482848 |
| Retail shopping center | 12,935247 |
| Hotel | 13,075791 |
| Retail high street | 15,457586 |
| Lodging, leisure & recreation | 16,505153 |
| Healthcare | 16,526042 |

the 31 scores (relative to the year) for each country for the same real estate category, as determined in the previous phase.

For example, considering the *Office* sector for Belgium, after obtaining the score of the office sector for each year from 2020 to 2050, these 31 values have been added. By repeating the same operation for each of the 10 real estate sector classes, it has been possible to obtain the first partial index for each country. This partial index makes it possible to understand which sector requires greater commitment in terms of policies to be implemented to achieve the net zero emissions target. At this stage, the scores of the property sector classes have been normalized. This means that the values have been normalized to values between 0 and 1, making them easier to interpret. The higher scores on the index correspond to higher GHG emissions from the property sector and therefore poorer performance on a decarbonisation pathway. The sectors with lower scores are better performing and therefore closer to the net zero target.

Taking Belgium as an example, Table 2 shows the calculated values in ascending order for each of the real estate sectors included in the analysis. It can be seen that for Belgium, the sector most responsible for GHG emissions is the *healthcare* sector. In contrast, the sector closest to the decarbonization target is the *industrial distribution warehouse*.

The second step of the methodology showed that the *healthcare* sector has the highest GHG emissions for 46% of the countries[10]. However, for 93.5% of the nations, i.e., almost the entire sample, *industrial distribution warehouse* is the most efficient sector.

[10] Latvia, Belgium, Lithuania, Croatia, Estonia, Romania, Slovakia, Slovenia, Spain, Hungary, Ireland, Switzerland, Italy and the United Kingdom.

**Table 2.** Index Belgium, describing GHG emissions performance by real estate class sector.

| Belgium | |
|---|---|
| Real Estate sector classes | Score of the sector |
| Industrial distribution warehouse | 0.0320 |
| Industrial distribution warehouse cooled | 0.063 |
| Residential multi-family | 0.072 |
| Retail warehouse | 0.090 |
| Office | 0.106 |
| Hotel | 0.111 |
| Retail shopping center | 0.113 |
| Retail high street | 0.133 |
| Lodging, leisure & recreation | 0.137 |
| Healthcare | 0.139 |

### 3.3 Construction of the $I_{BDP}$

The aim of the third step of the proposed methodology is to develop the $I_{BDP}$. The second step has led to the construction of a national scale index consisting of 10 values, each corresponding to a real estate class sector. In the third step, the 10 scores of each real estate use class have been added together for each nation. This operation carried out similarly for each of the 30 nations in the sample, has led to the construction of an overall index consisting of 30 values, each describing the energy performance of the buildings in each nation. As in the previous phase, the index values have been normalized after summation to obtain values between 0 and 1. Similar to the second phase, lower $I_{BDP}$ scores indicate that a country is closer to its 2050 decarbonization targets; conversely, higher scores indicate that countries need to adopt more stringent and urgent policies to meet the Paris Agreement targets. Table 3 shows the $I_{BDP}$ scores calculated for the 30 countries considered, in ascending order.

The $I_{BDP}$ has been then georeferenced to allow a geographical comparison of the results obtained (see Fig. 2).

Based on the $I_{BDP}$, it can be seen that Denmark has the best energy performance, with a lower GHG emission rate, and therefore is more in line with the targets defined in the Paris Agreement. In contrast, Cyprus, Malta, Sweden, and Spain have the highest GHG emissions. Therefore, in the context of the decarbonization path, which is mandatory at the global level, it is highlighted that it is necessary to apply more stringent policies to achieve the net zero emissions target in these countries.

**Table 3.** $I_{BDP}$ calculated for 30 European nations

| Nations | $I_{BDP}$ |
|---|---|
| Denmark | 0.031007 |
| Slovenia | 0.032291 |
| Latvia | 0.032356 |
| Lithuania | 0.032374 |
| Estonia | 0.032382 |
| Ireland | 0.032561 |
| Slovakia | 0.032587 |
| Poland | 0.032679 |
| Hungary | 0.032704 |
| Belgium | 0.032790 |
| Romania | 0.032800 |
| Luxembourg | 0.032815 |
| Norway | 0.032855 |
| Bulgaria | 0.032902 |
| Germany | 0.032953 |
| Austria | 0.032026 |
| Croatia | 0.032986 |
| Finland | 0.033039 |
| Switzerland | 0,033103 |
| Netherlands | 0.033655 |
| United Kingdom | 0.033715 |
| Czech Republic | 0.034008 |
| Portugal | 0.034181 |
| Greece | 0.034190 |
| France | 0.034348 |
| Italy | 0.034689 |
| Spain | 0.035229 |
| Sweden | 0.035238 |
| Malta | 0.035720 |
| Cyprus | 0.035815 |

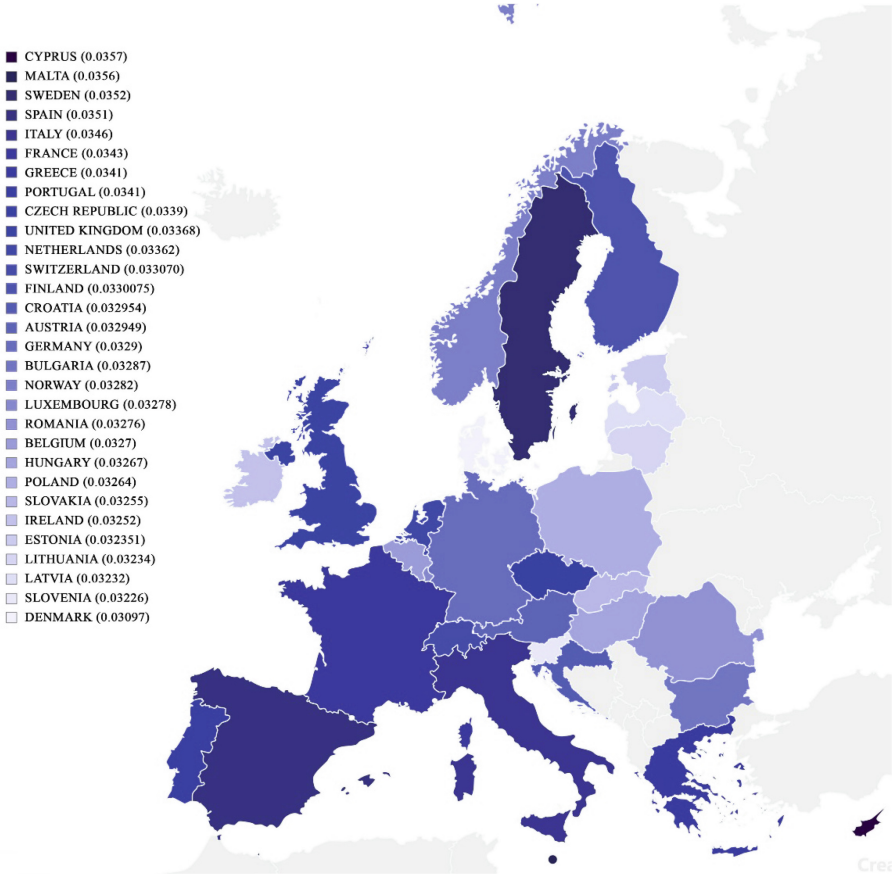


**Fig. 2.** Georeferenced $I_{BDP}$ representing the building energy performance of 30 European countries.

## 4 GHG Emission Driver

The $I_{BDP}$ aims to provide a qualitative framework that outlines European nations that deserve greater attention based on their performance in terms of GHG emissions associated with the building stock. However, this process assesses the location of emissions, and further consideration needs to be given to the processes and factors that determine a country's greater or lesser adherence to the required decarbonization pathway [28].

For instance, a nation's geographical location and level of urbanization influence its energy needs for heating, cooling, and lighting [29]. In 2019, an analysis of GHG emissions in 28 EU countries revealed that the energy sector is responsible for 77.1% of GHG emissions, making it the primary driver of this environmental problem [30]. Consequently, international policies have introduced more stringent measures to facilitate the transition to renewable energy sources. This is because countries that rely heavily on fossil fuels, such as coal, oil, and natural gas, tend to have higher GHG emission rates.

Similarly, it is necessary to consider emissions associated with industrial production. Industrial activities represent a significant contributor to global greenhouse gas emissions, largely due to the dependence on energy-intensive energy sources, the mismanagement of industrial waste, and the use of chemicals. Government policies, incentives, and cooperation between the public and private sectors play a pivotal role in the promotion of more sustainable industrial processes. Nevertheless, if industrial production were to be regarded as the primary contributor to GHG emissions in isolation, a false assumption might be made, that countries where industry plays a dominant role are the furthest from the net zero emissions goal. In this context, it is important to consider the role of consumption in addition to industrial activity. Countries with a larger population and less independence in terms of industrial production tend to have higher rates of consumption and imports, which have related consequences for the environment [31]. A comprehensive analysis of the factors believed to be responsible for greenhouse gas emissions would enable the assessment of all the parameters and aspects that need to be improved in order to ensure sustainable development.

### 4.1 Etiological Analysis

It is crucial to analyze the factors that may contribute to an increase in greenhouse gas emissions at the national level to identify those aspects that require attention and to determine the appropriate course of action.

In this context, an etiological analysis was developed in the present research to explore the correlation between socioeconomic variables selected by the authors GHG emissions of the analyzed nations. In particular, data from the main public statistics portals was extracted and subjected to correlation analysis to ascertain the relationship between the aggregated data and the $I_{BDP}$ index.

The selection of indicators for correlation analysis with $I_{BDP}$ was based on general data. For instance, academic literature indicates that countries with a higher level of industrialization and greater productivity tend to have a higher rate of pollution associated with GHG emissions. In order to investigate this issue further, it was deemed appropriate to investigate the possible relationship between developed $I_{BDP}$ and GDP associated with the nations under study. Similarly, an investigation into the correlation between the rate of renewable energy sources utilized within a nation and its $I_{BDP}$ is being conducted to elucidate to what extent the utilization of alternative energy sources constitutes a strategic solution to the global warming phenomenon. The correlation analysis between the structured IBDP and general aggregate indicators of this type represents the foundation for future developments in this research. The identification of macro-themes at the national level that are associated with a nation's GHG emissions allows for the development of a framework. Specifically, the future developments of the research will entail a deeper and more specific analysis of the indicators obtained in the first phase, to create a dataset of potential problems and issues that policy-makers should consider because of decarbonization pathways.

Specifically, the etiological analysis conducted considered 8 socio-economic variables to analyze their correlation with the $I_{BDP}$:

1. *Population*; Data have been extracted from the Eurostat database[11] [32]. Specifically, for 29 of the Nations analyzed, the latest available number of population for 2021 has been used. It should be noted that it has not been possible to correlate this variable with $I_{BDP}$ index for the United Kingdom.
2. *Share of imports (%) of mineral fuels, lubricants, and related materials*. Data have been extracted from the Eurostat database. Specifically, for 27 of the Nations analyzed, the latest available percentage share data for 2022 have been used. It has not been possible to correlate this information with the $I_{BDP}$ index for Norway, Switzerland, and the United Kingdom.
3. *Share of exports (%) of mineral fuels, lubricants, and related materials*. Data have been extracted from the Eurostat database. Specifically, for 27 of the Nations analyzed, the latest available percentage share data for 2022 were used. It has not been possible to correlate this information with the $I_{BDP}$ index for Norway, Switzerland, and the United Kingdom.
4. *GDP*. Data have been extracted from the Trading Economics[12] [33] database. Specifically, for all 30 Nations analyzed, the latest available data on GDP expressed in USD, for 2022 have been used.
5. *Deaths*. Data have been extracted from the Eurostat database. Specifically, for 25 of the Nations analyzed, the latest available number of deaths data for 2021 has been used. It has not been possible to correlate this information with the $I_{BDP}$ index for Cyprus, Italy, Luxembourg, Slovenia, and the United Kingdom.
6. *Population density*. Data have been extracted from the Eurostat database. Specifically, for 29 of the Nations analyzed, the latest available data on population density expressed in person/$km^2$ for 2022 have been used. It has not been possible to correlate this information with the $I_{BDP}$ index for the United Kingdom.
7. *Soil sealing*. Data have been extracted from the Eurostat database. Specifically, for 29 of the Nations analyzed, the latest available data on $km^2$ of land sealed with impermeable materials due to urban development and construction for 2018 has been used. It has not been possible to correlate this information with the $I_{BDP}$ index for the United Kingdom.
8. *Renewable energy*. Data have been extracted from the Eurostat database. Specifically, for 28 of the Nations analyzed, the latest available data on the share of renewable energy consumption in gross final energy consumption for 2022 have been used. It has not been possible to correlate this information with the $I_{BDP}$ index for the United Kingdom and Switzerland.

All numerical data of the variables were normalized to eliminate the unit of measurement and to obtain values between 0 and 1, which could be easily compared with the $I_{BDP}$. A correlation analysis was conducted between the identified variables and the $I_{BDP}$, employing scatter plots and subsequently constructing a correlation matrix.

[11] Eurostat is the statistical office of the European Union.

[12] Trading Economics provides its users with accurate information for 196 countries, including historical data and forecasts for more than 20 million economic indicators, exchange rates, stock market indexes, government bond yields and commodity prices.

Figure 3[13] illustrates one of the eight scatter diagrams produced as an illustrative example of the analysis performed. The diagrams produced enabled an initial series of reflections to be formulated, which were then expanded upon with the results derived from the correlation matrix.

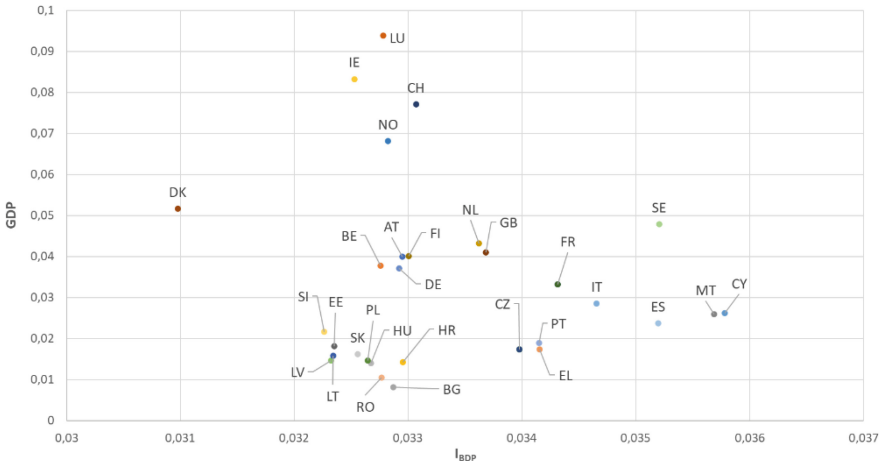


**Fig. 3.** Scatter plots for analysis of the correlation between $I_{BDP}$ and GDP

Correlation analysis allows to assess the strength and direction of the relationship between two quantitative variables, i.e., the extent to which variations in one variable are associated with variations in another variable.

The scatterplot is a useful tool for correlation analysis because it provides an initial view of the possible relationship between two variables and helps to identify the possible presence of outliers that may alter the correlation coefficient. Several conclusions can be drawn from the analysis of the generated scatterplots.

There is no strong correlation between $I_{BDP}$ and the selected demographic and socio-economic variables, but there is clustering around $I_{BDP}$ values between 0.032 and 0.034.

In addition, in some cases outliers appear in the graph: i) Germany for the correlation between $I_{BDP}$ and population; ii) Germany for the correlation between $I_{BDP}$ and deaths; iii) Netherlands for the correlation between $I_{BDP}$ and fossil fuel export rate; iv) Malta for the correlation between $I_{BDP}$ and population density.

From the scatterplots, the correlation matrix allows the relationship between $I_{BDP}$ and the selected variables to be made explicit. The correlation analysis shows a moderate positive correlation between GHG emissions and population density, i.e., more densely populated countries have higher GHG emissions. All other selected socio-economic and

[13] Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Cyprus (CY), Czech Republic (CZ), Denmark(DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Ireland (IE), Italy(IT), Latvia(LV), Lithuania (LT), Luxembourg (LU), Malta(MT), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania(RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), United Kingdom (GB).

demographic variables show a weak positive correlation ($I_{BDP}$-population; $I_{BDP}$-fuels import; $I_{BDP}$-fuels export; $I_{BDP}$-decreases; $I_{BDP}$-sealing).

Two variables are an exception: GDP and renewable energy, where the correlation is weak but negative. It is clear, therefore, that lower GHG emissions are associated with countries that make greater use of renewable energy sources, and this is reflected in the analyses carried out by the European Union, for which the energy sector is one of the main contributors to GHG emissions. For this reason, the energy renovation of the European building stock is one of the main tasks of sustainability policies implemented by governments.

However, the correlation matrix has shown a weak negative correlation between GDP and $I_{BDP}$. Gross domestic product measures the aggregate level of production of a state, i.e. all final goods and services produced by a state in a given year. The correlation analysis shows that countries with lower GDP have higher GHG emissions. This result highlights that countries with a lower level of economic prosperity have the most difficulty in implementing the decarbonization pathway and require greater effort.

## 5 Conclusions and Future Insights

Anthropogenic activities are the main source of GHG emissions, which are the main cause of climate change. The effects of climate change are now visible worldwide through phenomena such as desertification, melting glaciers, uncontrolled fires, and loss of biodiversity. In this context, policies have been developed at the global level to encourage and commit all nations to sustainable development by implementing measures to mitigate and adapt to climate change. The European Union has been one of the main proponents, adopting urgent legislation forcing member states to embark on decarbonization pathways, especially for those sectors deemed most responsible for GHG emissions. The EU is aiming for complete decarbonization by 2050 to meet the target set by the United Nations in the Paris Agreement. This research aims to analyze the contribution of the EU building stock in this context. Buildings, which are energy intensive and have a long life cycle, are responsible for a high proportion of GHG emissions and increasingly stringent policies need to be implemented to encourage their energy renovation. The EU-funded CRREM project analyses the decarbonization pathway that 10 classes of the building sector in 30 European countries need to implement to meet international zero net emissions targets.

This paper has developed the $I_{BDP}$, an index based on data provided by CRREM. The index has been developed using the logic of multicriteria techniques, to understand which of the 30 countries included in the CRREM analysis are furthest away from the decarbonization targets to be achieved. The result has shown that Denmark is the most efficient nation, in contrast to Cyprus, Malta, Sweden, Spain, and Italy, which are furthest away from their decarbonization targets. This analysis, based on the developed index, serves as a starting point for governments to signal and highlight which countries need more urgent legislation to meet the targets set by the Paris Agreement.

Another important issue to investigate is related to the factors that affect GHG emissions in a country. A first approach to this analysis has been developed in this study by considering some aggregate indicators at the national level, reflecting the socio-economic

and demographic factors of the nation. In order to understand the possible correlation between these variables and the developed index, scatter plots and a correlation matrix have been developed. The analysis has shown that there is a weak positive correlation with population density and a weak negative correlation with GDP. This result points out that more attention should be paid to countries with lower levels of economic prosperity, as it is precisely these countries that need to make greater efforts and investments in sustainable development.

This research is a starting point for the extension of the analysis to other variables to analyze their possible correlation with GHG emissions. Another aspect to highlight is the scatter plots obtained. The presence of densities corresponding to concentrated values in the index (0.032–0.034) requires further investigation using a cluster analysis of the countries for which the same range of values is recorded.

## References


1. The Intergovernmental Panel on Climate Change (IPCC) homepage. https://www.ipcc.ch/srccl/. Accessed 15 Feb 2024
2. Malhi, Y., et al.: Climate change and ecosystems: threats, opportunities and solutions. Philos. Trans. R. Soc. B **375**(1794) (2020)
3. Eskander, S.M., Fankhauser, S.: Reduction in greenhouse gas emissions from national climate legislation. Nat. Clim. Chang. **10**(8), 750–756 (2020)
4. Sica, F., Tajani, F., Sáez-Pérez, M.P., Marín-Nicolás, J.: Taxonomy and Indicators for ESG Investments. Sustainability **15**(22), 15979 (2023)
5. De Paola, P., Tajani, F., Locurcio, M., Di Liddo, F.: Sustainable real estate and resilient cities: management. Assess. Innov. Sustain. **14**(15), 8984 (2022)
6. United Nation, Sustainable Development Goals (SDGs) homepage. https://unric.org/it/agenda-2030/. Accessed 10 Feb 2024
7. United Nations Climate Change homepage. https://unfccc.int/. Accessed 03 Feb 2024
8. Fetting, C: The European green deal. ESDN report, 53 (2020)
9. Basbagill, J., Flager, F., Lepech, M., Fischer, M.: Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build. Environ. **60**, 81–92 (2013)
10. European Enviroment Agency homepage. https://www.eea.europa.eu/en. Accessed 27 Jan 2024
11. UN environment programme homepage. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction. Accessed 28 Feb 2024
12. Röck, M., et al.: Embodied GHG emissions of buildings–the hidden challenge for effective climate change mitigation. Appl. Energy **258**, 114107 (2020)
13. Sáez-Pérez, M.P., García Ruiz, L.M., Tajani, F.: Assessment of the thermal properties of buildings in Eastern Almería (Spain) during the summer in a Mediterranean climate. Sustainability **16**(2), 746 (2024)
14. Hirsch, J., Spanner, M., Bienert, S.: The carbon risk real estate monitor—developing a framework for science-based decarbonizing and reducing stranding risks within the commercial real estate sector. J. Sustain. Real Estate **11**(1), 174–190 (2019)
15. GRESB homepage. https://www.gresb.com/nl-en/about-us/. Accessed 20 Jan 2024
16. Guide to LEED certification homepage. https://www.usgbc.org/guide-LEED-certification. Accessed 20 Feb 2024
17. BREEAM homepage. https://bregroup.com/products/breeam/. Accessed 12 Feb 20245

18. About CREEM homepage. https://www.crrem.eu/about-crrem/. Accessed 27 Feb 2024
19. Cahen-Fourot, L., Campiglio, E., Godin, A., Kemp-Benedict, E., Trsek, S.: Capital stranding cascades: the impact of decarbonisation on productive asset utilisation. Energy Econ. **103**, 105581 (2021)
20. Spanner, M.M., Wein, J.: Carbon risk real estate monitor: making decarbonisation in the real estate sector measurable. J. Euro. Real Estate Res. **13**(3), 277–299 (2020)
21. You, Y., Yi, L.: Energy industry Carbon neutrality transition path: corpus-based AHP-DEMATEL system modelling. Energy Rep. **8**, 25–39 (2022)
22. Locurcio, M., Tajani, F., Morano, P., Anelli, D., Manganelli, B.: Credit risk management of property investments through multi-criteria indicators. Risks **9**(6), 106 (2021)
23. Vaidya, O.S., Kumar, S.: Analytic hierarchy process: an overview of applications. Eur. J. Oper. Res. **169**(1), 1–29 (2006)
24. Guarini, M.R., D'Addabbo, N., Morano, P., Tajani, F.: Multi-criteria analysis in compound decision processes: the AHP and the architectural competition for the chamber of deputies in Rome (Italy). Buildings **7**(2), 38 (2017)
25. Tajani, F., Anelli, D., Di Liddo, F., Morano, P.: An innovative methodology for the assessment of the social discount rate: an application to the European states for ensuring the goals of equitable growth. Smart Sustain. Built Environ. (2023)
26. Hottenroth, H., et al.: Beyond climate change. multi-attribute decision making for a sustainability assessment of energy system transformation pathways. Renew. Sustain. Energy Rev. **156**, 111996 (2022)
27. Papapostolou, A., Karakosta, C., Kourti, K.A., Doukas, H., Psarras, J.: Supporting Europe's energy policy towards a decarbonised energy system: a comparative assessment. Sustainability **11**(15), 4010 (2019)
28. Bastianoni, S., Pulselli, F.M., Tiezzi, E.: The problem of assigning responsibility for greenhouse gas emissions. Ecol. Econ. **49**(3), 253–257 (2004)
29. Dodman, D.: Forces driving urban greenhouse gas emissions. Curr. Opinion Environ. Sustain. **3**(3), 121–125 (2011)
30. European Parliament: EU greenhouse gas emissions by country and sector: Infographic (2018)
31. Satterthwaite, D.: The implications of population growth and urbanization for climate change. Environ. Urban. **21**(2), 545–567 (2009)
32. Eurostat homepage. https://ec.europa.eu/eurostat/web/main/home. Accessed 1 Mar 2024
33. Trading Economics homepage. https://tradingeconomics.com/. Accessed 04 Mar 2024