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Embodied energy for sustainability in construction and other production sectors. The EmCoin experience

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Abstract. In order to achieve the sustainability objectives of the UN Agenda 2030 and the climate neutrality objectives of the European Union 2050, in recent years in the building sector, design and construction efforts have been mainly aimed at containing consumption for heating and cooling and reducing dependence on fossil gases. In particular, the construction sector has paid increasing attention to the performance of the building envelope, both opaque and transparent, in search of solutions that allow the building to achieve high energy performance while consuming as little energy as possible during its useful life. However, the energy actually used in building processes and in all industrial processes includes a non-negligible share of "hidden" energy, the so-called grey or embodied energy, which corresponds to the overall quantity of non-renewable primary energy necessary for all the processes involved: from the extraction of the raw material to the production and processing processes up to disposal, including that necessary for transport and secondary processes. This paper aims to highlight the importance of calculating embodied energy for the purposes of a correct eco-balance and the overall sustainability of the building and reports on a recent research experience aimed at creating an application useful for this purpose, which can also be exported to the building sector.

Keywords: Embodied energy, Building Sector, Sustainability, Digital App.

1 Introduction

When the issue of sustainability was brougth to the attention of designers and various operators in the construction market, design and construction efforts primarily focused on reducing energy consumption for heating and cooling, as well as decreasing dependence on fossil fuels. The solutions to these problems have been mainly oriented towards improving the energy performance of the building envelope, to reduce consumption during operation as much as possible. The objectives of the UN 2030 Agenda for Sustainable Development, the Paris Climate Agreements, and the European Union's sustainability goals for 2050, along with the need

to drastically reduce dependence on oil and other climate-altering gases at the European and national levels (also in relation to the geopolitical tensions that in recent years have made the energy market more susceptible to speculative actions), are driving the construction sector to innovate products and processes. National and international regulations have particularly focused attention on improving the energy performance of buildings.

In recent decades, the 27 countries of the European Union have reduced net greenhouse gas (GHG) emissions by almost one third as shown by sectorial progress towards 2030 of the emissions trends in Fig. 1.

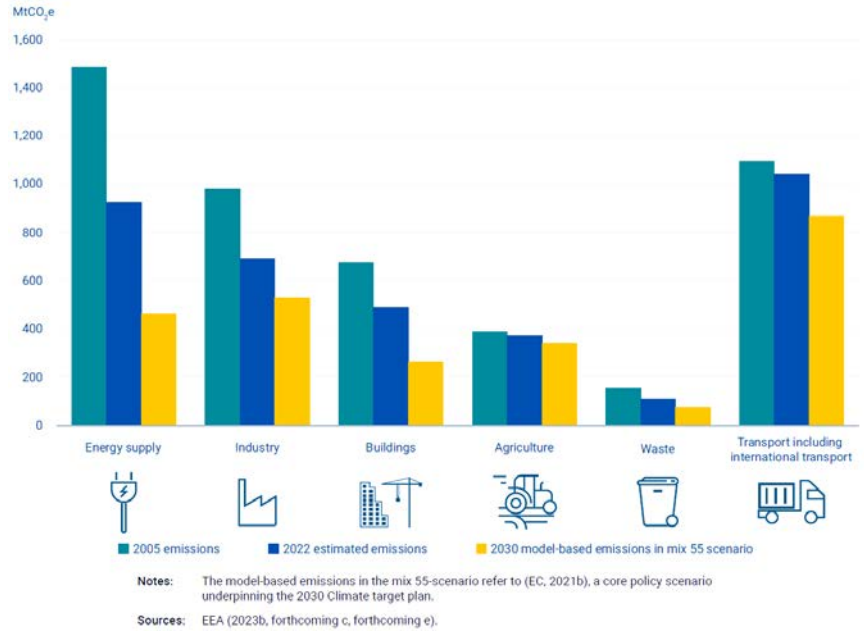


Fig. 1. Trends Emissions EU Countries, sectorial progress towards 2030, by EEA Report 07/2023

In 2021, net GHG emissions (including the contribution of airlines) decreased by 30% compared to 1990 levels, with renewable energy sources contributing substantially (21.8%) to the energy mix. The EU's commitment to energy efficiency has led to a reduction in energy consumption since 2005, both for primary energy (-12%) and final energy (-7%) [1].

To achieve the energy and climate goals set for 2030, and to reach climate neutrality no later than 2050, an acceleration of efforts across all dimensions is necessary. Despite some hesitations, especially between 2022 and 2024 saw the establishment of a solid energy and climate regulatory framework for the 2030 target of a net reduction of at least 55% in GHG emissions compared to 1990. These are ambitious goals, as the absolute net reduction rate of GHG emissions must more

than double compared to the 2005-2022 period, and regarding final energy consumption and the share of renewable energy, annual efforts must at least triple compared to the 2005-2022 period. The contribution of the building sector has been 14% of the total direct GHG emissions of the EU in 2021 (EEA data 2023, see reference 1). Since 2005, emissions from the building sector have recorded an average decrease of 1.4%, thanks to improved energy performance of buildings on one hand and reduced energy demand for heating due to milder winter temperatures on the other [2].

However, these benefits have been partially offset by an increase in energy consumption by households and other factors that practice and literature have partially overlooked, which will be discussed in the next paragraph. In any case, the reduction of consumption and the production of energy from renewable sources in the building sector are important measures for achieving the goals of the European Union's energy and environmental policies.

2 The issue of embodied energy

Among the factors that are often overlooked in current practices related to energy saving, the issue of grey or embodied energy should be highlighted. The term “embodied energy” was introduced in the scientific literature by researcher Robert Costanza in 1980 and corresponds to the energy consumed directly or indirectly by products, processes and services [3]. Embodied energy allows us to understand not only the energy consumption of a specific phase of the product or process but also the energy consumption of the entire life cycle [4].

Remaining within the construction sector, the energy consumed by a building during its life (or life cycle) concerns that used during the operating phase (heating, cooling, lighting, etc.) and that exploited during the construction, maintenance and demolition phases, i.e. the embodied energy. The use phase generally represents the largest share of the energy consumption related to the life cycle of the building [5]. For this reason, the mitigation of environmental impacts caused by the construction sector and the reduction of the sector's energy needs have primarily focused on reducing energy consumption during the use phase. Today's low-energy houses generally consume no more than 40 MJ m^2/year of energy reference surface. The grey energy used for the same new buildings, in the form of construction materials and technology, usually amounts to between 80 and 100 MJ m^2/year of surface, calculated over the duration of use [6]. Over the years, the established standards have become increasingly stricter until the concept of n-ZEB or “Net Zero Energy Building” was introduced [7]. A n-ZEB is characterized by high thermal performance capable of producing energy from on-site renewable sources to independently meet its energy needs. However, achieving such high performance in energy savings during the use or operation phase of a building involves production and construction phases with high energy demands. Consequently, the evaluation of the energy-environmental performance of buildings through energy balances that encompass all phases of the building's life cycle becomes increasingly important, rather than being

limited to just the use phase (see the standard UNI EN 15978: 2011). In fact, if creating a highly energy-efficient envelope during the building's operation phase requires a very high energy expenditure (accompanied by equally high greenhouse gas emissions), the final balance between energy consumed during the construction phase and primary energy consumption during the building's useful life may not be accurate and could be much less favourable than it appears.

2.1 The calculation of embodied energy

One of the problems in calculating embodied energy is that the methodologies used (which, in general terms, refer to the sum of all direct and indirect energy consumption associated with the life cycle of a product or service) can vary significantly, depending on the approach adopted to calculate the overall energy balance of the good/service examined. The results obtained in this way are difficult to compare. A scheme of the most used calculation methods is shown in Fig.2.

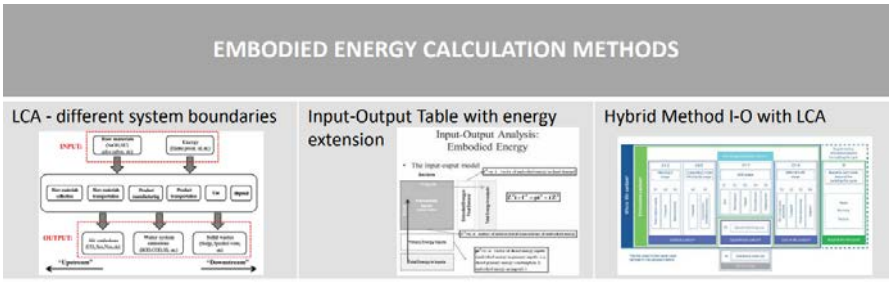


Fig. 2. Embodied energy calculation methods, authors' elaboration

If an LCA analysis methodology is adopted, there may be significant differences in terms of results depending on the scope of the system boundaries analyzed. In fact, very different results may be obtained with a "From cradle to gate" approach, which includes primary energy for the extraction phase of raw materials, for their processing and assembly into finished products, or vice versa "from cradle to grave", which also includes - in the construction sector - transport to the construction site and the end-of-life phase of the building, i.e. the deconstruction or demolition of the building and the treatment and disposal of waste. Even more different results can be obtained if a "From cradle to cradle" approach is adopted, which expands the overall energy balance of primary energy consumption to include the energy required for the conversion in the end-of-life phase of components/materials into new raw materials of the same quality or lower quality [8]. The input-output method in the context of embodied energy, defined as "Input-Output with energy extension", is based on the use of input-output tables and data regarding the energy consumption of various production processes and final consumers of a specific economic system and allows for the examination of the interrelationships between the economy and

energy through the processing of multiple data [9]. By combining energy consumption values per unit of output from various economic sectors with intermediate and final consumption of goods and services (derived from input-output tables), it is possible to estimate the energy requirements, both direct and indirect, of end users. A third calculation method is based on an Input-Output/LCA combination.

This method utilizes process data when available and data from input-output tables to evaluate the entire supply chain of a product. In the case of the building system, for example, LCA is used to quantify the energy consumption of the processes that make up the main production chain, while input-output tables are used to quantify the energy consumption of other areas of the building system involved in a high number of production chains.

2.2 The Sustainability of buildings and embodied energy

Regardless of the analysis method used to calculate the embodied energy in products/processes, and the differences in the results obtainable by expanding the boundaries of the analysed system, it seems appropriate, in any case, to have a truthful and comprehensive energy balance of the building system by extending the computation of primary energy consumption not only to the use life phase of the construction but also to other phases of the life cycle of the building product.

In this regard, the results of a study by Enea-University of Palermo are particularly interesting, which, through LCA analysis of the "from cradle to grave" type, examines 9 different case studies based on construction technique, intended use, climate and geographical incidence, and type of intervention (retrofit and new design) as see in Fig.3 [10].

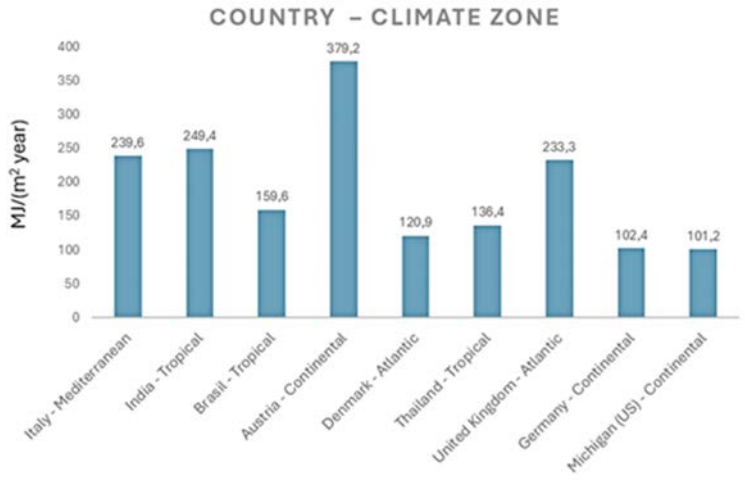


Fig. 3. Comparison of embodied energy in different building case studies, source from Cellura M.& al. 2015, Enea Report; authors' elaboration

The analysis shows that the phase of production of building materials and components has a variable contribution of embodied energy between 40.1% and 90.3%; the construction phase between 3.2% and 12.1%; the end of life between 2.2% and 8.3%

Therefore, the phase of production of building materials and components constitutes a significant energy contribution in the overall energy balance of the construction process. Furthermore, it is interesting to observe that, in one analyzed case of retrofitting a small residential building (reinforced concrete structure and brick envelope, Mediterranean climate), at the conclusion of the intervention aimed at reducing energy consumption during the use phase and utilizing renewable energy sources to meet energy demand, there is an increase of 25% in the embodied energy of the building despite a reduction in energy consumption during the use phase. Further investigations conducted in recent decades tend to confirm the trend highlighted by these case studies, namely that buildings designed for high energy performance generally have higher embodied energy values than traditional ones. In particular, energy consumption during the use phase is lower for low-energy buildings, but they have a higher embodied energy value [11]. Despite the variables arising from heterogeneous elements such as the calculation methods used, it seems evident that, for a correct assessment of the total energy cost of a building, it is necessary to extend the energy analysis to the entire life cycle of the building, including the contribution of embodied energy. It follows that to declare a building sustainable, it is evidently not sufficient for the energy consumption during its use phase to meet the highest performance requirements set by current regulations. A building can only be truly declared sustainable if, throughout its life, it is able to return to the environment the energy that was necessary to produce it, plus an additional portion that will be needed for its decommissioning or reuse [12].

3 European Directives and Ecodesign tools

From what has been said above, it seems evident that calculating the embodied energy in products and processes can play a strategic role in concretely achieving the sustainability goals of the UN Agenda for Sustainable Development 2030 and the European Union 2050. The professional, in our case an engineer or architect, in addition to correctly using regulatory tools and the standards of environmental certification protocols, will increasingly need to take into due account the value of the embodied energy in products and processes related to the construction phase. Accurately assessing the embodied energy in building materials and generally in the transformative processes of products available on the market is, however, not simple. Alongside the issues arising from the different methods of calculating embodied energy, which have been briefly mentioned, one must consider the differences in results due to the varying scope of the applied analysis, and above all, the difficulty of obtaining reliable and comparable emergy values for similar products and materials. Recently, in the European context, new regulations related to the ecodesign of

industrial production have been developed in relation to environmental sustainability goals [13].

The regulation introduces a "digital product passport" (DPP), a sort of digital identity card for products, aimed at providing information on the life cycle of each product, including technical performance, materials and their origins, reparability, recyclability, essentially the environmental impacts of the entire life cycle. The consumer or end user will be able to access this information by scanning the barcode or a QR Code present on the products, using a regular smartphone [14]. The implementation working plan of the regulation foresees that by the first half of 2025, the Commission will determine which products the DPP should be prioritized for in the coming years. Following this, the development of product standards will be initiated based on an inclusive planning process, with detailed impact assessments and regular consultations with stakeholders, within a dedicated Ecodesign Forum. It seems likely that the first products to be affected by the DPP may pertain to widely consumed sectors, such as the textile and clothing, where environmental damage from fast fashion is extremely significant.

The field of construction has very different characteristics; however, it is a sector with a high environmental impact, given the extensive use of raw materials and energy.

It would therefore be desirable a tool similar to the DPP to be introduced in the construction sector, to be made available to professionals and operators, capable of easily providing the main information on the life cycle of products and building materials. On the emissions side, internationally, tools for accounting for embodied carbon in buildings and construction materials have been developed. A free tool was launched by the environmental consultancy agency Circular Ecology in 2020 in the UK, aimed at calculating and comparing the embodied emissions in different concrete mixes [15]. This is a spreadsheet where various materials and quantities expected to be used for a construction can be entered. In the United States, the "Embodied Carbon in Construction Calculator" (abbreviated as EC3) has also been developed, thanks to Skanska USA and the Carbon Leadership Forum at Washington State University, as well as representatives from the construction industry, and funded by Skanska and Microsoft [16]. The aim is to facilitate and disseminate calculations related to the actual greenhouse gas emissions of buildings, as it could even become secondary how efficiently buildings are managed or improved over time if emissions produced upstream of the construction process are not significantly reduced.

In 2018, an open-source platform was launched to maximize the impact of this tool. The database contains over 16,000 materials, and during the pilot phase of the EC3 tool, development projects achieved embodied carbon reductions of up to 30%, simply by accessing detailed technical information and without significant financial impacts; in fact, in most cases, they are cost-neutral [17].

4 The EmCoin Project and its exportability

While there are already tools available to facilitate the quantification of GHG emissions related to the construction sector, there are currently no equally effective tools for the embodied energy in buildings and construction materials. Since environmental sustainability cannot be separated from reducing the consumption of physical resources used (raw materials, land, air, water, energy), we believe that reducing the energy present in all products and services on the market is a fundamental condition for all sustainability goals, including climate change. Moreover, reducing energy consumption is essential for the transition of the global production system to renewable energies, which currently cannot yet guarantee the same performance as the fossil fuel-based system.

From these considerations, the experimentation of the EmCoin project (Embodied Energy as a Coin) was born, as a result of a partnership between the Politecnico di Torino and the Resconda and Sequs Associations, initiated thanks to the 8x1000 funds from the Waldensian Church. The underlying logic of the project is that every product or service exchanged has an environmental cost, as resources are used for its creation, distribution and consumption. The main objective of the EmCoin project is therefore to highlight the cumulatively accumulated energy (Cumulated Energy Demand),"hidden" in the products available on the market, in order to provide the end user with a new awareness of the impact of their purchasing and consumption choices [18]. The CED can be calculated starting from the embodied energy, which measures the energy impact of the product in question by analysing all the phases included in the process, according to an LCA approach “from cradle to grave”.

In concrete terms, the EmCoin project aims to create a widely usable tool based on a digital app that allows the user, through the reading of the barcode present on products, to know their embodied energy, distinguishing between fossil and renewable energy. The project is being carried out in three main phases as shown in the Fig. 4.



Fig. 4 Main phases of Emcoin project, authors' elaboration

During the first phase (completed), the project focused on creating a first prototype of a system for accounting for the CED of products on a limited sample of common products available on the market.

The second phase (launched, thanks to a contribution by the European initiative SEFIT) includes the implementation of an information system (App + online plat-

form) through which consumers will be able to understand the impact of their purchasing choices for products/services and relate it to their sustainable energy "budget." In this second phase (currently underway), once the tool has been developed beyond the beta version, it will be possible to calibrate it with greater precision and specialization for different types of products.

The third phase includes testing and validation of the system as well as expansion to other product categories such as capital goods and construction materials, mainly using data made available by companies' EPDs (Environmental Product Declarations). The main difficulties encountered in fine-tuning the CED accounting system for the creation of the first prototype concern, first and foremost, the data, which are difficult to obtain and to finalize in order to define a standard model of individual consumption based on energy. As a preliminary hypothesis, different spending categories were analysed, hypothesizing a direct and significant correlation between the driver of economic spending and that of energy consumption. The categories were identified using the 12 indicated in the ISTAT 2022 data basket: food products, transportation, education, healthcare, clothing, etc [19].

Once identified the 12 macro categories, those to be considered for the analysis (complete or partial) for this phase of the project were identified. This decision was made based on the following parameters: the relative percentage weight of the category, the plausible level of correlation between monetary expenditure (as per the ISTAT Basket) and energy cost (CED), the availability and ease of obtaining data related to the CED, and the correspondence of the category with the frequency of purchase, favouring frequently purchased goods and services over durable goods whose purchases occur at wider intervals (such as furniture, appliances, etc.). Therefore, the first sample chosen to test was the group of most used products, namely food products. The first result of the research work was the structuring of the database with the different categories of goods that will subsequently need to be implemented to arrive at the construction of the final application (App). Below are the levels considered for each of the twelve macro categories of the EmCoin database: Group (X.X); Class (X.X.X); Subclass (X.X.X.X); Segment (X.X.X.X.X); Aggregate and/or product (X.X.X.X.X.X). A unique progressive numerical code was assigned to each level, allowing the reconstruction of the previous divisions from which it derives, thus creating a tree diagram for each level. The sources used for the research of CED values were primarily Ecoinvent and Agribalyse [20] [21]. It was decided to refer to these two different databases because Agribalyse is more comprehensive and suitable for researching CED values for the macro-categories included in the group of food products. In fact, in addition to the greater variety of products considered by Agribalyse, it includes life cycle analyses of many products in the "food" area (specific transformation processes, packaging, retail phase of products) that are not considered in Ecoinvent. The Ecoinvent database can be accessed through specific LCA analysis software, the most famous of which is SIMA PRO. In the context of the EmCoin project, the Open LCA software, which is freely accessible, was used. In Ecoinvent, CED values are expressed in Joules per unit of measurement, which varies depending on the specific product/service, although in most cases the adopted unit of measurement is weight (expressed in grams). In the

database, these values have been converted to kWh/EmCoin unit and will need to be verified in light of the specificities of the products available in the reference market. The EmCoin project, after completing this first phase of data analysis and defining the structure of the database that underpins the development of the App tool, requires revisions, in-depth studies, and implementations validated by numerous tests.

5 Conclusions

The experience of the EmCoin project, still in development and implementation, despite the difficulties in validating and implementing the data of the various tested products, has already demonstrated its feasibility and its potential for exportability to other sectors, in our opinion. The development of the tool (app), to be made available in its final version to users via a simple smartphone, requires further investments in time and resources for subsequent in-depth analyses of the results, verification of their consistency with the objectives and identification of the causes of any discrepancies. Another significant element will be the verification and deepening of the data collected with companies. The subsequent phases of the project aim to refine and define the missing data, particularly regarding new categories of products and services that the ISTAT basket does not always manage to represent. Only at a later stage, and after an adequate number of tests, will it be possible to consider the possibility of extending this experience to other commodity sectors, such as materials and processes in the construction industry. A tool of this type could be very useful upstream, in the design phase where it is possible to intervene effectively to reduce and optimize the grey energy of the process.

We believe that precisely in the name of the necessity for concrete results in the challenge of sustainability, which concerns both our present and even more our future, it is essential to make it clear that without an effective reduction in energy consumption in every sector and production area, sustainability goals will remain unattainable. Easy-to-read and easy-to-use tools can be strategic allies in making the hidden energy components of industrial processes visible (and therefore modifiable) to a wide audience of even non-specialist users.

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