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Co-benefits of Plus Energy Buildings: more than just energy efficiency to advocate for tomorrow's building technology

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Contents

1 Introduction

Abstract

According to the International Energy Agency (IEA), buildings and building sector are responsible for over one-third of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions.

Guided by greater awareness and new policies, the European construction sector has entered a period of transition that will lead it towards greater energy efficiency with a consequent reduction in consumption and emissions.

This is also one of the goals of Cultural-E, an EU-funded project, which aims to define modular and replicable solutions for Plus Energy Buildings (PEBs). These buildings are the next step after the n-NZEBs (near and Net Zero Energy Buildings). Starting from climate and cultural differences analysis, the project aims to develop technologies and solution sets that are tailorable to specific contexts and energy demands. PEBs are equipped with cutting edge technologies, which cost is not only justifiable by the energy saving. Other benefits, and related monetary values, can be find in their implementation. After a careful research of the available literature, it will be addressed the definition of "co-benefit”, identifying and describing them in the context of Plus Energy Buildings. This is the first step to set a reproducible methodology suitable for co-benefits quantification, in order to give a more accurate estimation of the true potential of this type of buildings and related technologies.

The importance that the quality of the indoor environment (thermal, visual, acoustic and air quality) has for users will also be addressed, particularly during this period of global pandemic due to the SARS-CoV-2 virus.

The reduction of energy consumption and carbon emissions in the building sector is an important target for actions meant to mitigate the climate changes. Nevertheless, this cannot be done at the expenses of healthy and comfortable indoor conditions.

1. Introduction

1.1 Buildings Sector and Environmental Impact

According to the United Nations' projections, the current (2020) world population of 7.8 billion is expected to reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100 [1].

This will lead to an inevitable rise in energy usage, which will increase by nearly 50% by 2050, driven primarily by economic and population growth in Asia [2].

Unfortunately, coal, gas and oil are still covering the greatest share of the world's energy production. In 2019, in a developed country like the U.S, about 63% of the electricity generation was from fossil fuels: coal, natural gas, petroleum, and other gases. About 20% was from nuclear energy, and only 18% was from renewable energy sources [3].

For most countries in the world, the amount of clean energy is even smaller. Therefore, there is the need to employ renewables as the primary source of energy. This transition to a carbon-free economy is necessary in order to reach the environmental goals established by the Intergovernmental Panel on Climate Change (IPCC) to have a world that is habitable for everyone.

Talking about carbon dioxide emissions, they are usually related to the transport sector, intensive livestock farming or industry. However, another big player is often neglected: the building sector. In fact, the combined building and construction sectors are responsible for more than a third of the energy consumed globally and for almost 40% of direct and indirect CO_2 emissions [4]. An IPCC (Intergovernmental Panel on Climate Change) study showed that in 2010 buildings accounted for 32% of total global energy end-use (24 % for residential and 8 % for commercial), or 32.4 PWh, being one of the largest end-use sectors in the world.

Consumptions are even higher in Europe: residential buildings alone are responsible for around 40% of energy consumption and 36% of CO_2eq emissions [5].

A growth in the awareness that it is necessary to act to contain and solve the problem of climate change has led to a joint effort by different countries in the world and to the subsequent issue of various international agreements. The most renowned is probably the one that in 1997 led more than 180 countries to sign the Kyoto Protocol. According to this agreement, industrialized countries and economies in transition committed to limit and reduce greenhouse gases (GHG) emissions accordingly to set individual targets [6].

Another important step in fighting climate change was taken on December 2015. In this occasion, the IPCC had the role of leading the COP21 held in Paris, with the aim to disseminate scientific evidence. The resulting Paris Agreement, signed in 2016 by 195 countries, marked a turning point in the way Climate Change would have been addressed. In fact, for the first time, each country agreed to cooperate, "pushing" in the same direction and, therefore, issuing regulations to reduce its own emissions. Other factors were pivotal for the decision, in particular the decreasing prices of clean energy, the increasing costs connected to climate extreme events, but also the increasing demand for action driven by the community.

On 8 October 2018, the IPCC published the Special Report on Global Warming of 1.5°C (SR15). The report dealt with global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

The report illustrates that the Earth's global temperature has already risen by about 1°C (range between 0.8 and 1.2 °C) compared to pre-industrial levels and that, at the current rate, global warming is expected to reach an increase of 1.5°C in the period between 2030 and 2052.

It is important to remember that the global climate crisis will not be triggered when the 1.5°C threshold is reached but that it is already happening. The Arctic ice is melting, sea level is rising causing floods in hundreds of coastal cities, catastrophic events like hurricanes and typhoons are more violent and frequent, acidification of the ocean is causing the bleaching of the coral reefs with consequent loss of biodiversity and much more. Reaching 1.5°C will only amplify the effects that the temperature has on our planet. All these consequences are closely related to each other and are strongly intertwined with the increase in the concentration of greenhouse gases in the Earth's atmosphere. The largest emitters of CO_2 are currently China, followed by USA, EU, India, and Russia. However, looking at GHG emissions per capita, it is no longer Chinese people who are leading the ranking, but the Americans, followed by the

Russians, Japanese, Europeans, and Chinese, just as a reminder that a data must always be carefully analysed and interpreted.

Regarding buildings, Working Group 3 of the IPCC, in its Fifth Assessment Report (AR5) of 2014, dedicated a whole chapter to this sector, putting pressure on the necessity of making changes about policies regarding retrofits for existing buildings, along with higher environmental standards for new constructions.

Buildings' emissions can be distinguished between direct and indirect. Indirect emissions are the majority, and they are mainly caused from electricity generated off-site. Direct emissions, instead, come primarily from on-site combustion fossil fuels for heating, hot water, and cooking, and from leaks of compounds used in refrigeration and air conditioning [7].

The following graphic shows the building sector energy-related CO_2 emissions in gigatons (Gt) in the Sustainable Development Scenario (according to the IEA definition), 2000-2030. In light blue the direct emissions, in dark blue the indirect emissions (including indirect emissions from consumption of electricity and commercial heat in buildings).

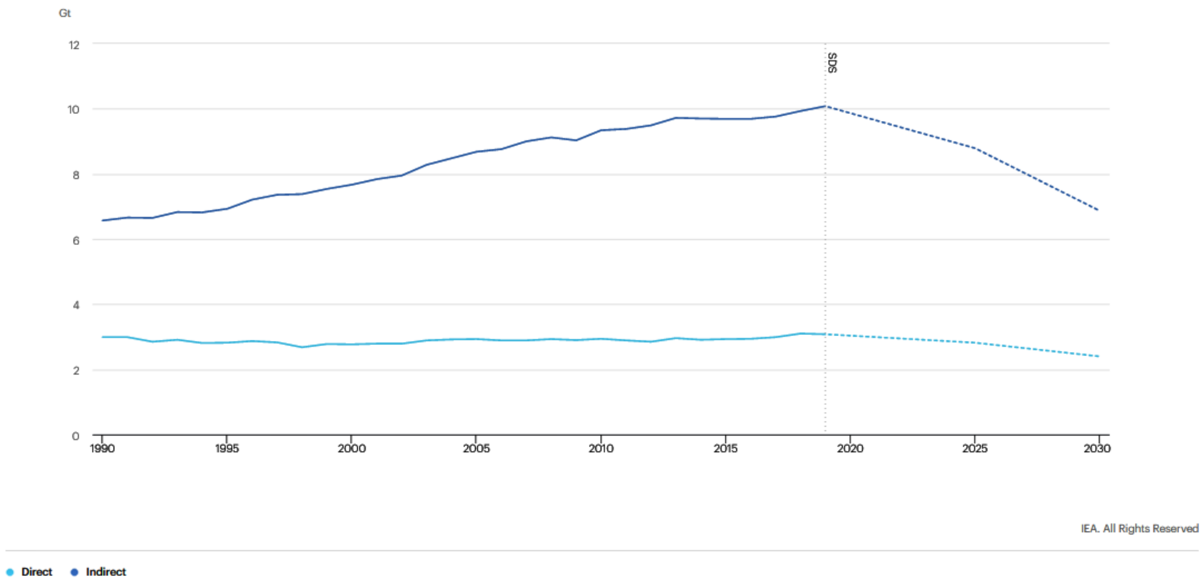

Fig. 1 Buildings sector energy-related CO2 emissions in the Sustainable Development Scenario, 2000-2030 [4].

Speaking of buildings, many factors need to be considered in order to understand the source of emissions. For example, altitude, latitude, and regional climate of the area where the building is located, influence the rate of heating/cooling as well as the energy consumption, but also cultural and behavioural aspects of a given population are worth of consideration.

Globally, the final energy consumption by end-use in 2010 shows that about one third of the total energy consumption in both, residential and commercial buildings, comes from space heating [8].
In residential buildings another big share comes from cooking. To tackle the problem successfully, it is necessary to understand how to minimize every single consumption, both in terms of implementation of new policies and technological innovation. It is also important to train the consumer on the importance of certain behaviours to create a more effective user-building interaction.

1.2 nZEBs & PEBs

A Nearly Zero -Energy Buildings (nZEB) is a very high energy performance building where the little energy required should be provided primarily by renewable sources, including sources produced on-site or in proximity [9]. Not to be confused with the NZEB, which stands for Net Zero-Energy Buildings. As the name suggests, this is a type of building with remarkable energy performance, which takes the small portion of energy it requires mostly from renewable sources. In other words, the performance of an NZEB achieves a zero-energy balance between consumption and onsite production within one calendar year. This means that in a year, the autonomous production of energy by the building from renewable sources (mainly photovoltaic and wind) must be equal, or almost equal, to its consumption.

The member states of the European Union have recognized the potential of this type of buildings and the importance of shifting the paradigm in the construction sector, considering the advantages that such action would bring, in the future years, to the European economy and even more to development at the local level. Increased investments will help create jobs, fight energy-poverty, improve health, increase comfort, and fight against climate change. Since 2002, the Energy Performance of Buildings Directive (EPBD) [9] has been the EU's key legislation in the perspective of reducing energy consumption in buildings, although it has undergone many revisions since the first issue.

Along to the Energy Performance of Buildings Directive 2010/31/EU (EPBD) there is also the Energy Efficiency Directive 2012/27/EU. Together, they aim to decarbonise the building stock by 2050 achieving high energy efficiency. Other objectives are to create a stable environment for investment decisions and to educate consumers and businesses to make more informed choices to save energy and money.

In 2016, the European Commission proposed updating the requirements for energy performance of buildings. In this direction, they launched a public consultation involving organizations, companies, citizens, and public authorities so as to gather recommendations. The main requests included better access to finance for renovations, higher standards for new buildings, smarter technologies, a greater share of renewable energy sources, maintaining the same or higher indoor comfort levels for occupants while consuming less energy and having lower energy bills. The new directives were built around these demands, resulting in more energy efficient, smarter, healthier, and greener buildings.

The new amendment, released in 2018 [10], introduced new elements, sending a further strong political signal about the EU's commitment to evolve the construction sector in the light of technological improvements and to encourage renovation campaigns of the existing building stock.

nZEBs are explicitly mentioned in the directive [10] as a solution to achieve the final goal:

“To achieve a highly energy efficient and decarbonised building stock and to ensure that the long-term renovation strategies deliver the necessary progress towards the transformation of existing buildings into nearly zero-energy buildings, in particular by an increase in deep renovations, Member States should provide clear guidelines and outline measurable, targeted actions as well as promote equal access to financing, including for the worst performing segments of the national building stock, for energy-poor consumers, for social housing and for households subject to split-incentive dilemmas, while taking into consideration affordability...”

In particular, the Art. 9 of directive states that Member State shall ensure that from 2018 all new public buildings must be nZEBs and that all new residential buildings must be nZEBs by the end of 2020.

According to the Energy Performance of Buildings Directive, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient. At the same time, only 0.4-1.2% (depending on the country) of the building stock is renovated each year. This is a key point in the direction of a proper and comprehensive legislation, which shall include and highlight, besides new buildings, the need for existing buildings to be improved and retrofitted so as to cope with the new set energy performance goals.

It is also agreed that each Member State should develop national plans to increase the number of these buildings, requirement that has led to a delay in achieving the prescribed targets. Especially in Southern Europe, many Countries are poorly prepared for the implementation of nZEBs and especially for what concerns the challenging retrofit of existing buildings [11].

nZEBs have all the potential to bring this positive change to the old European building system, but research in the building sector has already moved the interest to the so-called Plus Energy Buildings (PEBs), which constitute the innovative and performative future to which governments and citizens must aspire to reach the sustainability goals.

The Plus Energy House concept is probably older than people would expect. Architect Rold Disch, in 1994, was the visionary creator and designer of the first buildings with a positive energy balance. Since even passive houses and nZEBs still emit CO_2 into the atmosphere, Disch's goal was to create a building that would use energy exclusively from renewable sources, with zero emissions and a positive energy footprint. The very first example was the Heliotrope building in Freiburg, a rotating solar house capable to generate five times the energy it consumes (fig. 2).

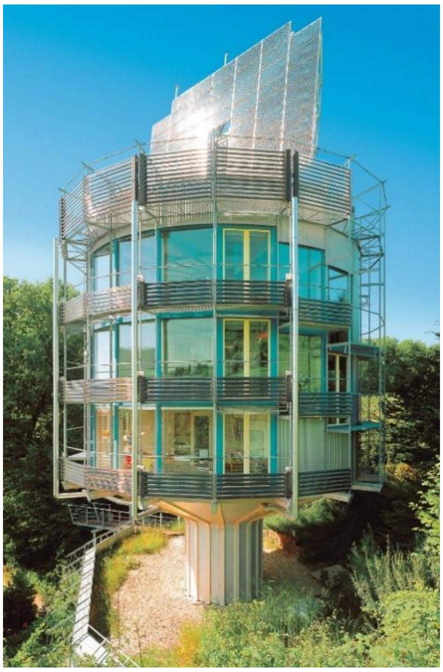

Fig. 2 The Heliotrope in Freiburg – The First Plusenergy House Wolrdwide (http://www.rolfdisch.de/en/architects-office/)

From the Heliotrope model, the concept of PEBs has evolved toward less "extreme" but conceptually similar grid-connected buildings, capable of producing more energy in a calendar year than they need for their normal operation. Thanks to the connection to the neighbourhood grid, the surplus of energy produced with renewables can be sold to the grid, making each individual building a small power plant producing clean energy. Its application on a larger scale, involving entire neighbourhoods, could be even more advantageous, leading to a completely different concept of housing.

It is critical that the smart grid concept spreads with the right timing if the transition to this type of building is to be implemented smoothly. The electric grid we use every day is based on a model conceived more than 100 years ago. The amount and quality of energy consumers need has increased over time, which is why the way that energy is distributed is changing with it. The old model involves a one-way movement of energy flow, from producer to consumer. The smart grid, on the other hand, introduces a two-way dialogue, where electricity and information can be exchanged between the utility and its customers. This allows not only for the integration of newer technologies such as wind and solar energy production and plug-in electric vehicle charging, but also for smart management of electricity needs, avoiding peaks and distributing it more efficiently. Since renewables are not programmable, managing distributed power generation systems also requires "intelligence" that manifests itself in the management of the overall power system so that it can locally manage any surplus energy by redistributing it to nearby areas, preventing or minimizing a potential outage. The network operator who uses smart solutions for his network can therefore manage in a smarter way the electricity available, knowing in detail and in real time the consumption of the various users. This has a significant advantage: if in a certain area there is a potential energy overload, this energy can be redistributed by the network manager in other areas according to the actual electricity demand, thus avoiding possible supply interruptions (blackouts) or other types of inefficiency [12]. With this system users are also more aware of their own consumptions and the use they make of electricity.

The building, as for the nZEBs, allows to minimize both primary energy consumption and greenhouse gases emissions, guaranteeing high levels of living comfort, accounting for economic and financial optimization.

Although energy efficient, a standard building gets its energy from the power grid. Even assuming this energy is produced from renewable sources, the fact remains that this energy is produced decentrally, often fluctuates over time, and is difficult to store. However, because the buildings are fixed to their location, they can exploit the renewable energy available on site and use it directly, effectively becoming small power plants.

The clean energy is generated “in-site” from renewable energy sources in so called micro-generation processes that usually use wind and solar radiation for the purpose but can also rely on water or geothermal energy depending on the possibilities and location.

Along with the production of energy, also storage technologies have become more and more accessible during the recent years. In fact, the price of photovoltaic cells has progressively dropped while their efficiency has risen. Now it is the right time for batteries to do the same, and although the technology is not yet perfect, it is certainly promising, especially looking at the new energy tariffs which are meant to encourage more and more the self-consumption.

1.3 CULTURAL-E

Cultural-E (https://www.cultural-e.eu/) develops and tests technologies to build Plus Energy Buildings that host more families.

The project aims to define modular and replicable solutions for Plus Energy Houses (PEHs) that take into account the climatic and cultural differences that may be present in a territory rich in ethnic groups, customs and climate zones such as Europe. Creating these tailor-made solutions will be the strong point of the project that, being able to adapt to specific contexts, will increase the overall energy efficiency, optimizing the cost/value ratio of PEHs.

It is a project that has received funding from the Horizon 2020 of the European Union, a funding program created by the European Commission to support and promote research in the EU area.

Ca' Foscari is one of the partner universities of the project and deals with the influence of the cultural aspect in energy consumption, the differences in the perception of comfort and temperature control between different countries, and the definition of technological packages that ensure an effective decarbonisation of energy demand.

An accurate mapping of European climates, building archetypes, and cultural energy habits is the basis for the success of the whole project.

The choice of the various types of climates is based on the Köppen-Geiger subdivision. This is in fact one of the most widely used climate classification systems. The system is based on the concept that indigenous vegetation is the best expression of climate. Thus, the boundaries of climate zone were chosen with vegetation distribution in mind. It combines annual and monthly average temperatures, precipitation, and precipitation seasonality. With this type of classification, the majority of European climate can be divided in four main climatic areas (fig. 3):

- Oceanic climate, which corresponds to Cfb, Cfc, Cwb, Cwc in the Köppen classification;
- Mediterranean climate, which corresponds to Csa, Csb in the Köppen classification;

- Continental climate, which corresponds to Dfa, Dwa, Dfb, Dwb, Dsa, Dsb in the Köppen classification;
- Sub-arctic climate, which corresponds to Dsc, Dsd, Dwc, Dwd, Dfc, Dfd in the Köppen classification.

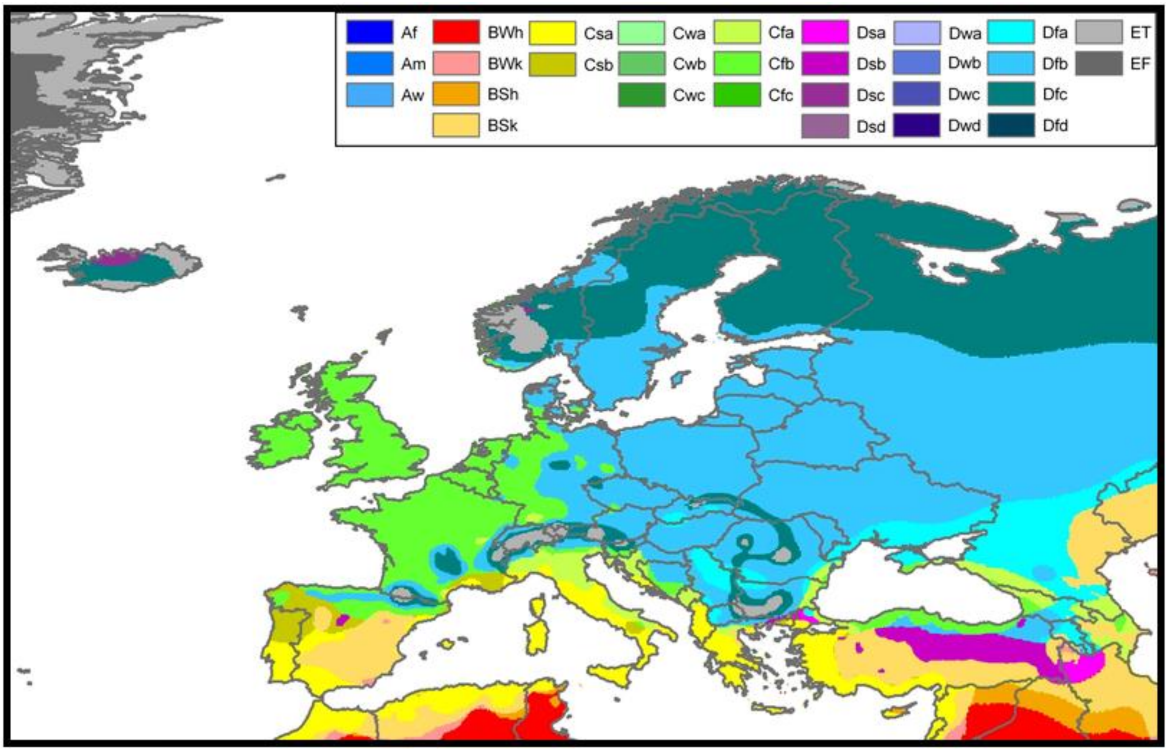

Fig. 3 Köppen-Geiger climate classification

The four climate zones identified are the basis for mapping the cultural aspects related to them in order to divide the European territory into 8 climate-cultural clusters.

The experimentation will take place during the project over 5 years thanks to the construction of four apartment complexes in:

- Bologna area (IT), for the Mediterranean area;
- Lille area (FR), for the Oceanic area;
- Eislingen/Fils (Stuttgart – DE), for the Continental area;
- Oslo (NO), for the Sub-Arctic area.

Two of these complexes will be destined to for social housing and two will be on the market.

Cultural-E is innovative for the large number of conditions considered (climate, cultural, social aspects) and in particular for research in an area previously little explored, namely that of multi-family houses. Plus Energy Houses already exist but usually they are isolated realities, difficult to reproduce. It is precisely on the reproducibility and on making this technology available to multiple households that Cultural-E wants to make a difference.

To do so, an integrated climate and cultural approach is fundamental. It must include overall configuration, selection of the most appropriate technologies for each socio-cultural context, and user/systems interaction. The solution-sets will be comprehensive and easily replicable, thanks to reliable methods and practical guidelines.

In order to reach its main objective, there are many aspects that are needed to be considered.

There is enough evidence to say that current design practice for energy efficient housing does not reflect cultural and climate needs. Cultural-E aims precisely at defining the differences that are present in Europe in order to make the building more suited to its climatic and cultural context. This allows to have an even greater impact on its energy efficiency. A building designed to be in Sweden, for example, will have different requirements than the same type of building in South Italy. This applies not only to the obvious climatic differences (sub-arctic against Mediterranean climate in the Köppen-Geiger classification) but also to cultural aspects such as time and resources spent in different areas of the house. For example, an Italian, compared to a Swedish, will tend to spend many more hours in the kitchen, but in the room designated as a study/office, the situation will be reversed as smart working is more common in Nordic countries.

Being aware of these peculiarities is key to being able to propose tailored solutions for energy positive homes and in this way also lower their price.

Not less important, users are considered as an integral part of the technology, as the latter alone is not sufficient. Studying their needs, behaviour, and strategies to actively involve them is essential to design buildings that can really achieve the goal of producing more energy than they consume. Since “buildings don’t use energy, but people do”, understand better the user’s role in the built environment is crucial in order to have the full vision on the energy efficiency issue, since having a performing building might not be enough to meet energy reduction goals [13].

Cultural-E aims also to create a built space that is regenerative for the indoor and outdoor environment in the life cycle. The concept of regenerative design consists of a design that tends to a harmonious fusion between anthropized space and natural context. It is not just a matter of 'taking' from nature, as happens in most cases, but of 'giving', of restoring it. This approach focuses on salutogenesis (this term was coined by Aaron Antonovsky in 1979 in his book Health, Stress and Coping and basically means "generation of health") and on projects that are attentive to social and cultural justice and ecologically robust [14].

The project also addresses the electro-mobility factor dedicating a system designed to avoid peak loads at the building level due to charging of multiple vehicles. It is based on a multiple charging cars optimizer strategy, with a technology that will be directly integrated to the grid in order to manage the data coming from it. This is another step further to the future, which aims to predict the trend of mobility in the years ahead, tackling and solving problems before they occur.

Climate-resiliency is another of the objectives of Cultural-E. Despite the inevitability of climate change, the goal is to ensure results in terms of reduced CO_2 emissions, positive energy balance and improved living conditions and comfort levels. This is possible thanks to the application of climate-resilient technologies that can allow stability of the performance over time.

NZEBs are now widely proven, while PEBs are still considered pioneering projects. The attention and complexity that their design and construction require, inevitably raises the price. Cultural-E, however, aims to make the extra costs, compared to an nZEB, repayable in 8 years. This is possible thanks both to the higher level of efficiency and to the role that can have a correct economic evaluation of the co-benefits that derive from constructions of this type. The project has a dedicated work package to this issue.

2. The concept of co-benefits

Among the various tasks of the Cultural-E project, the research team of the University of Venice, Ca' Foscari, leads Working Package 5, focusing on the potential co-benefits of Plus Energy Houses. The goal of this WP is to identify and evaluate co-benefits for the households and for the community. In order to do so, there is the need to define what a co-benefit really is so that we can select the co-benefits that best fit the PEBs and combine them with their respective technologies. This initial definition and identification phase is the basis for then being able to give an economic evaluation to these co-benefits and estimate when or not they contribute to justify the extra cost of this type of building.

Regarding the term co-benefits, so far, a unified common definition is still uncertain. In fact, the term is used differently depending on the subject or the perspective and depending on the study.

A literature research of the various definitions of the concept of 'co-benefits' has been conducted and it is presented in Table A, with the aim of tracking the evolution of the term and of assessing the different uses of the terminology.

The term co-benefits was coined in 2001 by the IPCC in the Third Assessment Report (TAR). The concept is therefore initially used in the context of climate change ad was described as: "The benefits of policies that are implemented for various reasons at the same time – including climate change mitigation – acknowledging that most policies designed to address greenhouse gas mitigation also have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity)" [15]. In the same statement, the concept of 'co-impact' is introduced, which is used as a more generic synonym to cover not only the positive, but also the negative aspects of co-benefits. 'Ancillary benefit' is another term introduced, and it defines: "side effects of policies aimed exclusively at climate change mitigation. Such policies have an impact not only on greenhouse gas emissions, but also on resource use efficiency, like reduction in emissions of local and regional air pollutants associated with fossil fuel use, and on issues such as transportation, agriculture, land-use practices, employment, and fuel security" [15]. Again, as done for co-benefits with co-impacts, the term 'ancillary impacts' is introduced to include possible negative consequences of these side effects.

Until 2007 no further definitions have been found, and in the Fourth Assessment Report (AR4) by IPCC, the definition of co-benefit does not change conceptually but only minimally in its description: “The benefits of policies implemented for various reasons at the same time, acknowledging that most policies designed to address greenhouse gas mitigation have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity)” [16]. Also the distinctions made with co-impacts, ancillary benefits and ancillary impacts remain practically unchanged.

In the following years, the concept begins to expand into new areas, not just climate change.

In 2012, the International Energy Agency (IEA), choose the term ‘Multiple Benefits’ to describe the necessity “to capture the multiplicity of benefits from energy efficiency improvements” [17]. They explain that the term has been chosen because it “evokes the varied and numerous outcomes that can be derived from energy efficiency” and because it has been used before by the US Environmental Protection Agency (EPA). In their approach, the concept includes the terms co-benefits, non-energy benefits, and ancillary benefits.

In a paper by Jiang et al. [18], "Analysing co-benefits of the energy conservation and carbon reduction in China's large commercial buildings", which was published in 2013, it is reiterated that the term has not yet received particular attention with regard to the construction sector and that consequently there are no definitions of it in this area of interest.

In 2014 the Fifth Assessment Report (AR5) of the IPCC was issued, bringing some novelties in the definition of co-benefits. No more distinction is made between co-benefits and ancillary benefits, which were now defined as: “The positive effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on, among others, local circumstances, and implementation practices" [19].

In the same year, IEA continues to call them multiple benefits justifying the choice: "Ancillary benefits/co-benefits have been traditionally used to describe the impacts of energy efficiency beyond reductions in energy demand – i.e. the benefits that occur in addition to a single prioritised policy goal. While these terms have been used interchangeably with multiple benefits in other literature, this publication opts to use multiple benefits in order to avoid a pre-emptive prioritisation of various benefits; different benefits will be of interest to different stakeholders" [20]. In saying this, they acknowledged the fact that some problem with terminology exists but made a stand so as not to contradict choices made in the past.

The first comprehensive definition of co-benefits found in the construction sector dates back to 2017. Annex-56, a project that aims at developing a new methodology for cost effective renovation of existing buildings, proposes its own definition of co-benefits, as related to energy renewal: "The effects (either positive or negative) beyond the energy savings and the reduction of carbon emissions that may arise from high efficiency energy buildings and from an energy-related building renovation" [21].

In 2018, Deng et al. made a systematic literature review where they classified by type, mitigation sector, and geography the co-benefits. They identified eight sectors: AFOLU (Agriculture, Forestry and Other Land Use) sector, electricity sector, transport sector, residential sector, governmental sector, industrial sector, marine sector, and buildings sector. It has been found that the co-benefits of mitigation in the buildings sector is the subject with the smallest percentage of publications (1.4%) (fig. 4). Another evidence to the fact that the term is still little used, particularly in this field. The following figure visualizes part of their research results [22].

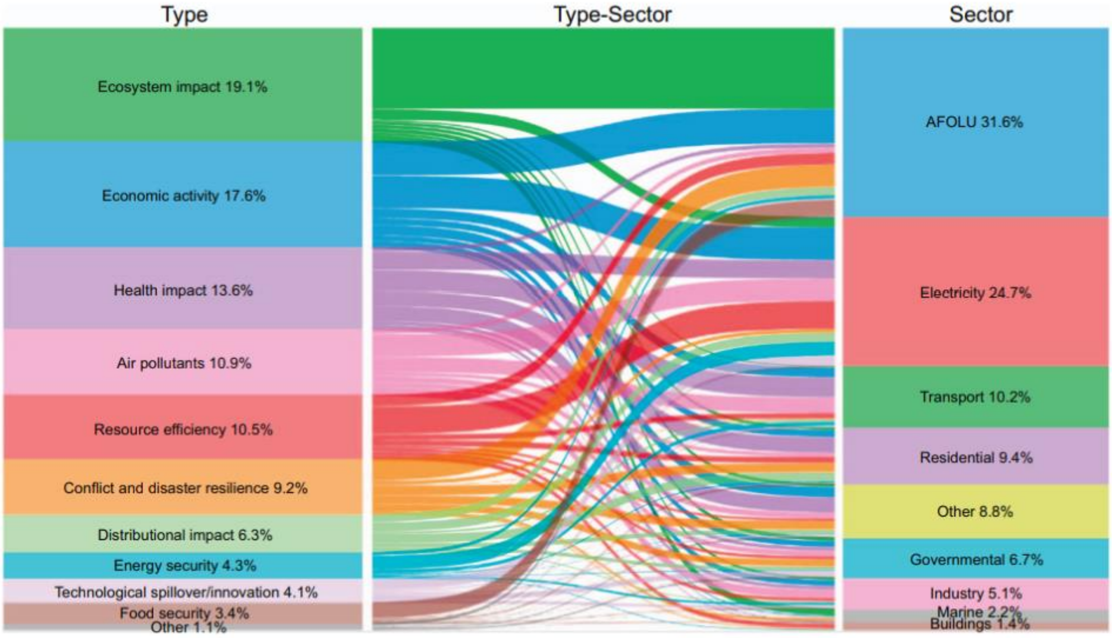

Fig. 4 Co-benefit types in different mitigation sectors. The width of the lines connecting a particular co-benefit with mitigation in a particular sector is proportional to the number of papers studying that issue. Building sector has the smallest percentage of publications [22].

In 2018, Ferreira and Almeida, who are also among the contributors to Annex-56, distinguish co-benefits by type of perspective: macro-economic or private.

From the macro-economic perspective, “the co-benefits represent indirect benefits from investments in the improvement of the energy performance of buildings accruing to society at large”, while from the private perspective, co-benefits “represent the overall increment of the building value resulting from the renovation process, not explained by direct benefits” [23].

Back in the field of climate change, in 2019 Grafakos et al. define co-benefit as “an additional positive adaptation (mitigation) effect that can be achieved from a planning and/or policy measure aimed at improving mitigation (adaptation)” [24].

In 2020, the Horizon2020 project “CRAVEzero” briefly defines co-benefits as “specific additional incentives” [25], specifying that these very often refer primarily to the occupants and employees who are in the buildings every day.

The results of the above literature research are summarized in table A.

YEAR	DEFINITION	CATEGORY / FIELD	SOURCE	LINK / DOI
2001	The benefits of policies that are implemented for various reasons at the same time – including climate change mitigation – acknowledging that most policies designed to address greenhouse gas mitigation also have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity). The term co-impact is also used in a more generic sense to cover both the positive and negative side of the benefits.	climate change mitigation	IPCC TAR Climate Change 2001: Mitigation of Climate Change	https://www.ipcc.ch/report/ar3/wg3/
2007	The benefits of policies implemented for various reasons at the same time, acknowledging that most policies designed to address greenhouse gas mitigation have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity). The term co-impact is also used in a more generic sense to cover both positive and negative side of the benefits	climate change mitigation	IPCC AR4 Climate Change 2007: Mitigation of Climate Change	https://www.ipcc.ch/report/ar4/wg3/
2012	Multiple benefits: One of the challenges is to capture the multiplicity of benefits from energy efficiency improvements. The term multiple benefits has been chosen because this term evokes the varied and numerous outcomes that can be derived from energy efficiency. It is used by several important organisations, including the US Environmental Protection Agency (US EPA, 2012). It appears to be the broadest and most inclusive term relating to the outcomes of energy efficiency policy, covering the terms co-benefits, non-energy benefits, and ancillary benefits. It does not rank or prioritise the outcomes as primary or secondary or energy or nonTenergy benefits (which arguably is implicit in the use of such terms as eco-benefits).	energy efficiency	Spreading the net: the multiple benefits of energy efficiency	https://doi.org/10.1787/5k9crzjbpkkc-en
2013	The urban climate co-benefits approach in this paper refers to the implementation of initiatives (policies, projects, etc.) that simultaneously contribute to reducing the pressure on man-made global climate change while solving local environmental problems in cities, and in turn potentially having other positive developmental impacts, such as improvements in citizen health, energy security and income generation.	urban climate	Learning how to align climate, environmental and developmentobjectives in cities: lessons from the implementation of climateco-benefits initiatives in urban Asia	http://dx.doi.org/10.1016/j.jclepro.2013.08.009
2014	The positive effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on, among others, local circumstances and implementation practices. Co-benefits are often referred to as ancillary benefits.	climate change mitigation	IPCC AR5 Climate Change 2014: Mitigation of Climate Change	https://www.ipcc.ch/report/ar5/wg3/
2014	Ancillary benefits/co-benefits have been traditionally used to describe the impacts of energy efficiency beyond reductions in energy demand – i.e. the benefits that occur in addition to a single prioritised policy goal. While these terms have been used interchangeably with multiple benefits in other literature, this publication opts to use multiple benefits in order to avoid a pre-emptive prioritisation of various benefits; different benefits will be of interest to different stakeholders.	energy efficiency	IEA, Capturing the Multiple Benefits of Energy Efficiency	https://webstore.iea.org/capturing-the-multiple-benefits-of-energy-efficiency
2017	The effects (either positive or negative) beyond the energy savings and the reduction of carbon emissions that may arise from high efficiency energy buildings and from an energy-related building renovation	energy efficiency / buildings renovation	Annex-56 project	http://www.iea-annex56.org/index.aspx?MenuID=1&SubMenuID=5
2018	From a macro-economic perspective, the co-benefits represent indirect benefits from investments in the improvement of the energy performance of buildings accruing to society at large. From a private perspective, the co-benefits represent the overall increment of the building value resulting from the renovation process, not explained by direct benefits	Building renovation	Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation.	https://doi.org/10.1016/j.buildenv.2018.06.036
2019	"Co-benefit is the more common term and is defined as an additional positive adaptation (mitigation) effect that can be achieved from a planning and/or policy measure aimed at improving mitigation (adaptation). A co-benefit occurs when a plan, policy or measure that aims to enhance an adaptation (mitigation) objective leads simultaneously to the enhancement of mitigation (adaptation) objective. [Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities, Stelios Grafakos et al.]"	Urban climate change	(Grafakos et al., 2019; Berry et al., 2015)	https://www.sciencedirect.com/science/article/pii/S0048969720351718
2020	Specific additional incentives. These relate very often primarily to the occupants and employees who are in the buildings every day	NZEBs	CRAVEzero project	https://cravezero.eu/

Table A: 'co-benefits' definitions summary

The term is finding its dimension in the last decade. Using Scopus as a platform, searching for the word "co-benefits" among the keywords and limiting the search to the areas of interest "Environmental Science" and "Energy", the result is 460 documents. From the analysis of the results, it is immediately noticeable how the term has become more important and has had a greater response in research in particular in the last 7-8 years (fig. 5).

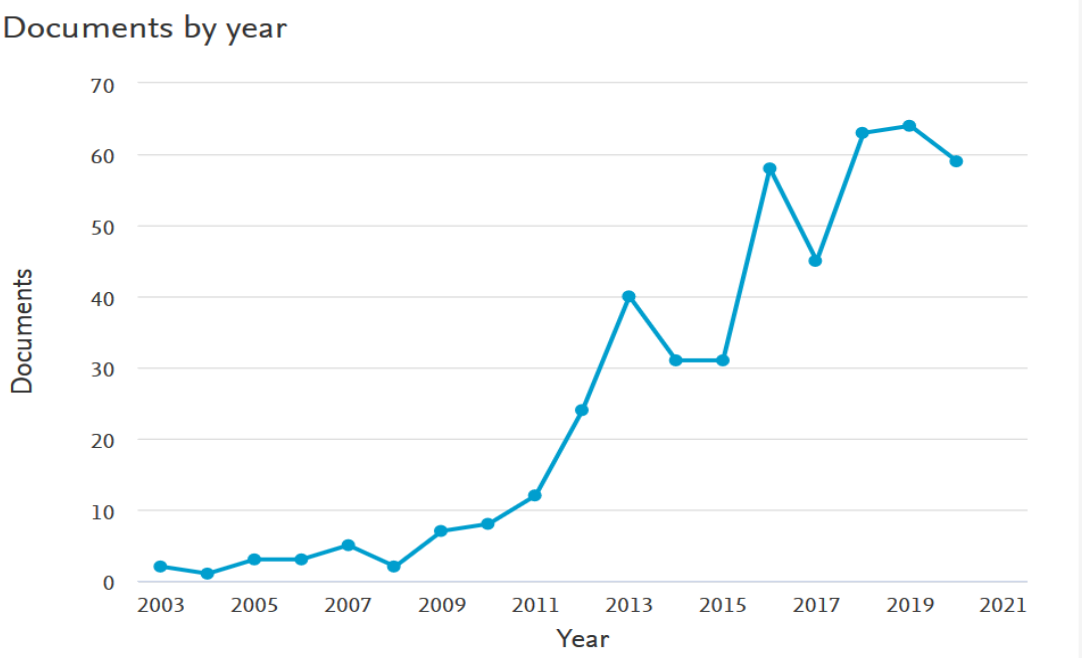

Fig. **5** Trend of the use of the term ‘co-benefit’

What is clear is that co-benefits can have various impacts, from an environmental aspect, to a social or an economic one.

To make an example, a policy that is not specifically designed to address climate change can have anyway positive impacts on it, maybe manifesting mitigation effects that were not considered by the law itself.

This is also transferable to the building sector, which is our area of interest. The installation of a certain type of technology can have multiple effects, which do not only focus on the savings on the bill, but also lead to benefits that if quantified prove to have an equal, if not greater, importance to that addressed by the intervention. Most of the time, in the old approach, these impacts are not considered, they are not evaluated. Things are starting to go different, more and more importance is given to the side effects, even if a unified method to evaluate them is still not in use.

It is also true that these effects are not necessarily positive. An example of co-benefit identified is the ease of use of the systems in a PEH. This can be as true for a young user as it can have the completely opposite effect on an older user, or one not used to a certain technology. Since the term co-benefit by its very nature and also in many of the definitions found recalls an exclusively positive meaning, it is not suitable for the purposes of our research. Annex-56, after specifying it by giving its own definition of the term, used the term to refer also to the negative aspects. Based, however, on all other definitions found in the literature and in particular those of the IPCC, we can undoubtedly distinguish the term 'co-benefit', referring to it for the positive aspects, from that of 'co-impact', which will instead include both effects, positive and negative.

As a generic definition of co-benefit I would therefore propose the following:

“Co-benefits are the added benefits we get when we implement a policy or a measure, which are often equally, and many times more, important than direct benefits. It is fundamental to define them in order to not under-estimate the outcomes of the policy/measure.”

As for the construction sector, instead, the following seems to me the most accurate definition of co-benefit:

“Co-benefits are the added benefits we get, above the direct and measurable impacts (e.g. reduced energy use, reduced CO2 emissions and reduced Life-Cycle Cost), that derive from highly energy-efficient buildings and their technologies or from the energy refurbishment of existing buildings.”

As reported above, since they only consider positive aspects, the definition does not present the full picture, so the use of the word 'co-impact' might be more appropriate for the purpose. This is also important to give a unified and common basis for future projects, so that there is no more confusion about the use of terminology. Co-impacts could be therefore defined:

“Co-impacts are the either positive and negative effects we get, above the direct and measurable impacts (e.g. reduced energy use and reduced CO2), that derive from highly energy-efficient buildings or from the energy refurbishment of existing buildings. They can be <u>household co-impacts</u> if they influence the user's well-being

and finance (e.g., indoor comfort, health improvement, lower cost of energy bills), or community co-impacts if they have wider economic, social and environmental effects (e.g., new business opportunities, urban heat island mitigation, reduction of atmospheric pollution).”

An article by Ürge-Vorsatz et al. came to a similar conclusion, choosing the term 'co-impact' to encompass both positive and negative effects. The terms 'co-benefit' and 'multiple benefits' are then used to refer to positive co-impacts while negative co-impacts are described by the term 'adverse side effects' [26].

The confusion in the general definition of co-impacts has also led to a consequent difficulty in classifying their composition and subcategories. Ürge-Vorsatz et al. in 2009 are among the first to give a classification to the typology of benefits of energy efficiency and distributed energy use in the buildings sector. They identified 5 categories: health effects, ecological effects, economic effects, service provision benefits and social/political effects [27].

In 2014, in its AR5, the IPCC WG3 dedicated an entire chapter to the buildings sector and analysed potential co-benefits and adverse side-effects associated with mitigation actions in buildings. In this work the division consisted of 3 categories: economic, social, health/environment [19].

In the Annex-56 project, the classification of co-benefits is more articulated. The distinction has been made on several levels. A first distinction is between co-benefits and direct benefits, being the latter those immediately visible and calculable impacts resulting from the implementation of energy renewal measures and in general from high efficiency buildings. A secondary distinction is made between private co-benefits and macroeconomic co-benefits. With regard to the private perspective, it is specified that co-benefits could have a positive or negative impact depending on the building and its owner, and they are divided into 3 categories: building quality, economic and user well-being. On the other side, considering the macroeconomic perspective, co-benefits are composed of 3 main categories: environmental, economic, social [21].

Schematically, the categorization of Annex-56 could be represented as follows:

Co-benefits		Direct benefits
Private	Macroeconomic	• Energy use reduction • Carbon emission reduction • Life cycle cost reduction
• Building quality • Economic • User well-being	• Environmental • Economic • Social	

Another significant work in this research is the one conducted by Reuter et al. [28]. Working on the multiple benefits of energy efficiency, they classify them into three groups: environmental, social and economics. Progressively, for each group they identified some sub-categories:

- ‘energy/resource management’ and ‘global and local pollutants’ for the environmental category;
- ‘energy poverty’ and ‘quality of life’ (which includes health and well-being) for the social category;
- ‘innovation/competitiveness’, ‘macro-economic’, ‘micro-economic’, and ‘energy security/energy delivery’ as far as the economic category is concerned.

Their research aimed to build a comprehensive indicator set for measuring multiple benefits of energy efficiency [28].

Reuter et al. classification's scheme:

Multiple Benefits		
Environmental	Social	Economic
• Energy/Resource Management • Global and Local Pollutants	• Energy Poverty • Quality of life	• Innovation/Competitiveness • Macro-economic • Micro-economic • Energy Security /Energy Delivery

Based on the following studies, I developed a model that could include the largest number of co-benefits related to Plus Energy Buildings in the smallest number of categories. The proposed model is the following:

Household level		**Community level**	
Direct effects (impacts)	Co-impacts	Direct effects (impacts)	Co-impacts
Reduction of energy consumption costs	Thermal comfort	Reduction of CO2 emissions	Lower cost of energy
	Acoustic comfort	Reduction of energy use	New business opportunities
	Visual comfort		Mitigation of climate change
	IAQ indoor air quality		Reduction of atmospheric pollution
	Building Physics		Reduction of construction / demolition waste
	Health improvement		Environmental resource protection (ecosystems and biodiversity)
	Easy of use		Aesthetics of the building - neighborhood enhancement
	Safety		Mortality / morbidity reduction
	Resilience to climate change		Urban heat island mitigation
	Increase in productivity (smart working)		Energy security
	Lower energy bills		
	Lower maintenance costs		
	Increase in the value of the building (Easier to sell / rent at higher real estate prices)		

USER WELL-BEING	ECONOMIC	ENVIRONMENTAL	SOCIAL

Table B: classification of co-impacts

Each category includes a certain number of co-impacts. The choice that was made was to keep environmental and social co-impacts in the 'public domain', which refers to the community, because they are categories that have a broader impact. "User well-being", instead, includes co-impacts that influences only the 'private sphere', at the household level. Economic effects can be perceived in both, household and community level.

In the following chapters I will analyse the individual co-impacts of each category. A research work in literature has been done, mainly using Scopus and Google Scholar as platforms. The purpose is to identify, where it is possible, the classifications and definitions proposed for each co-impact.

2.1 User well-being

User well-being is fundamental to the project and the type of goals it sets, which is why it has been chosen as a stand-alone category even considering that, in other works, it was generally included as a sub-category in the "social" category (e.g. [28]). The co-impacts related to this category all directly affect the person using the Plus Energy Building and range from the user's comfort to his/her physical and mental health (health is also incorporated into the category of social co-impacts), to the user's perception and interaction with the building itself.

Thermal, acoustic and visual comfort together with indoor air quality (IAQ) are the parameters of indoor environmental quality (IEQ) (fig. 6), which is defined by ASHRAE as: "a perceived indoor experience of the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings. Fields of specialization include architecture, HVAC design, thermal comfort, indoor air quality (IAQ), lighting, acoustics, and control systems" [29].

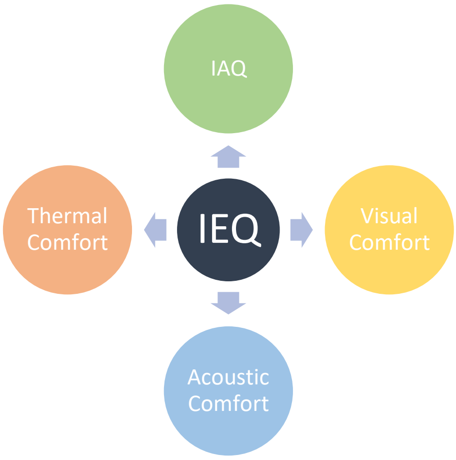

Fig. 6 Indoor Environmental Quality (IEQ)

Even if complicated to quantify, the relationship between IEQ and well-being is evident, and still requires a lot of research to fully embrace these aspects and thus to have a proper quantification and economic estimate of its influence on the user.

For each component of IEQ and more generally for every co-impact in each category, definitions have been searched in the literature, describing the co-impacts and their effects, both positive and negative, in the context of PEBs, nZEBs, green buildings and in general of buildings with high energy efficiency and attention to the sustainability factor. Where possible, the respective technologies of each co-impact have been reported, especially in the case of IEQ, being it studied on a large scale and thus being easier to find information on the related technologies.

In the following pages each identified co-impact will be presented, starting with those inherent in the IEQ.

Thermal comfort

Thermal comfort can vary from person to person, and comfort in general is more of a subjective condition that affects both the body and the mind. It can be influenced by physical, psychological, and behavioural personal differences, as well as culture and by other factors such as individual, organizational, and social norms [21].

There are numerous solutions for controlling the temperature in a building, some of which are listed below: external and internal façade insulation, cellar ceiling insulation, roof insulation, ground floor insulation, insulation of entire building envelope, mechanical ventilation with heat recovery (MVHR), air renewal systems, optimized glazing, windows replacement, an integrated design approach that involves a careful selection of the materials and a complete set of installations, high air tightness, reduction of thermal bridges [21]; solar shading, openable glazing area increase, thermal mass of the external walls increase [30]; multiple glazing with a cavity where the vacuum is realized in order to reduce conduction and convection and therefore the dispersion of heat, and “smart” glazing i.e. photochromic (which becomes dark when exposed to solar radiation) or thermo-chromatic (which changes its transmittance when struck by incident solar radiation, becoming darker as the temperature increases) [31]; different type of heating and cooling distributions and terminals.

Acoustic comfort

We speak of acoustic comfort when, immersed in a sound field, we are in conditions of well-being, in relation to the activity that we are performing [32]. This can also be evaluated in a very subjective way but the technologies and solutions that allow us to obtain it are quite universal.

The geometry of the room is an important factor, for example if the area is square then the acoustic comfort is higher, a soft material has a major capability to absorb noise than a hard one, wall treatments could reduce airborne noise, floor system and insertion treatments can help to reduce airborne and impact noise, and ceiling treatments can be effective on reducing impact noise [21]. For Marques et al., a new approach to fight noise pollution is necessary, which uses a real-time IoT noise monitoring system that compresses 24 hours noise events into a one-minute summary, in order to monitor and identify acoustic discomfort [33].

Visual comfort

Lighting within an environment, whether artificial or natural, is considered to be primarily responsible for visual comfort; inadequate lighting causes general feelings of discomfort and eye fatigue that can adversely affect user comfort, health and performance. Daylight is associated with economic and ecological, due to reduced energy consumption and CO_2 emissions and psychological impacts, as daylight effectively stimulates the human visual and circadian systems [34]. Also, the visual contact with the outside is associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain [21].

Roof light or sun pipes, position, shape and quantity of glazed spaces, artificial light systems, number of windows, geometry of windows, photometry of surfaces and amount of glazing [21] are all associated with an improvement of the visual comfort.

Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) is the only indicator among those that make up the IEQ that explicitly refers to healthiness rather than comfort, and for this reason should be carefully considered. It can be evaluated through several parameters, among them we have concentration of volatile organic compounds (VOCs, and formaldehyde in particular), carbon dioxide and monoxide, relative humidity, presence of microbial contaminants, suspended particulate matter and ventilation rate.

IAQ directly relates to comfort and psychological and physical health of the users, depending also on the frequency and the duration of the exposure [35].

More modern buildings tend to be more airtight than older ones, what happens is that air change is often not high enough and therefore, as a result, indoor air quality worsens. This co-impact can therefore have a negative implication since high energy efficiency does not always translate into higher air quality, but this can be avoided coupling building technologies and techniques necessary to achieve adequate results that maximize building occupants’ wellness.

It is important that the HVAC system is accurately designed so to have an efficient and complete air exchange, that the materials for construction and furniture are not treated with chemicals that could release over time VOCs and other toxic compounds [21]. Good solutions could be also natural ventilation and the use of extractors or air purifiers.

Health improvement

Improved IEQ conditions result in an overall improvement in health. Reduced respiratory illness, reduced allergies and asthma and reduced Sick Building Syndrome symptoms are just some of the health benefits resulting from improved IEQ [36].

Decreases in morbidity and mortality are two factors directly related to an increase in health, which also affects productivity and consequently the economy. In Chapter 3 will be presented some examples from studies that have tried to monetize these correlations.

Especially in these times, when smart working from home is more and more practiced, in part because of the Covid-19 emergency, it is necessary to make more studies on the residential sector and about how the dwellers are affected by IEQ conditions in terms of health, performances and productivity.

Building physics (increase of useful areas)

Construction techniques have varied greatly over time and are still doing so today. The structure of a prefabricated house, for example, can be assembled in just a few hours. New technologies and innovative materials are features that provide a different layout and presentation of spaces. Also the care in the details and design of the house, creating solutions tailored to the user, thanks to the attention to different cultural factors, can give excellent results in this direction. The reduced heat loss from windows and the resulting increase in comfort from reduced drafts make it more comfortable to sit closer to windows and other surfaces that may be uncomfortable in other types of homes, thus giving access to areas that often remain unused [21].

Ease of use

The buildings we live in are becoming increasingly "smart". The adjustment of many parameters of the house (temperature, lighting, windows, household appliances ...) can now be done directly from your smartphone or laptop. This can certainly have positive feedback in everyday life in terms of convenience, but the ease of use may not be so obvious, especially for certain categories of people, especially the elderly.

The proposed interfaces however tend to be built to be intuitive and easy to use [21], to test even the most inexperienced user, but it remains however a factor of subjectivity, also dictated by different habits, rather important.

Uncertainties about technology performance and ease of use are greater in households that are installing smart home technologies for the first time [37].

Safety

Modern buildings are safer than old ones. Building elements at the latest standards provide fewer risks such as accidents, fire, or intrusion [21]. Smart systems ensure more secure access control, in order to authenticate authorized persons, modern buildings can detect irregular intrusions and even alert an emergency center if necessary. Sensors continuously monitor the environment, alerting in case of anomalies such as a fire. An increasing number of consumers and businesses are willing to pay for greater security and serenity [38]. As previously noted, the quality and attention paid to the choice of materials ensures safety in terms of physical health.

Climate change resilience

The IPCC refers to climate resilience as:“the outcomes of evolutionary processes of managing change in order to reduce disruptions and enhance opportunities” [39]. When we talk about climate change, we are talking about effects of global magnitude that can, however, affect the lives of individual citizens. Tangible effects are an increase in the number and destructiveness of catastrophic events such as hurricanes, rising sea levels, or advancing desertification. All of these are situations that can have a great impact on the lives of people in the most affected areas. Such phenomena, however, generally seem almost imperceptible, distant in our everyday lives, so an example closer to home might be more appropriate. Frequency, duration, and violence of heat waves is increasing [40]. In 2003, for example, a heat wave caused more than 30,000 deaths in Europe, including about 15,000 in France alone [41]. The category most affected was the elderly. Such events, in the future, may become less and less rare and more catastrophic. As already highlighted, PEBs in addition to the great

energy efficiency, are able to ensure adequate levels of comfort, there is therefore the possibility that they help to reduce the risks in such situations.
It has also been seen that the impact of heat waves, as well as having an impact on mortality and morbidity, would also lead to problems in electricity distribution due to peaks in demand caused by the use of air conditioners [42]. Another of the advantages of PEBs is the independence from the electric grid provided by micro-generation of energy through renewable resources. On these particular occasions, therefore, this feature proves even more advantageous. In a world of increasingly unpredictable climate that we are moving towards, unlike other building types, solutions such as PEBs can be effective not only in adapting to new conditions but also in reducing their effects, improvement at the level of both the individual user and society. Another type of building can lead to simple adaptation, relying for example solely on the use of air conditioning, which although it cools the indoor environment, still increases the external heat triggering a kind of feedback that does not lead to any improvement in the long term. The PEB, however, has the potential to be one of the solutions to mitigate the problem of climate change, as it makes efficiency its strong point, cutting waste, relying on numerous technologies, and focusing on clean energy.

2.2 Economic

Economic co-impacts are shared between the user and the community perspective, given that they can affect both individual households and, more broadly, the community.

2.2.1 “Household” economic co-impacts

For this category, four main co-impacts were identified: lower energy bills (more a direct impact than a co-impact), lower maintenance costs, increase in the value of the building which, as a consequence, leads to a greater ease of selling / renting it and increase in productivity (related to the smart working).

Lower energy bills

Having an energy-efficient home is also beneficial due to the fact that the higher initial investment, over the years, pays for itself in lower utility bills.

Cultural-E aims to make the extra costs compared to nZEBs repayable within 8 years, this is possible also due to the energy efficiency superiority of PEBs over any other building type. The reduced energy demand driven by the energy efficient measures adopted by this type of buildings will lower the cost of energy for the users. After the building's thermal insulation, the second most productive area for improving energy efficiency (and reducing costs) is the HVAC system, which is responsible for ventilating rooms and heating and cooling them [43]. Operational cost reductions also result from the use of technologies such as heat pumps that if properly operated and designed have lower (or comparable) costs to heat water than traditional boilers using natural gas, with the extra advantage of using electric energy produced by the PV systems. Cultural-E plans to use these solutions in the most cost-effective way possible, so as to make PEBs even more attractive to future consumers and more competitive in the marketplace.

Lower maintenance costs

Retrofitting older buildings also includes retrofitting existing, and often aging, building technologies. In addition to energy cost savings, this results in a net reduction in maintenance costs for the building owner [44]. We can assume that the adoption of such new technologies even in the case of new building construction can typically require less maintenance.

Increase in the value of the building (easier to sell / rent at higher real estate prices)

The value of a property depends on a number of factors, including its level of energy efficiency and its energy performance [45].

Thanks to energy efficiency measures, it is likely that the agreed rent is higher than the rent for a standard building.

Buildings that have the qualities to obtain a green certification are a profitable investment that leads to an increase in rents between 4% and 21%. This means that companies and individuals are willing to pay a surplus on the rent or sale for this type of property [44].

The fact that climate-resiliency is one of the aspects considered by Cultural-E and that the economic performance of these buildings is now well proven, could make more appealing these buildings in the real estate market with consequently higher prices [27].

When the transition to this type of building will be more common, the co-impact could assume a negative societal aspect as higher rents could particularly impact the most vulnerable social groups who will not be able to afford higher rents [25].

Increase in productivity (smart working)

The one of smart working is a concept that has been around for several years now, but it was in 2020, due to the Covid-19 pandemic, that it became more prevalent.

Particularly healthy home environments have an additional positive impact on those individuals who work from home, which goes beyond improving overall health.

Having fewer indoor pollutants, better acoustics and lighting can increase satisfaction levels and the ability to concentrate, leading to an increase in occupant productivity [25]. Many studies on these factors have been done at the office level, not as much literature can be found on the case of smart working but we can infer that the results are very similar.

In a Buildings Performance Institute Europe (BPIE) publication, a first step is taken to define, measure, quantify and monetize the impact of key components of indoor environmental quality - indoor air quality, thermal comfort, acoustics, and lighting - on students and employees across Europe. In the following table some of their results are reported, to demonstrate how much a healthy and well-designed environment is important for the performance of both students and workers [46].

PARAMETER	CATEGORY	CO-IMPACT
IAQ	Students	For every 1 litre per second per person (l/s/p) increase in the ventilation rate up to 15 l/s/p, academic performance increases by 1%
		Every 100ppm decrease in CO2 concentration is associated with a 0.5% decrease in illness-related absence from schools
	Employees	Every 1 l/s/p increase in ventilation increases a worker's performance by 0.8% (up to 15 l/s/p maximum)
TEMPERATURE	Students	Every 1°C reduction in overheating increases students' learning performance by 2.3 %
	Employees	Every 1°C reduction in overheating increases a worker's performance by 3.6%
LIGHTING	Students	Every 100 lux in improved lighting in schools is associated with a 2.9% increase in educational performance
		Better daylight is associated with a 9% to 18% increase in educational performance
	Employees	Every 100 lux increase in lighting level increases a worker's performance by 0.8%
		Better daylight is associated on average with a 10 % increase in performance
ACOUSTICS	Students	For every 1 dB decrease in excess noise, academic performance increases by 0.7%
	Employees	For every 1 dB decrease in the excess noise, performance improved by 0.3%

Table C: IEQ parameters and related co-impacts in productivity

Even if they relate to schools and offices, these data tell us a lot about the impact that the indoor environment has in user performance. Despite the apparently surprising results, this study should still be taken with caution as it still has several limitations. The temperature as a parameter, for example, does not consider the user's thermal comfort. Another limitation is that the methods used to calculate performance and productivity vary widely. A major shortcoming of the study is that it risks having the misleading effect of leading to increased energy consumption in order to increase performance instead of finding solutions that allow for optimal working conditions and productivity with a cut or containment of consumption.

Although this is just one example, there are many other studies that focus on the same aspects. Thus, these are noteworthy data that certainly require more study so that they can be translated into smart working related performance.

2.2.2 “Community” economic co-impacts

Lower cost of energy

In the future, having entire neighborhoods of Plus Energy buildings will also drive a change in the price of electricity itself. These buildings offer some level of independence from the grid, which will increase as they are deployed through the development of, for example, smart micro-grids. This transition will maximize system efficiency, providing cleaner energy and some resilience as well as energy security. A PEH neighborhood will need considerably less energy infrastructure for developers and theoretically lower infrastructure charges. To quantify the infrastructure savings and the network benefits of a decentralized network consisting of interconnected micro-grids, more research is needed in this area [47].

A direct consequence given by transitioning to this system would be to have less need for energy subsidies. Energy for the population is highly subsidised in most developing countries, but also in more developed ones. Substantial subsidies can be avoided if electricity is more effectively used [27]. Precise figures on how much a country like Italy spends on government subsidies to fossil fuels alone are not easy to assess, but the various sources agree that spending is in the billions, while the total subsidies invested in renewables are a few tens of millions of euros [48] [49] [50]. This approach as well as wrong, is totally unsustainable. Reforming policies to support fossil fuels is an urgent matter. The increased use of energy from renewable sources in the sector that consumes more energy, which is the building sector, will hopefully lead over the years towards a more sustainable future, where the production of energy from renewable sources will no longer need to be incentivized.

New business opportunities

The transition toward the PEBs model, in the long term, will bring new business opportunities, for example for the energy service companies (ESCOs). This will lead to new industry niches that result in higher GDP growth depending on the degree to which the traditional companies are forced out of the market (if this happens) [27] [21].

As mentioned in the previous chapter, opportunities would also be created in the real estate market for buying, selling, and renting PEBs.

New businesses such as stores, offices, services, or commercial activities could arise thanks to the fact that the construction of this type of building can increase the value of the context in which the building is inserted, acting as an incentive for the redevelopment of an urban, suburban, or rural area and consequently can lead to a greater interest of people to move to that land. [25].

2.3 Environmental

Reduction of atmospheric pollution

Worldwide, the largest outdoor air pollution source is the one that derives from residential and commercial energy use. [51]

With PEBs. an increase in outdoor air quality is guaranteed by the increased use of energy from renewable sources and the consequent reduction in the use of fossil fuels [21]. Also, the increased efficiency of PEBs and the smart grid dedicated to them result in less waste and therefore less air pollution. If coupled with the design solutions of green infrastructures such as green walls and roofs, PEBs could be even more effective in reducing pollution in streets and open roads, playing an important role in reducing air pollution in urban areas [52].

Indicators of the improvement of the local air could be the concentrations of avoided local pollutants from PM2.5, PM10, NOx included from electricity and heat generation [28].

Research by Lelieveld et al. indicates that in air pollution management policies, emissions from residential energy usage should be considered [51].

Reduction of construction/demolition waste

In the process of reducing environmental loads and minimizing construction and demolition waste, a key role is also played through the application of life cycle assessment techniques, LCA. It allows, in practice, to acquire awareness of environmental damage in each of the phases that make up the life cycle of a product (and therefore also of a building): from production, transport, use, recycling, reuse until disposal.

Grey energy is the energy hidden in a product; essentially it is the energy that was used to produce and transport it. The production of lightweight buildings, with well-considered design and careful choice of materials, also based on LCA analysis, allows to minimize the consumption of raw materials and thus reduce construction waste. It has been estimated that a typical residence in Germany contains enough grey energy in the materials to keep the building running for 25 years. This is because the materials they are made from require a lot of energy and therefore fossil fuels [53].

Considering LCA in the evaluation of the building design could lead to waste reduction, reuse, and recycling, especially when, in the future, a decision has to be taken between renovation or replacement of a building [21].

Environmental resource protection (ecosystems and biodiversity)

Promoting the use of renewable energy in the building sector, thereby strengthening the clean energy market, can lead to emission reductions both globally and locally. One of the consequences of this pathway is the improvement of environmental resources (for example lower contamination of the ecosystems), in particular due to the lower air pollution resulting from the reduction of greenhouse gas emissions [54].

This transition to clean energy will contribute to ecosystem preservation and biodiversity protection [19].

A solution that relies on nature could be the most suitable to safeguard it: as pointed by the IPCC, the implementation of green roofs and walls, roof and balcony gardens, or sky terraces, can lead not only to an increase in air quality (CO2 absorption), but also to an increase in biodiversity (especially if indigenous species are used) [19].

The "Vertical Forest" in Milan, designed by Stefano Boeri Architetti studio, is a striking implementation of these principles (fig.7).

Fig. 7 The “Vertical Forest” in Milan, Italy (www.stefanoboeriarchitetti.net)

Although this residential building complex may be considered almost on the edge of the exaggeration of the concept of green roof design (more “green terraces and balconies” in this specific case), it is the numbers that prove otherwise. In fact, the numerous plant species used in the project have attracted more than 1,600 species of birds and insects [55]. In the words of Boeri himself, this is nothing more than a "model of vertical densification of nature within the city", so as to expand urban biodiversity without having to expand the city itself.

This could obviously work on a smaller scale, but the impact could be even greater if it becomes commonplace to have a green roof.

Mitigation of climate change

As already reported in the introductive chapter, building sector contributes to great part of energy consumption and the related CO_2 emissions. Carbon dioxide is a greenhouse gas that is naturally present in the atmosphere and allows to trap part of the thermal radiation from the Sun, maintaining an average temperature of the Earth around 14 °C and thus allowing the existence of life as we know it. The excess of GHGs in the atmosphere from anthropogenic sources, however, increases the amount of solar radiation retained, causing an increase in the Earth's average temperature and all the climate-related events such as floods, storms, droughts, and heat waves that are becoming more common and catastrophic due to these changes. Limiting global warming to a maximum of 2, and preferably 1.5 degrees Celsius, compared to pre-industrial levels is the goal of the Paris Agreement. The IPCC in its Fifth Amendment Report already focused on the mitigation perspective and the respective options and benefits related to the construction industry. The IPCC is clear about the importance of this sector in the low-carbon future and the need for sustainable development. They also argue that the co-benefits (positive co-impacts) from energy efficiency measures, if monetized, can easily outweigh the energy cost savings and perhaps even the associated climate benefits [19]. Since PEBs solutions aim at reducing energy consumption and thus emissions, they are automatically buildings that make an effort towards reducing the effects of climate change and thus have a mitigating effect on them.

2.4 Social

Mortality / morbidity reduction

Green structures, by definition, focus on limiting climate effects by decreasing energy and water use and minimizing environmental disturbances at the construction site but also focus on human health. As already addressed in the previous chapters, PEBs can positively affect user comfort and health (household-level co-impacts) but also air quality (community-level co-impacts). On a larger scale, this improvement in the internal and external conditions leads to reduced mortality. Morbidity also tends to decrease for the same reasons, but also for better lighting and mould reduction. Direct consequences are the avoided hospital admissions, medicines prescribed, restricted activity days and productivity losses [21] [27].

Reduced mortality would translate also into higher employment and more working days [27].

Fortunately, more and more attention is being given to building standards that focus on health and green buildings, a category which includes PEBs, are usually very conscious of the needs of their users, including in terms of health. There is a tendency to see lower levels of VOCs, formaldehyde, allergens, NO2, and PM in green buildings, all contaminants that have more or less marked effects on the health and well-being of households [56]. This gives us evidence and confidence that the way we build, on the grand scale, can seriously impact mortality and morbidity, giving us hope for the future and the increasing attention and importance given to such facts.

Urban heat island mitigation

The term ‘urban heat island’ refers to an urban or metropolitan area that is significantly warmer than the rural areas surrounding it due to anthropogenic activities [57]. As widely demonstrated, the highest consumption in buildings occurs due to the active use of technologies to maintain indoor comfort [58]. Especially during the summer months, when the use of cooling systems is more intense, there is a significant increase in the urban heat island effect caused by heat losses from these devices [59].

As you would expect, green infrastructure has the power to mitigate the urban heat island. Greater efficiency also means less dispersion, so less energy is needed to achieve adequate comfort levels, even in summer. In addition to this, certain types of technologies such as green roofs, green facades, balcony gardens, etc., that reduce the concentration of GHGs also contribute to the reduction of the urban heat island effect [19] [60]. Another effect that these technologies have on buildings is to increase insulation which, as already mentioned, has the effect of reducing the need for air conditioning.

Passive design strategies could also prevent the formation of urban heat island (e.g. solar shading, natural ventilation, building orientation, low temperature radiant surfaces…) [58].

Energy security

Many European countries still rely on a restricted number of fossil fuels providers. This situation makes them very susceptible against supply disruptions that can be about political or business disputes, or infrastructure failure [28]. Plus Energy Buildings guarantee a certain independency from the electrical grid. In a larger scale this translates in a reduction on the dependence from imported energy since the amount of energy the house needs is produced locally [21] [27]. Therefore not only the import dependency changes but also the supplier diversity, leading to a reduction of the share of the predominant provider thanks to the higher integration of renewables [28].

Aesthetics of the building / neighbourhood enhancement

It has been proved that aesthetic improvement is often one of the main reasons for building renovation. The architectural, cultural, and historical values and context of a building must be carefully considered in order to have a quality design that is also attentive to the aesthetic effects the building may have [21]. It is well documented how buildings aesthetics can impact people's psychology and well-being. Although the research seems promising, further investigation is needed to know whether variations in aesthetic patterns really have the power to improve mood, cognitive functioning, or other psychological effects [61]. In addition, the aesthetics of a building play a crucial role in defining the value and market relevance of the building itself, thus having a positive impact on the customer through increased visibility and consequently higher economic revenue [25]. This co-impact is not an easy one to evaluate since it may seem quite subjective and very difficult to quantify.

2.5 Sick Building Syndrome

When the internal conditions of the environment do not reach optimal levels, there is a risk of negative side effects in residents. These effects can be both physical and psychological, and lead to a deterioration of health as well as user productivity. These building-related symptoms can affect differently people based on their health status, age, sex, and other factors. The effects are usually directly proportional to the time spent in the building. The concept has been studied for many decades and the literature on the subject is therefore extensive and detailed, particularly regarding offices, where indoor environmental quality conditions are strictly related to workers productivity.

Sick Building Syndrome (SBS) is recognized by the World Health Organization and the term is used worldwide to describe the medical condition where people in a building suffer from symptoms of illness or feel unwell for no apparent reason [62]. The research on SBS originated in the 70's and it is still a significant and interesting topic of discussion.

Often the symptoms of SBS are non-specific and relatively minor but, to a wider final extent, they may impact public health and the economy, especially considering office buildings due to widespread absenteeism and lowered productivity amongst affected workers [35].

The number of symptoms associated with SBS is high. Usually they are mild effects, certainly annoying but not dangerous, however, in extreme cases, they can also lead to severe health consequences and also to death. Those affected complain of eye, nose, respiratory tract and occasionally skin irritation as well as general symptoms such as headaches, fatigue, malaise, dizziness, difficulty concentrating and more. Once they leave the building, the symptoms decrease. Most SBS-related reports and examinations relate to the workplace. However, SBS can also occur in household scenarios.

Based on the work of C.A. Redlich et al., M. J. Finnegan et al. and P. S. Burge, in this work symptoms have been divided into 5 main categories: i) mucous-membrane irritation, ii) neurotoxic effects, iii) respiratory symptoms, iv) skin symptoms, and v) chemosensory changes [63], [64], [65]. The symptoms that refer to each category are listed in the following table.

Common SBS symptoms	
Mucous-membrane irritation	Eye irritation, blocked or stuffy nose, throat irritation and dryness, cough
Neurotoxic effects	Headaches, nausea, fatigue, lack of concentration, dizziness, lethargy
Respiratory symptoms	Shortness of breath, cough, wheeze
Skin symptoms	Rash, pruritus, dryness
Chemosensory changes	Sensitivity to odors, visual disturbances

Table D: common Sick Building Syndrome symptoms

The causes of SBS are many and usually caused by various factors. A wide range of pollutants are associated with SBS symptoms. However, it is not only contaminants in the air that generate undesirable effects on the user's condition. In studies of SBS in offices, a number of risk factors have been identified, related to a wide and heterogeneous range of aspects, including insufficient ventilation, unhygienic air conditioning systems, the emission of odorous and irritating substances and volatile compounds from materials and appliances, damage due to humidity, but also an unpleasant climate in the room, permanent annoying noises, and inadequately installed video terminal work-stations. The frequency and intensity of the disturbances also depend on psychological stress in the workplace. This can be caused, for example, by overwork, lack of influence, lack of privacy or problems with employees or superiors.

In the following table, the most common causes leading to SBS symptoms are presented:

Possible causes of SBS symptoms		
Chemical contaminants	VOCs	Formaldehyde, paints and resins, solvents, printed materials, printer, and photocopier emissions
	Contaminants generated by human activity	CO2, cigarettes smoke, perfumes, pollutants from motor vehicle exhausts, and building exhausts (e.g. bathrooms and kitchens)
Biological contaminants	Bioaerosols	Bacteria, fungi, pollen, moulds, dust mites, viruses, animal dander and excreta
Physical factors	Indoor environment conditions	Temperature, humidity, noise, lighting, inadequate ventilation
	Dust / fibres	Asbestos, man-made mineral fibres (fibreglass). Dirt, construction, and paper dust
Psychological factors	Excessive work stress or dissatisfaction, poor interpersonal relationships, and poor communication	

Table E: possible causes of Sick Building Syndrome symptoms

Nowadays there is a higher awareness toward indoor air contaminants, like volatile organic compounds (VOCs), and building materials are expected to emit less and less harmful compounds. Nevertheless, the problem for indoor air pollution is not solved. The list of potentially harmful substance that can be found in indoor environment is growing with the increase of interest and research on the topic [66].

It is often repeated in the literature the fact that, on average, 90% of our time is spent indoors. It is therefore logical to correlate health and quality of the indoor environment and to spend resources and attentions trying to improve it. Research seems to lead toward the fact that green and sustainable buildings can reduce the incidence of SBS symptoms. SBS, in fact, can be avoided by transforming our approach to construction in favour of more natural choices, with materials that are less chemically treated and whose origin is certified. An example of certification is the Declare label which tells where a particular product comes from, clearly states its composition, and where it ends up at the end of its life cycle. In this way, the quality of the product and its environmental impact are made clear in order to direct towards more sustainable choices [67]. Once attention has been paid to the project site and to the quality of the built environment, it is therefore fundamental to put the building in conditions where it can "breathe", always maintaining a high level of well-being. Proper design of ventilation systems since, for example, people who work in buildings with natural ventilation have fewer sick days than workers in air-conditioned offices [68], reduction of mould/dampness, careful arrangement of room layouts, sanitizing frequency, installation of external devices on openings such as sun shades and providing visual/physical access to nature are also valid solutions to reduce SBS symptoms [69]. A more careful attitude is good for the environment and our health, achieving a high energy and building performance, without any compromise. In the same way that an inadequate indoor environment can create health damage, it is also true that optimizing a building can also lead to human health benefits. This is the direction in which Cultural-E is also moving, among the many initiatives and projects that are increasingly adopting solutions and increasing attention towards the user and his well-being, in what is gaining ground as user-centric building design.

2.6 IEQ and COVID-19

2020 will be remembered in the history books as the year of the global pandemic SARS-CoV-2, a zoonotic virus (that has jumped from a non-human animal to humans) that infected tens of millions of people around the globe, causing more than one million reported deaths. The first cases of Covid-19 (Corona Virus Disease 2019), which is the name of the disease, caused by SARS-CoV-2 (scientific name of the new strain of coronavirus), were detected in Wuhan in December 2019. Wuhan, is a city of 11 million inhabitants, the capital of Hubei Province in the People's Republic of China (fig. 8).

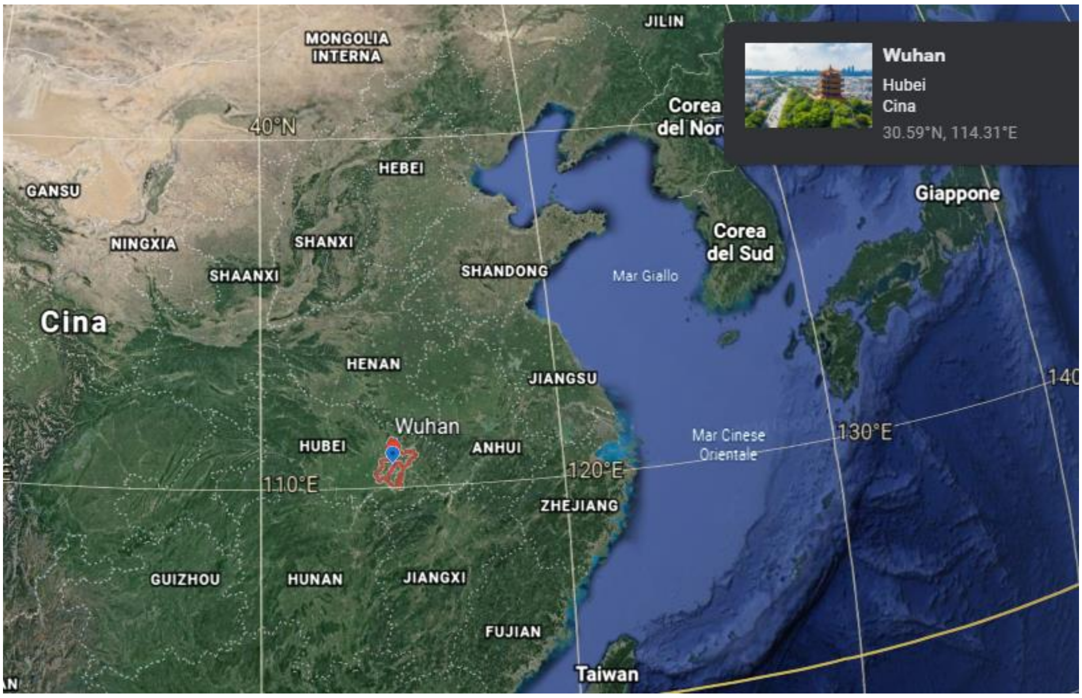

Fig. 8 Wuhan position (Google Earth, 2020)

It is important to make clear that SARS-CoV-2 is not the only coronavirus, in fact there are many types of human coronaviruses including some that commonly cause mild upper-respiratory tract illnesses. For example, between 2002 and 2004 there was an epidemic of SARS (Severe Acute Respiratory Syndrome), which spread to about thirty countries and infected more than 8000 people, causing about 700 deaths. COVID-19 is a new disease, caused by a new coronavirus that had never been detected in humans before.

Although the exact origin of the virus is unclear, the majority of early cases in Wuhan trace back to Huanan Seafood Wholesale Market. Wet markets are large outdoor markets dedicated to the sale of perishable goods, such as fresh meat, fish, or fruit. Some wet markets sell and slaughter live animals on site, including chickens, fish, and shellfish. More rarely, wet markets also sell wild animals and their meat and Wuhan's Huanan Seafood Wholesale Market is one of those, and it is probably where the SARS-CoV-2 was transmitted the first time [70].

Coronavirus disease (COVID-19) affects in various ways. The infection is very similar to seasonal flu with the most common symptoms of fever, headache, shortness of breath, cough, muscle aches, and tiredness [71]. Most people have mild or moderate symptoms and recover without the need for hospitalization. Unfortunately, however, the symptoms can be aggravated to the point of difficulty breathing, chest pain or pressure, and loss of speech or movement. In these cases, urgent medical attention is needed.

In order to contain the transmission of the virus it is crucial to understand the dynamics of its spread, how it passes from individual to individual.

The lungs are the primary site of infection, and the air, in fact, is the main medium used by the virus to spread. The routes of human-to-human transmission among individuals include direct inhalation of contaminated droplets released into the environment by sneezing or coughing, and contact transmission via oral, nasal, and eye mucous [71].

As already stated, clean air is synonymous of health and poor room ventilation has long been known to be one of the causes of transmission of infectious diseases.

As with other infectious diseases, the role of room ventilation in the spread of the disease has not yet been fully clarified in the case of COVID-19, although initial research indicates an increased risk factor for offices, restaurants, and other places where people stay indoors for a long time.

A research carried out in China analysed the origin and evolution of 318 small epidemic outbreaks, detecting how all outbreaks with 3 or more cases had developed indoors, confirming that indoor space sharing is a major SARS-CoV-2 infection risk. Another important point of the study is that the 79.9% (254 of 318) of the outbreaks occurred at home [72]. This occurs for two main reasons: in the home environment there is very close contact from person-to-person and the air the members of the family breath, is the same for everyone because it comes from a limited, close space.

There are two main issues that correlate SARS-CoV-2 pandemic and the indoor environmental quality of a building:

1- The role of indoor air and HVAC systems in the spread/containment of the virus.
2- The lockdown forced people to stay closed at home. In a lot of cases spaces were not designed to maintain for so many days (the lockdown in Italy, for example, lasted 69 days, from March 9 to May 18, 2020) at strict contact a certain number of family members that usually spend most of their days at school or work. This has led to a drop in air quality in the living space, a problem that becomes more acute for low-income families.

SARSCoV-2 is present in the aerosol and its concentration (number of particles per unit volume) is expressed in terms of viral load number of viruses per unit volume). The introduction of virus-free outside air into an environment where there is a source of viral load, in this case the infected patient, leads to dilution of the average viral load in the environment. The greater the amount of clean outside air that is introduced, compared to the virus, the greater the dilution of viral load that is obtained. It is also evident that, if the source is always active, the average viral load in the environment can never be completely eliminated, but it can be greatly reduced.

To limit the possible airborne propagation of the virus (both droplets and aerosols), you can also intervene directly on the source with the use of surgical masks.

The objective of these masks is not to prevent us from inhaling the virus if it is present in the air but to prevent the infected subject present in the shared environment from spreading droplets and aerosol in the air. Hence the need to wear masks in the closed environment is mandatory to significantly minimize the risk of infection however, the best possible safety condition is a combined implementation of masks and proper ventilation.

Unfortunately, a ducted HVAC system can create air currents that could carry larger viral particles around the room, exposing the people inside at a higher risk of contracting the virus. This is what can happen if there is not a careful management of the air conditioning system. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) both published their guidance, providing information and suggesting mitigation measures [73] [74]. Both associations share the position that ventilation and filtration provided by heating, ventilating, and air-conditioning systems can reduce the airborne concentration of SARS-CoV-2, but this can happen only with changes to building operations.

A distinction between types of air conditioning systems is necessary. The air conditioning system, which also provides ventilation, by introducing external air helps to reduce the risk of infection by dilution. Not all air conditioning systems (i.e. that control the temperature and humidity of the indoor environment) are equipped with the ventilation function. The advantage of mechanical ventilation, whether dedicated or included in the air conditioning system, is the possibility to filter the external air introduced into the room, i.e. to purify it from dust, suspended particulate matter, pollen, etc., which is obviously not possible by simply opening the windows, and to be able to provide each room at any time, regardless of external climatic conditions, the desired amount of external air. These types of systems are those usually used for the air conditioning of large common areas, such as supermarkets, because in their design is always required to provide ventilation air (i.e. the introduction of a certain amount of external air). To reduce the risk of infection in such contexts, such systems should operate with as much external air as possible compatible with the characteristics of the system itself.

In order to economize on energy consumption, the air conditioning introduced into the rooms usually consists of a mixture of external air and "recirculated" air, in order to allow the recovery of heat from exhausted air. The recirculated air is the air taken from the internal environment, passed through a filter, and fed back into the machine that treats the air, where it is mixed with the external air, cooling it (if we are in summer) or heating it (if we are in winter) and thus reducing the need for thermal power that the system must provide to bring it to the desired conditions [75]. Mounted filters are not able to clean the air from the viral charge (each SARS-CoV-2 virion is approximately 50–200 nanometres in diameter), for this reason the use of recirculated air could be dangerous, even if this has not been demonstrated.

As already stated, the transmission of COVID-19 disease occurs mainly by direct airborne transmission through inhalation of respiratory droplets produced when an infected person coughs, sneezes or simply exhales. It is important to note that droplets larger than 5μm generally propagate only over short distances. Less frequently, transmission can occur indirectly by touching a surface or object, on which the virus is present, and then touching the mouth, nose, or eyes. Another possible mode of transmission of the disease, exclusively in hospitals, is that due to the formation of aerosols in infected patients who undergo some medical manoeuvres such as performing nasopharyngeal swabs, tracheal intubation, bronchial aspiration, bronchoscopy, cardiopulmonary resuscitation. These particles smaller than 5μm can remain in the air for long periods of time and travel, transported by turbulent movements, several meters.

Referring to this last aspect, it has been hypothesized, but not demonstrated, that the air conditioning can aerosolize the virus and transmit it at a distance.

Despite this, in an outbreak of infection that occurred in January 2020 in a restaurant in Guangzhou, the transmission of the infection between people sitting at different tables and more than one meter apart was demonstrated. In this situation, Chinese researchers have shown that the air conditioning jets created strong air currents that could push the droplets of saliva emitted by the infected customer at a considerable distance. After this study, the researchers recommended that, to prevent the spread of the virus in restaurants, is necessary to increase the distance between tables and to improve ventilation [76].

In the light of current knowledge, therefore, ventilation and air conditioning systems are not a direct cause of transmission of the infection but could promote the dispersion and diffusion of possibly infected saliva droplets.

However, it has been proven that ensuring a good air exchange (natural or mechanical) and regularly cleaning the rooms and filters of ventilation systems are actions that limit diffusion, just as it is not recommended to keep air recirculation active.

The second point is strictly related to the lockdown. Well over 100 countries worldwide had instituted either a full or partial lockdown by the end of March 2020, affecting billions of people (BBC News, 2020).

The obligation to stay at home has disrupted the everyday life of citizens and has had a strong impact on their day and the way they spend their time.

Although in the short term, the lockdown definitely had a positive impact on the environment. Smart working has made it possible to reduce home-office travel, resulting in improved air quality in cities, reduced PM, reduced emissions of CO2 and other greenhouse gases. The significant drop in emissions from airlines has also played an important role. This small revenge of the environment on mankind, unfortunately, has been paid dearly but the hope is that it has managed to teach something to humanity.

Apart from these positive aspects, the lockdown has generated a not insignificant economic collapse, difficulties for many families and people who had to close, in some cases irreversibly, their businesses.

There are many issues touched by this unique situation, and it is difficult, if not impossible, to analyse them all. An aspect that might have been left in the background is the quality of the interior environment of citizens’ home. People's attention in recent months and especially in the first period of 2020, focused mainly on the risk of infection, disregarding the indoor air quality of the buildings.

A study made in Madrid describes a comparative longitudinal survey of air quality in four types of housing in the city before and during lockdown. The paper analysed indoor temperatures and variations in CO2, 2.5 µm particulate matter (PM2.5) and total volatile organic compound (TVOC) concentrations before and during lockdown, with very interesting outcomes. As can be expected, the average PM2.5 concentration decreased as the city's air quality was clearly improving. Despite this, however, the exposure of the population to pollutants within the domestic environment was more acute and prolonged than in the pre-lockdown period [77].

It is common that the concentration of pollutants inside a house is higher than outside and often this is due to poor ventilation. Never more than now, during this health emergency, good air exchange is essential.

SBS symptoms are likely to have increased during the pandemic lockdown. The Sick Building Syndrome, as mentioned above, manifests itself through a combination of symptoms related to permanence in the building such as: irritation of the skin and mucous membranes, psychic fatigue, difficulty in concentration, eye irritation, blocked or stuffy nose, throat irritation and dryness, cough, headaches, nausea, fatigue, lack of concentration, dizziness, lethargy and more. Since SBS disorders afflict individuals who spend many hours indoors, lockdown was the perfect context for the manifestation of these symptoms. During the lockdown period there has been an increase in the use of household products, in particular to disinfect rooms. What was supposed to be a way to protect oneself, in many cases, had the opposite effect. The excessive use of disinfection and evaporation of these products combined with the lack of adequate ventilation can increase chemical pollution of indoor air and thus the risk of contracting SBS symptoms [78].

The situation generated by the COVID-19 emergency represented a singular event, which will allow to deepen the study of air quality and may provide useful elements to evaluate and review the measures, in the short and medium term, that are adopted by the authorities to reduce indoor air pollution.

It could be seen also as an opportunity to create awareness toward healthy housing and construction techniques. Tendentially, as already stated, green, sustainable, and high efficiency buildings like nZEBs and PEBs are more focused on user’s health and well-being. Unfortunately, as about one third (35%) of the EU building stock is over 50 years old, more than 40% of the building stock was built before 1960 and 90% before 1990 [79], a large-scale renovation and reconstruction work is necessary not only to achieve the objectives that the European Union has set for itself in terms of energy efficiency but also for the needs of citizens in terms of welfare and health, especially in this period of great uncertainties for what concerns the virus.

3. Follow-up and the economic impact

Co-impacts definition and categorization were just the first steps towards their economic evaluation. The first phase in Cultural-E WP5 deals with identifying the nature of the co-impacts of PEBs and related technologies. Now, assessing the magnitude of these co-impacts and estimating their monetary value is the follow-up of this working package. Once this is done, it will be easier to define within which values an increase in benefits is no longer justified by the extra costs. One of the ambitions goals of CULTURAL-E is to be able to propose to investors the most accurate estimation of the different co-impacts and an effective evaluation method. Specifically, the evaluation will initially be based primarily on 'household level' co-impacts with a strong focus on IEQ conditions and the impact they have on user health and well-being. Successively, the monetary estimation of co-impacts will include the community level.

Searching the literature, most attempts have been made with a direct specific interest in offices, mostly related to air quality and thermal comfort and the resulting increase in productivity. This is mainly because, up to this point in research, there is not an applicable evaluation method and a common methodology to quantify the effect of each co-impact has not yet been developed. There is still a large gap between methods used to quantify co-impacts related to more direct measurements versus others that are more difficult to assess. Based on a study by Bleyl et al. [44], for example, the already mentioned CRAVEzero project, repurposed a graph showing relevance for business case of the co-impact and the difficulty of quantification (fig. 9). Some co-impacts identified by CRAVEzero are similar or the same as those presented above in this thesis, and the graph shows how more abstract concepts such as aesthetics and reputation are among the most difficult to evaluate economically, while on the opposite side we find avoided CO2 emissions, which are easier to evaluate as they are measurable, or at least simpler to estimate [25].

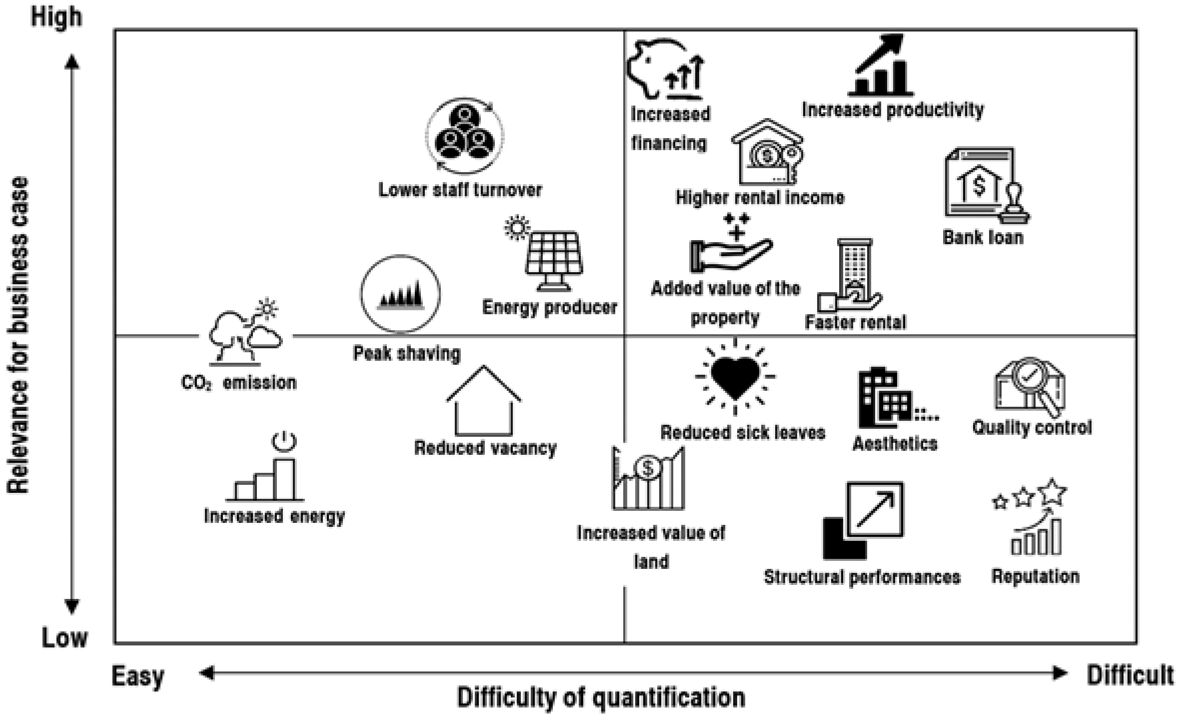

Fig. **9** Co-benefits classification (CRAVEzero project)

A few examples may help to better understand why it is important to quantify and monetize the co-impacts.

Regarding the co-impact identified as 'health improvement', for example, we can report studies done on dampness and mould in buildings. Scientific literature has already shown that there is a correlation between dampness and mould in buildings and the increase of the risk of health effects usually associated with the respiratory system [80]. In a study published in 2007, Mudarri and Fisk tried to evaluate the economic impact of dampness and mould exposures at home in the US. In their study they estimated that approximately 4.6 million cases of asthma in the USA result from exposure to dampness and mould and that the resulting economic cost of this health impact is approximately $3.5 billion annually [81]. Despite the significant uncertainty of some estimations, they demonstrate the importance that a healthy environment can have also in economic term. Many examples of this type are readily available in the literature, too often, however, the methodologies used differ. There is therefore a need to identify a methodology that best exploits each co-impact in the most accurate way, and to be structured and reproducible as a significant contribution to the field of the building sector.

A brief overview of the various methods used so far is reported below as a prompt for further developments of this work.

According to the investigated works, two types of techniques are mainly used to evaluate environmental assets:

- monetary valuation, where the reference criterion is the willingness to pay;
- non-monetary evaluation, by using multi-criteria analysis.

Monetary methods can be either indirect or direct. Indirect methods use the relationships established between environmental goods and private goods during the consumption activity. The fruition of the environmental good is often possible because there is a complementarity with the consumption of private goods whose price is easy to obtain (e.g. to visit a park it is generally necessary to sustain a cost for the movement, for the consumption of the meal outside the house and eventually to buy the entrance ticket). Through the construction of a demand curve of private goods and services involved in the use of environmental resources, it is therefore possible to derive the demand function of the latter. These methodologies do not allow the determination of the value of non-use of the resource; thus they imply as a premise the actual use of the asset.

Travel cost and hedonic price are two typical indirect approaches. They relate to existing markets and actual consumer behaviour. These methods estimate use values only and operate on the basis of the behaviour or choices made by operators.

When it is not possible to establish a connection between consumption or the value of private goods and the environmental asset being evaluated, or when the objective is to determine values not associated with actual use of the resource, direct methods are used.

Direct methods try to estimate the value of an environmental good by simulating the market (hypothetical market). This simulation is based on interviews where the subjects consulted are asked to express their willingness to pay (WTP) to preserve a certain environmental resource, or their willingness to accept (WTA) compensation for giving up the use or existence itself.

Among the direct approaches, Contingent Valuation abstracts from actual behaviour and directly asks potential consumers for the measures sought. This method refers to potential users operating in the absence of real markets. It can be used to estimate measures of well-being in a variety of situations and is particularly well suited to assessing qualitative and quantitative improvements or deteriorations. This method is implemented through a questionnaire that asks a sample of respondents what value they place on the asset to be valued.

The main limitation of this method is that it is subject to distortions linked to the strategic behaviours of the interviewees and other errors linked to the hypothetical nature of the evaluation. The results can be influenced by factors such as market structure, the information provided, the way in which the value measure is expressed, and the technique adopted to arrive at the final value.

Non-monetary methods are used for technical investigations in which each environmental asset is evaluated according to the most appropriate technical parameter to express its status.

The assessment is carried out by means of multiple-criteria analysis techniques. This approach has at least two strengths:

- First, it provides a framework for bringing together quantitative and qualitative information;
- Second, it allows for the incorporation of stakeholder preferences, which often vary on environmental issues.

Multiple-criteria decision analysis (MCDA) includes a number of techniques aimed at providing a general order of options from most important to least important, thus allowing for the effective treatment of choice problems characterized by aspects that are difficult to evaluate in monetary terms.

In the context of the Cultural-E project, the assessment and quantification will focus starting on indoor environmental quality (IEQ), being a key aspect connected with users. The analysis will therefore assess the co-impacts strictly connected with the four main aspects of IEQ, namely thermal comfort, acoustic comfort, visual comfort, and indoor air quality.

Up to this point, no method has been yet conducted and tested, since the discussion on which to be used is still opened and only first assumptions have been done. Contingent valuation is one of the methods that might be taken into consideration since it allows to estimate goods that do not have market values, reason why it is already widely used in the environmental field [82]. For this purpose, the use of questionnaires is common, in order to collect data for the estimation of the users' willingness to pay [83]. A statistical analysis will then be implemented with the data collected, thus, in order to maximize the accuracy of the evaluation, the sample must be representative of the reference population.

It is relevant to note that the available literature comes from a limited number of studies limited to a few countries and it cannot be assumed that the same results will be achieved in all countries in the same way and at the same time. Despite co-impacts definitions are quite universal, their values depend from case to case, from the geographical location and other socio-cultural factors, hence it is not easy to obtain significant conclusions and achieve a generalization [27]. One of the main goals of CULTURAL-E, with this study, is to be able to help accelerate the deployment of energy-plus homes and related technologies by strongly supporting their widespread application and inclusion. To do so, this process is vital in order to provide evidence to building owners, users, and decision makers, showing them that taking into account co-impacts is necessary and can be beneficial and to a final extent, to provide stakeholders in the market with a strategy for promoting and raising the engagement for this new generation of buildings. Policy makers, thanks to this study, may also be encouraged and urged to elaborate further policies for supporting the increase of the share of energy-plus homes in the residential building stock.

4. Conclusions

With the building sector responsible for almost one-third of global CO_2 emissions, there is the need of a change of pace. The residential sector needs projects that have to go beyond the emission reductions aiming for complete decarbonization. To make this a reality that has an impact, the concept of Plus Energy Building has to become the common practice, and the extra-cost associated with the more advance technologies has to be justified with an all-embracing benefit analysis. Understand all the benefits of energy efficient technology is key. To refer to the secondary, indirect benefits of energy savings or certain building types, there are numerous terms in the literature, sometimes conflicting with each other, that can lead to confusion and lack of clarity. The literature review that has been conducted has led to the proposal of the term "co-impact" to encompass both the positive and negative secondary effects that a Plus Energy Building can have. The need was precisely to propose and adopt terminology that would bring some uniformity so that it could be adopted with clarity and confidence from this point forward. This is something that was essentially absent or only briefly mentioned. Adding this element was critical to being able to create a solid baseline so that we could then proceed with the economic analysis of the individual co-impacts. Next, I grouped these co-impacts into macro-categories and then I defined the individual ones in order to have a good starting point for the economic evaluation that will be done in the near future. Subsequently, the problem of Sick Building Syndrome and the recent Covid-19 problem were addressed to emphasize the importance of a proper indoor environment for the well-being and health of the user.

As stated in the IPCC AR5, the building sector is changing not only because of technological development, but more importantly because of its extensive systemic application, in part as a result of advanced policies, as well as in improvements in the performance and cost reductions of various technologies [19].

The hope is that this work will be a starting point to help expand a more sustainable type of building, attentive to both the needs of users and those of the planet. Plus Energy Buildings have the potential to become the leading building type in the construction market, and projects like Cultural-E that aim to offer reproducible technologies tailored to the user and the context in which they live can help further reduce consumption and incentivize this type of building technique.

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