White Paper

Task Force 2: Efficient Building Operation

Topic C:

Smartness to reduce environmental impacts

Revision: V4

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Executive summary

The SmartBuilt4EU project has set up four task forces investigating issues related to smart buildings: their objective is to identify the remaining challenges and barriers to smart building deployment, and the associated research and innovation gaps that should be addressed in the near future.

*Task force 2 focuses on the optimal integration and use of smart solutions to allow an efficient building operation. The task force investigates what are the interoperability requirements to ensure a seamless operation, as well as the optimisation in terms of building costs and reduction of environmental impacts, over the full life cycle. The third topic addressed by this task force and presented in this paper is **'Smartness to reduce environmental impacts'.***

The way we live in the built environment needs to become more sustainable - and even go beyond sustainability, towards "regenerative" buildings that will both restore and improve the natural environment (and humans likewise).

Most of the environmental impacts of buildings are generated during the operation phase, the main impacts being on energy use (fossil fuels) and climate change. The operational energy can indeed vary between 70% and 90% of the whole life cycle energy consumption of a building, whilst the embodied energy generally ranges between 10% and 30%. Beyond climate change mitigation, the minimisation of environmental impacts should also tackle other key challenges: ecosystem quality, human health and wellbeing, resource availability.
Smart technologies can support this change of paradigm, from "less bad" to "more regenerative". However the way smart systems can contribute to the reduction of environmental impacts (beyond operational energy), is still to be investigated. And the environmental impacts of the devices themselves as well as potential rebound effects are a cause for concern which has to be addressed.

This white paper therefore aims to provide an overview on what is known and what should be further investigated to answer the following questions:

- Is there a direct link between a building's smartness and automation level and the reduction of the environmental impacts linked with the operational phase of the building?
- If so, is it possible to quantify the net benefit taking into account the emissions released in the entire lifecycle of the installed smart devices?

In its first part, this paper provides a state of the art regarding the following points, with specific attention being paid to EC-funded projects:

- Environmental impacts that can be reduced by smartness,
- Smart tools, devices and solutions to reduce the environmental impacts of a building,
- Environmental impacts of the devices themselves.

A brainstorming process then enabled to identify some key barriers and drivers regarding the optimisation of building costs. The next diagrams provide an overview of the main barriers and drivers discussed.

BARRIERS	
VALUE CHAIN	Fragmentation of the construction sector with no flow of information between the different players and across the different phases of the building life
	Lack of skills and awareness from the construction sector with regard to energy efficiency and more generally environmental impacts
SOCIAL	Lack of awareness and knowledge from building owners of environmental impacts of buildings and how they can be alleviated by smart technologies
	Low acceptance and lack of commitment from users, leading to an inefficient use of smart systems limiting the environmental impacts
	Unclear responsibility with regard to decision-making and investment in smartness, especially in condominiums
TECHNICAL	Integration challenges across solutions and sectors, with interoperability issues
	Lack of information on the environmental impacts of smart devices themselves (with a life-cycle approach)
	Lack of unified LCA tool and lack of standardised life-cycle approach using Digital Twins
ECONOMIC	Lack of financial incentives targeting smart systems that limit the impacts on the environment
	Unattractive Return on Investment and Cost Benefit calculations (partly because those to do not integrate externalities such as environmental impacts)
	Recent increase in prices of building material and equipment
REGULATION & STANDARDS	Lack of standardisation for smart devices and smart buildings
	Lack of compatibility of EU and national network codes with latest digital tools
	Slow transposition and/or implementation of EU Directives (EPBD in particular)

Top barriers according to the Task Force

Figure 1: Overview of main barriers

DRIVERS	
VALUE CHAIN	Market push: business opportunity for smart solutions
	New opportunities arising from the ESCO business model
SOCIAL	Increasing citizens awareness of their individual environmental impacts
	Increase in citizens engagement and citizen-driven actions to contribute to the clean energy transition, better connect within communities and with their environment
TECHNICAL	Broader use of BIM and Digital Twins, enabling automated LCA
ECONOMIC	New data-driven services and financial return from the exploitation of smart systems data
	Availability of funds through the EU Recovery and Resilience Facility
REGULATION & STANDARDS	Uptake of SRI, Digital Building Logbooks, etc. with potential to improve how they reflect the environmental impacts of a building
	Push from EU Regulation: ZEB and positive buildings (e.g. EPBD), EU directives and strategies on circularity and ecodesign
	Corporate Environmental and Social Responsibility as a driver for companies to invest in smart system proving a reduction of the impacts on the environment

Top drivers according to the Task Force

Figure 2: Overview of main drivers

Based on the State of the Art and the barriers and drivers, a number of research and innovation gaps were identified. They are synthetised in the next diagrams (the ones in bold are those that were identified as priorities in the last meeting with the task force members).

These 'gaps' will feed the elaboration of the Strategic Research and Innovation Agenda on smart buildings that will be produced by the SmartBuilt4EU consortium by mid-2023, together with some recommendations targeting policy makers.

R&D	**Develop common LCA methodologies and indicators tailored to smart systems and their environmental impacts, in cooperation with the industry**	*Top priorities according to the Task Force*
	Expand research on social acceptance, building upon Post Occupancy Evaluation methodology	
	Innovate in interoperable smart systems that allow to minimise environmental impacts, beyond energy (e.g. in the fields of water, waste)	
DEMO	**Run experiments and demonstration activities in pilot buildings to show the usefulness, effectiveness and optimal conditions of use of new smart systems minimising environmental impacts, in line with needs from the industry, and with shared assessment metrics**	
	Share results as open datasets, using building data semantics	
	Demonstrate how Digital Twins used throughout the lifecycle of a building can support the minimisation of environmental impacts (including using simulation to define best scenarios)	

Figure 3: R&I gaps

SCALING UP & INDUSTRLIALISATION	**Use lighthouse buildings to showcase good practices and provide long-term datasets to support replication & scaling up**	*Top priority according to the Task Force*
	Improve knowledge transfer from EU funded & research projects to industrials through e.g. industry associations	
REGULATION & LEGAL FRAMEWORK	Improve and implement business models such as Energy Performance Contracting and ESCO models to support the roll-out of smart systems	
	Enlarge the SRI to include broader environmental impacts as well as resilience and include the SRI score as part of EPC	
	Use data from smart systems as evidence of 'green' activities to support claims related to the EU Taxonomy, and to steer policy development	
	Set up minimum requirements for repairability and recyclability of smart sensors and actuators	
CERTIFICATION & STANDARDISATION	Expand the use of well-established building certification schemes, e.g. LEED, BREEAM, DGNB, and streamline the use of dynamic sensor data as proof of performance	
	Activate more widely the EN ISO 52120-1 standard (Energy performance of buildings — Contribution of building automation, controls and building management)	

Figure 4: 'Go-to-market' gaps

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List of abbreviations

AI	Artificial Intelligence
AoP	Areas of Protection
BACS	Building Automation and Control System
BCT	Blockchain Technologies
BDA	Big Data Analytics
BDT	Building Digital Twins
BE	Built Environment
BEMS	Building Energy Management Systems
BIM	Building Information Modelling
BMS	Building Management Systems
BREEAM	Building Research Establishment Environmental Assessment Method
BRP	Building Renovation Passport
DBL	Digital Building Logbook
DR	Demand Response
EC	European Commission
EEB	Energy Efficient Building
EMS	Energy Management Systems
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
EPD	Environmental Product Declaration
GHG	Green House Gases
HEMS	Home Energy Management System
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technologies
IEQ	Indoor Environmental Quality
IoT	Internet of Things
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
LCSA	Life-Cycle Sustainability Assessment
LEED	Leadership in Energy and Environmental Design
KPI	Key Performance Indicator
nZEBs	Nearly Zero Energy Buildings
PEBs	Plus Energy Buildings
POE	Post-Occupancy Evaluation
PV	Photovoltaic
RES	Renewable Energy Sources
R&I	Research and Innovation
SRI	Smart Readiness Indicator
TF	Task Force

1 Introduction

This white paper is produced in the context of the SmartBuilt4EU project, a coordination and support action funded by the European Commission to bring together the research and innovation community on smart buildings.

The SmartBuilt4EU project has set up four task forces with volunteers all across Europe, investigating topics related to smart buildings. They respectively address the interaction between building and end-user, efficient building operation, interactions between the building and the external environment, and cross cutting issues.

Figure 5: The four Task Forces set up by the SmartBuilt4EU project

SmartBuilt4EU task force 2 focuses on the optimal integration and use of smart solutions to allow an efficient building operation. The task force investigates what are the interoperability requirements to ensure a seamless operation, as well as the optimisation in terms of building costs and reduction of environmental impacts, over the full life cycle.

The task force will focus on 3 topics (one per semester):

1. **Interoperability:** Interoperability among building components & systems
2. **Optimised building costs:** Integrating tools for optimised costs over the full life cycle (incl. BIM, digital twin, predictive maintenance, Artificial Intelligence, weather forecast, predictive control)
3. **Smartness to reduce building's environmental impacts:** Integrating tools to reduce the environmental impact over the full life cycle, paying attention to the carbon footprint of smart solutions (incl. Resource efficiency, Environmental impact management, Integration of renewable energies)

The present white paper focusses on the third topic, i.e. 'Smartness to reduce building's environmental impacts' and presents the outcomes of a collective work, carried out with the members of the task force, in several steps:

- Agreement on the scope
- Review of the State of the Art and identification of the points to be investigated in particular
- Analysis of barriers and drivers
- Identification of R&I gaps
- Key conclusions on the topics and recommendations

2 Topic under investigation by the Task Force

2.1 Rationale

The way we live in the built environment needs to become more sustainable - and even go beyond sustainability, towards 'regenerative' buildings that will both restore and improve the natural environment (and humans likewise).

Most of the environmental impacts of buildings are generated during the operation phase, the main impacts being on energy use (fossil fuels) and climate change. The operational energy can indeed vary between 70% and 90% of the whole life cycle energy consumption of a building, whilst the embodied energy generally ranges between 10% and 30%. Beyond climate change mitigation, the minimisation of environmental impacts should also tackle other key challenges: ecosystem quality, human health and wellbeing, resource availability.
Smart technologies can support this change of paradigm, from "less bad" to "more regenerative". However the way smart systems can contribute to the reduction of environmental impacts (beyond operational energy), is still to be investigated. And the environmental impacts of the devices themselves as well as potential rebound effects are a cause for concern which has to be addressed.

This white paper therefore aims to provide an overview on what is known and what should be further investigated to answer the following questions:

- What are the types of environmental impacts that can be reduced by building smartness?
- What are the smart solutions and devices that enable the reduction of environmental impacts, e.g. through a better integration of RES, more resource efficiency, less energy/ water consumption, etc…
- What are the environmental impacts of the devices themselves, e.g. in terms of energy consumption, use of raw materials?

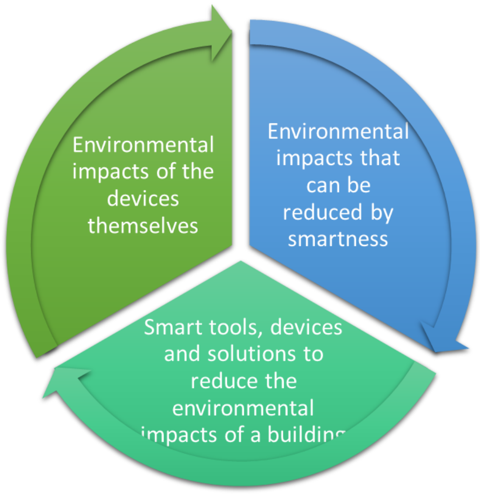
2.2 Scope

The purpose of this section is to define the scope of the topic being investigated. Potential interactions with other topics addressed by the different SmartBuilt4EU task forces are also clarified.

The following 'blocks of knowledge' were identified during the 1st meeting of the task force:

- **Environmental impacts that can be reduced by smartness**
- **Smart tools, devices and solutions** to reduce the environmental impacts of a building
- **Environmental impacts of the devices themselves**

Please note that life cycle costing (and more generally life cycle approach) was already covered in the 2nd topic addressed by task force 2. Well-being is covered in task force 1.



3 State of the Art

3.1 Literature review

3.1.1 Environmental impacts that can be reduced by smartness

Within the built environment, buildings are amongst the principal generators of environmental externalities. The environmental impacts of buildings over their lifetimes are determined by several factors including materials, design, construction, use, and demolition.

Environmental Impacts of buildings from a Life Cycle perspective

Life cycle assessment (LCA) can be used to quantify life cycle environmental impacts of buildings. This methodology enables to apply a complete life cycle perspective that combines materials (the embodied building impacts) and building operation (e.g. water and energy consumption).

As already outlined in the white paper of task force 2 Topic B, LCA supports optimal design through the minimisation of environmental impacts, and informed decision making. It can find several important applications in buildings to contribute to their quality, energy efficiency and sustainability. Although there is still room for further innovation and improvements in LCA methodologies (e.g. better account for indoor environment and the impact on well-being, performance and behaviour of occupants (Ingrao et al., 2018); harmonisation of methodology at international level in line with standards such as EN 15978; increased transparency of assumptions made (Röck et al., 2020)), they have proved their value in supporting environmental planning and stimulating sustainability of the built environment (Ingrao et al., 2018).

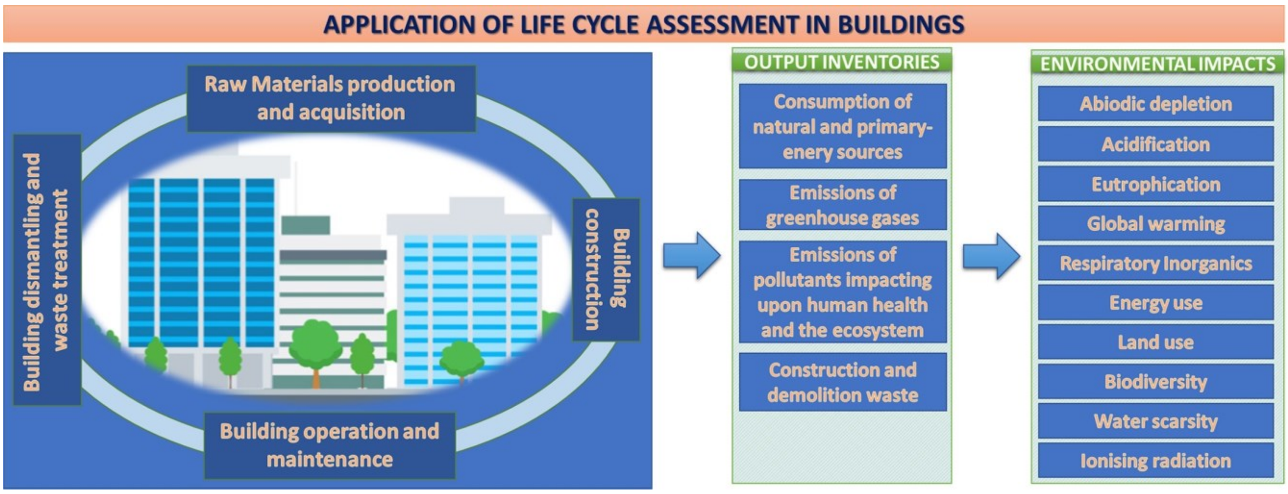


Figure 6: Application of Life Cycle Assessment in buildings – overview, after Ingrao et al. (2018)

An LCA organises the environmental impacts in different categories, for which specific indicators of impact are used. Along the impact pathway that leads from inventory flows (i.e., emissions into the environment) to the damage that they cause on the so-called areas of protection (AoP), they can be located anywhere. While different definitions of the AoP exist, a very often used one is the one that identifies three of them: Human Health, Natural Environment and Natural Resources (Hauschild et al. 2013). If the impact indicators are characterised along the pathway between the inventory flows and the AoPs they are called 'midpoint' indicators, while if they are characterised at the endpoint level they are called 'endpoint' indicators, as illustrated in Figure 6. Characterizing indicators at the endpoint level requires modelling of the whole impact pathway to the point where the impacted entities are the very areas of protection that are damaged by the impacts and this certainly entails more uncertainty than the estimation of the midpoint characterisation. Endpoint characterisation modelling is sometimes also called 'damage modelling'.

These categories depend on the method used for Life Cycle Impact Assessment, the following being suggested as most relevant for buildings by (Ingrao et al., 2018):

- Abiotic depletion
- Acidification
- Eutrophication
- Global warming
- Respiratory inorganics
- Energy use
- Land Use
- Biodiversity
- Water scarcity
- Ionising radiation

Most of the environmental impacts are generated during the use phase (or operation phase), the main impacts being on energy use (fossil fuels) and climate change. The literature indeed indicates that the operational energy can vary between 70% and 90% of the whole life cycle energy consumption of a building, whilst the embodied energy generally ranges between 10% and 30% (Ingrao et al., 2018).

This is illustrated in the LCA below, performed for a conventional Italian building by Asdrubali et al, 2013 (Figure 7).

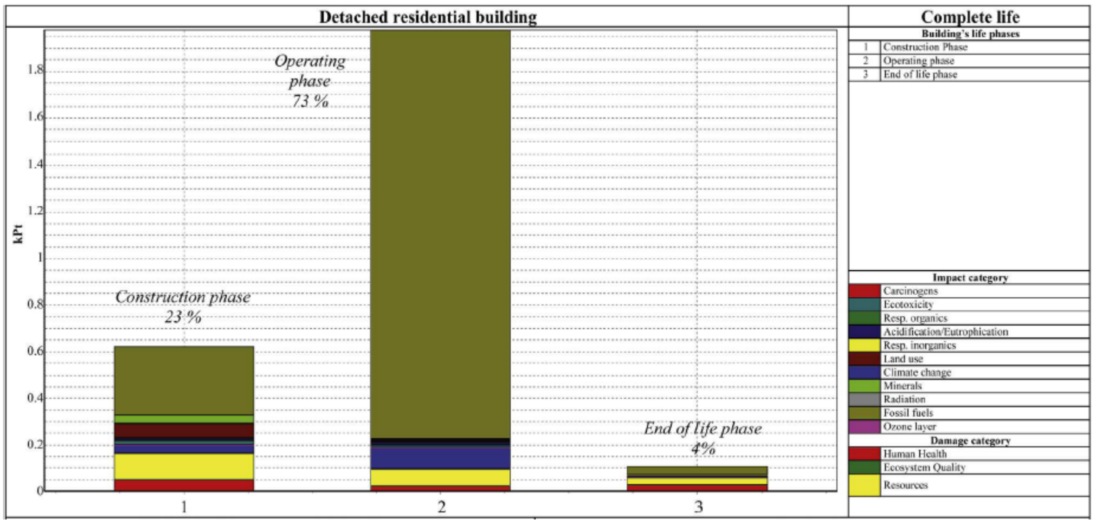


Figure 7: relative contributions of the life-cycle phases to the overall impact of the three buildings, using the Eco-indicator methodology (Asdrubali et al, 2013)

This LCA also shows that within the operational energy, heating has the highest impacts (Figure 8).

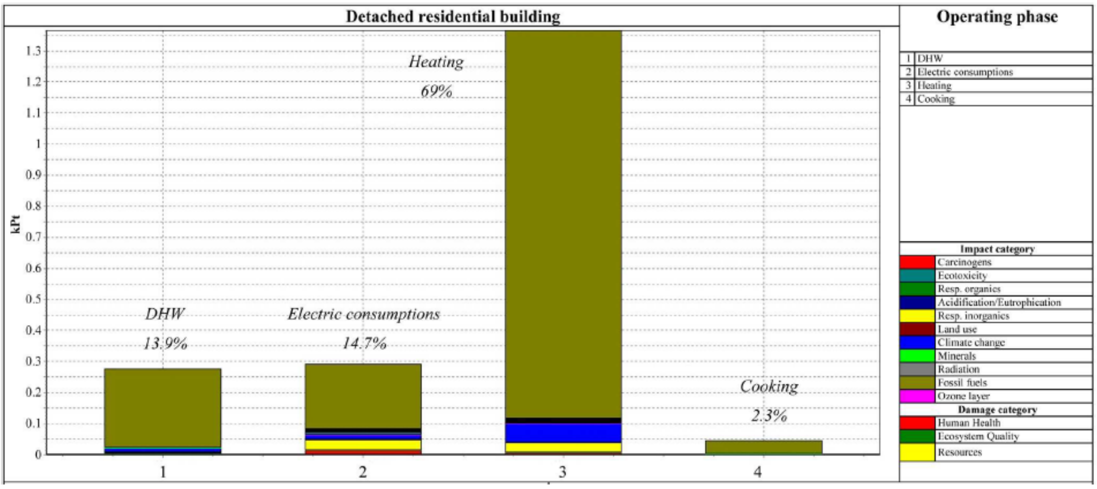


Figure 8: relative contributions of different energy usages to the operating phase (Asdrubali et al, 2013)

With regard to electric consumption from appliances, an average electricity use (excluding electricity used for heating purposes) was estimated[1] using data contained in (Gulotta et al. 2020) for single-family and multi-family houses (in a moderate climate context and referring to years 1990 to 2010), broken down in percentages for different types of electric appliances:

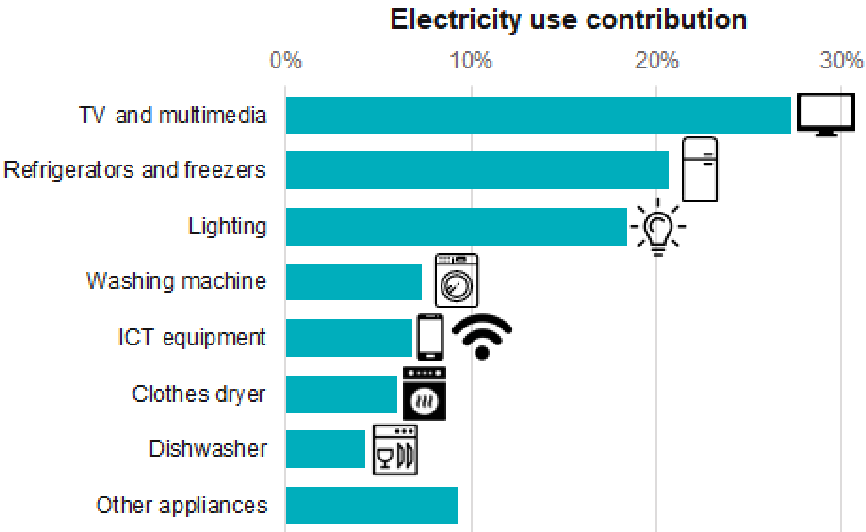


Figure 9: Average percentage contribution of electric appliances to household total electricity use.

ICT equipment contribute thus to about 7% of the total electricity use (excluding electricity used for heating purposes) in residential buildings.

Reduction of the Environmental Impacts of buildings

LCA is a valid tool to put Life Cycle approaches into practice. It should be implemented during the design of buildings for the assessment not only of the main environmental burdens, but also of the improvements to be made in the life cycle of that building for its enhanced quality and sustainability. LCA indeed leads to a

[1] https://www.youtube.com/watch?v=8wbVOzsHXxg

greater understanding of the ways each downstream phase is affected by the technological choices made upstream, and how that can be addressed and improved if needed (Ingrao et al., 2018).

Through several iterations of LCAs, it is therefore possible to compare different packages of technological solutions and designs so as to select those enabling the minimisation of environmental impacts. This scenario-based approach, which should ideally be updated at each key stage of the building lifecycle (e.g. when its heating system gets retrofitted, or when it goes through a deep renovation), could be supported by innovative approaches with dynamic data feeds, such as Digital Twins (Boje et al., 2021).

So far, most of the efforts have focussed on decreasing the energy use in the use phase, in particular related to space heating and domestic hot water. However as operational energy (and corresponding GHG emissions) decreases thanks to better insulation of the envelope and improved building energy systems and management systems, the share of embodied energy increases. While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings (Röck et al., 2020, Figure 10 – assuming a 50-year period).

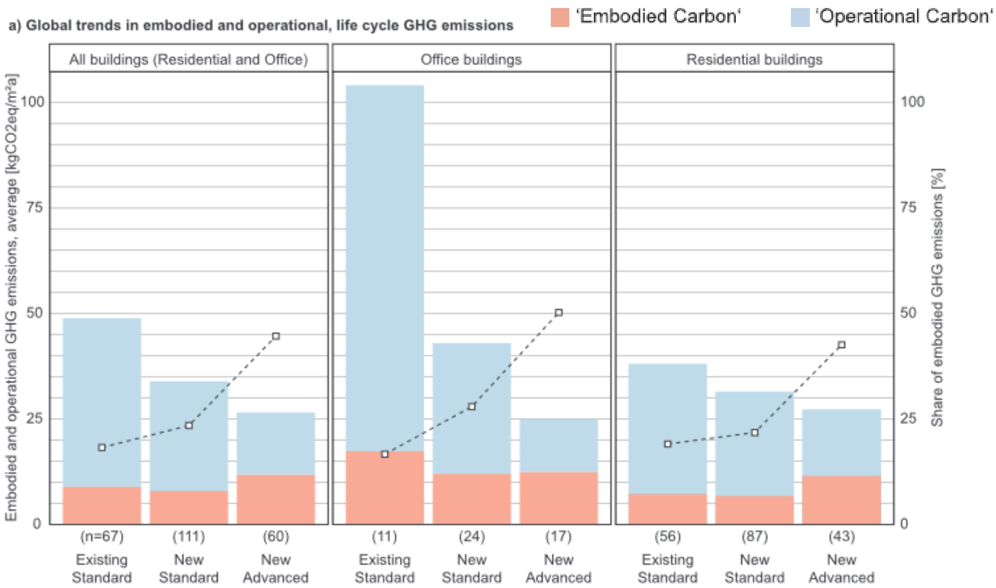


Figure 10: Global trends in embodied and operational, life cycle GHG emissions, after Röck et al., 2020

This calls for new approaches to reduce energy use in the building life cycle: to achieve the required 'near-zero' energy performance for both new and existing buildings, additional embodied GHG investments in building materials and systems are necessary. As these embodied GHG emissions are occurring upfront, i.e., at (or prior to) the time of construction, they are exceptionally relevant considering the need to decarbonise the global economy while respecting limited GHG emissions budgets (Röck et al., 2020). Construction industries therefore need to decarbonise their production (manufacturing of materials and construction processes – in line with the proposal for a revised Construction Products Regulation (CPR), adopted on 30 March 2022). They also need to move towards more circularity, including the reuse and upcycling of construction materials (according to the new Circular Economy Action Plan (CEAP) adopted in March 2020[2]), and better decision making between renovation and demolition.

[2] Circular economy action plan (europa.eu)

Beyond climate change mitigation, the minimisation of environmental impacts should also tackle other key challenges: ecosystem quality, human health and wellbeing, resource availability. This is the objective pursued by **regenerative design**, which strive to design buildings with positive impacts, enabling to restore ecosystems and resources, along different lines that go in the direction of a "system thinking" approach, which is the overarching concept of regenerative design and regenerative sustainability (Reith and Brajković, 2021)**:**

- Generating & storing energy
- Climate adaptation & adaptation to natural hazards
- Water storage and treatment: objective of net-zero water use
- Resource upcycling
- Assisting biodiversity (minimisation of impacts, habitat creation, etc)
- Enhancing relationships between humans, their community and their environment along time

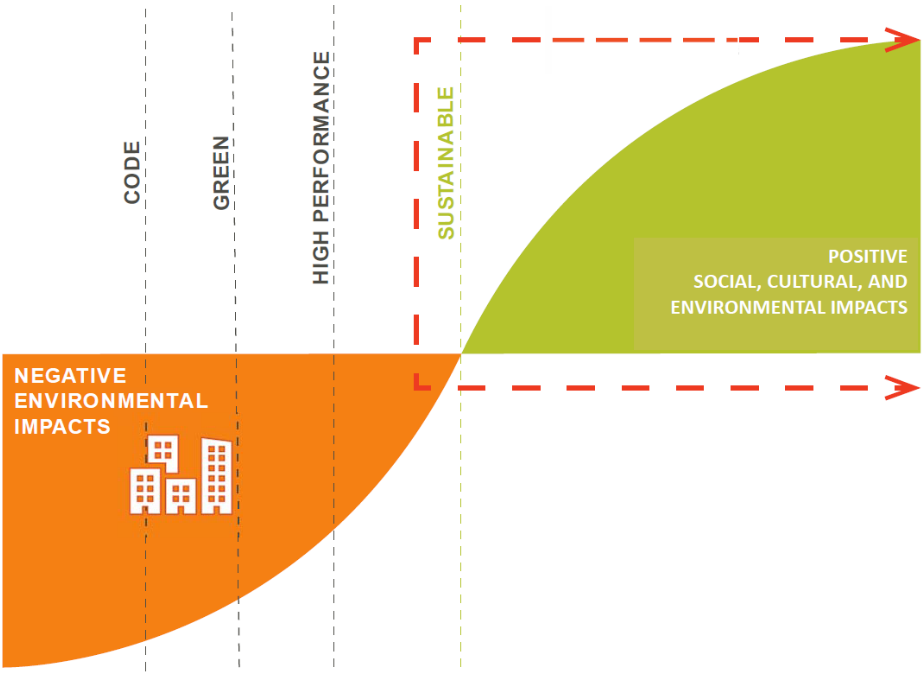


Figure 11: Going beyond sustainability, with regenerative buildings (after RESTORE COST Action)[3]

How can building smartness support the implementation of this approach and make it more accessible?

3.1.2 Smart tools, devices and solutions to reduce the environmental impacts of a building

Building smartness can be defined as "the ability of a building or its systems to **sense, interpret, communicate and actively respond** in an efficient manner to **changing conditions** in relation the operation of technical building systems or the external environment (including energy grids) and to **demands from building occupants"**

[3] https://www.eurestore.eu/

When investigating the environmental impacts that can be reduced by smartness, the reduction of the operational energy was the most cited by the task force members. This is reflected by the smart readiness indicator, which defines three key smart-readiness functionalities and seven impact criteria, most of them related to operational energy and comfort and well-being (Figure 12).

Van Thillo et al. (2022) have for instance investigated the potential of building automation and control systems (BACS) to lower energy demand in residential buildings, finding various levels of attainable percentage reduction in buildings' energy and water consumption depending on various factors like building design, installation design, occupants' behaviour, climate zone, latitude and orientation.

Figure 12: Smart-readiness functionalities and impact criteria defined in the Smart Readiness Indicator

The way smart systems can contribute to the reduction of other environmental impacts, beyond operational energy, is however less straightforward, and limited literature exists on this specific topic.
The Task Forces members listed the following:

- increased demand flexibility, RES generation and sharing (as illustrated in Figure 13)
- optimised operation & maintenance in terms of energy (see also Figure 13) & water consumption
- reduced waste and increased circularity/ re-use potential
- increased resilience to climate change and natural hazards
- reduced disturbance to the environment (e.g. light pollution)

Figure 13: Illustration of some of the expected advantages of smart technologies in buildings, according to the European Commission

The "ABC" building[4], in Grenoble, provides inspiring elements. It was designed as an autonomous building, with a zero-net annual energy consumption and an annual autonomy in energy and water amounting to up to 70%:

- 70% PV self-consumption: PV panels, batteries and optimisation of demand (with e.g. smart radiators)
- Water consumption divided by 3: Use of rainwater with time series to monitor quality, use of smart showers,
- 40% less waste (including weighting of individual waste)
- Use of BACS (Simulation + real-time data)
- Interfaces for users (app) enabling to monitor water and energy consumption and providing an interface to a building 'coach'

Figure 14: ABC building in Grenoble (left) and application developed for buildings occupants (right)

The Working Group 4 of the RESTORE COST Action also published a brochure on regenerative technologies for the indoor environment (Lollini et al., 2020), which goes beyond energy and includes aspects related to human health and well-being.

The below table provides an overview of various pathways in which smart buildings can decrease environmental impacts (or support approaches that have this objective):

Type of smart solution	Functionalities	Impact on ecosystems	Impact on resource availability	Impact on human health
Sensors embedded in materials	Track performance of buildings components & materials	Increased resilience	Improved maintenance, increasing lifetime Enhanced potential for reuse and	Improved indoor environment quality Increased safety

[4] https://www.linkcity.com/projets/sud-est-grenoble-abc/

			upcycling once building has reached end of life	
Lighting control	Dimmable lighting, optimisation of natural light, circadian lighting, …	Reduced light pollution at night	Reduced energy consumption	Increased visual comfort, in line with circadian rhythm (non-image forming effects of light)
Connected sensors + Building management system	Monitoring of temperature, CO2, humidity, noise HVAC control, occupancy zoning	Indirect effect especially via carbon emissions reduction and its contribution to global warming effect	Reduced consumption of energy from the grid	Improved indoor environment quality (air, noise…) Increased hygro-thermal comfort
Smart heating & cooling systems	Heating and cooling able to adjust to grid signals	Indirect effects via control of various emissions that lead to the area of protection Ecosystems through impact pathways	Reduced consumption of energy from the grid/ provision of grid services	Increased thermal comfort
Smart EV charger	EV charging able to adjust to grid signals	Indirect: lower environmental impact of energy consumption	Reduced consumption of energy from the grid/ provision of grid services	Indirect effects via control of various emissions that lead to the area of protection Human Health through impact pathways
Smart and/or connected appliances	Smart/ connected washing machine and other appliances, smart shower…	Indirect: lower environmental impact of energy consumption	Reduced consumption of energy from the grid Reduced consumption of water	Indirect effects via control of various emissions that lead to the area of protection Human Health through impact pathways
Waste weighting	Monitoring of generated waste	More biowaste to be used in the surrounding environment	Reduced waste, more recycling	
Dedicated app for building occupants	Monitoring of water and energy consumption, link to a (virtual) “coach”, etc.	Better integration/ connection of occupants to their environment	Virtuous behaviour ensuring the minimisation of use of resources	Improved acceptance of smart solutions; sense of belonging to a community; enhanced sense of control which leads to a better acceptance of hygro-thermal conditions

However only few of these potential benefits have been demonstrated so far, since most of the research is focussing on the reduction of energy consumption by BACS (which is sensitive to case-dependent parameters according to Van Thillo et al., 2022, and can amount to 12% for a single-family house according to Luis, 2015).

With regard to water consumption, the company DEFCON8, member of our Task Forces, calculated that thanks to real time feedback on water usage (with a smart water flow monitor), it is possible to save 15% of water in residential buildings (and 11% in hotels).

More recently, EU projects like PHOENIX have also investigated the potential for smart buildings to go beyond reducing energy consumption and provide grid services such as flexibility. It should however be reminded that smart buildings and smart homes technologies were first developed for "luxury" buildings & homes, for entertainment, health, security, comfort or convenience for instance (and efficiency to a lower extent). "Only later did the idea of putting home automation, sensing and remote control at the service of the electricity network into being" according to Darby, 2018. On the other hand, it is sometime necessary to bundle 'boring' management/ optimisation products with more attractive features (security, comfort) to persuade consumers to buy them.

As smart home development has never been primarily concerned with environmental impact, there is also cause for concern that it creates a demand for previously unwanted products and services (Darby, 2018), and therefore generates more impact that what smartness allows to reduce in the operation phase of the building. This is a known phenomenon termed *rebound effect* and has been studied in various contexts, including smart homes. In this last case, the estimations of the rebound effect vary, according to the type of house and smart systems installed, but also according to the behaviour of the users (as smart and automated systems also include a consistent user behaviour component) and the modelling approach used to study it. For example, Chen et a. (2018) estimated a size of the rebound effect in a smart home of 13.5% and Walzberg et al. (2020) estimate an average rebound effect of 4.7%. Chen et al. (2018) suggest that the rebound effect in future smart homes can be reduced by: (1) providing real-time electricity bills information combined with electricity use feedback; (2) offering electricity use suggestions through intelligent learning.

3.1.3 Environmental impacts of the devices themselves

Multiple sensors are necessary for recording data, and additional hardware and management software are required to process and store that data, and finally control the building systems through actuators. Smart devices and solutions themselves generated environmental impacts across the different phases of their life cycle:

Embodied energy, environmental impact from production phase and end-of-life:

These impacts come from mining, processing and disposing of materials in smart devices (Louis et al., 2015). This becomes even more critical given the short lifetime of these components, either because of their planned obsolescence, inadequate maintenance, or lack of interoperability due to vendor lock-in (which raises issues if this vendor/ operator goes out of business). There is also a concern that all this smart features and cables, sensors, etc. will hamper the recyclability of building components after their functional life.

Operational energy:

Operational energy includes the energy consumption of the devices themselves, as well as the use of data infrastructure (i.e. Internet traffic associated to the generated data, data hosting on remote servers).

An International Energy Agency (IEA) report estimated that mains connected sensors, switches and connected appliances in home automation systems consume standby electricity estimated at 0.4–2.2 W per device, headed for global growth from 7 to 36 TWh between 2015 and 2025 – almost 80% of the predicted increase from Internet of Things (IoT) over that period (Friedli et al., 2016).

With regard to energy use of IoT related to internet traffic and data hosting, the literature is again very scarce. In the LCA carried out by Pirson and Bol, 2021, one of the few LCA studies available for IoT, only edge devices and gateways are taken into account, the networks, data centres and clouds being out of the system boundaries.
The main impact of cloud computing is related to the vast amount of electricity required to power the servers and keep them cool: there are three million data centres in the US alone, accounting for over 2% of the total Unites States energy use (Bernheim, 2019). Lowering the energy usage of data centres is a complex issue since computing applications and data are growing so quickly that increasingly larger servers are needed to process them fast enough. O'Neal (2021) investigated the environmental concerns within this rapidly expanding industry: one of the conclusions was that the location of data centres is crucial to their environmental effect. The proposed solutions included optimisation of task scheduling and more energy efficient technologies within data centres, as well as the decentralisation of remote computing as a whole to a distributed, block-chain based approach.

Edge Computing, which is a new distributed Cloud Computing paradigm in which computing and storage capabilities are pushed to the topological edge of a network (Hamm et al., 2020), offers interesting opportunities with regard to decreasing IoT related energy consumption, at the condition that sustainability is correctly taken into account in the development of Edge Computing solutions.

Lifecycle perspective

A lifecycle approach is again very valuable to assess the overall environmental impacts of smart devices.

As pointed out by Pirson and Bol (2021), very few LCA results of IoT devices are available. Luis et al., 2015, carried out the LCA of Home Energy Management System (HEMS). The LCA study established that the largest environmental impact of HEMS is the use-phase electricity consumption of home automation devices, the impact of end-of-life management being very low. The paper concluded that the energy payback time of home automation in term of the electricity consumption of the devices is negative by 1.6 years (assuming a 5-years operation time). More recently, Van Thillo et al. (2022) cited a few studies that claimed a financial payback time for BACS of generally less than 5 years.

LCA carried out at building level usually does not include small components such as smart devices and appliances, as those had until now limited impact compared to other building systems. But as demonstrated by Röck et al., 2020, the operational energy of buildings is decreasing as buildings become more energy efficient: the share of smart systems may therefore be not as negligible as it used to be.

Some manufacturers of smart devices already communicate on the lifecycle impacts of their products through an **Environmental Product Declaration** (EPD). EPD is a widely used industry standard developed under ISO 14025, 14040, 14044, and EN 15804. EPDs create transparency along a product's whole life cycle by documenting its environmental impacts. These specific EPDs could be used as an input to building-level LCAs (Andersen et al., 2019).

Including LCAs of smart equipment to building-level LCA will assist in finding the right balance between what we actually need to control and the resulting energy consumption of the control system. This will in turn enable to design an optimal package of smart, active and passive solutions.

3.2 Lessons learnt from Horizon 2020 projects

3.2.1 Overview

Many H2020 projects – and other EU funded projects – have reviewed, developed and/or demonstrated tools and approaches to optimise building costs: some of them are pictured in Figure 15. Although it is likely that this list is not exhaustive, it covers the projects represented (or mentioned) in the Task Force. More details on these projects can be found in Annex 1.

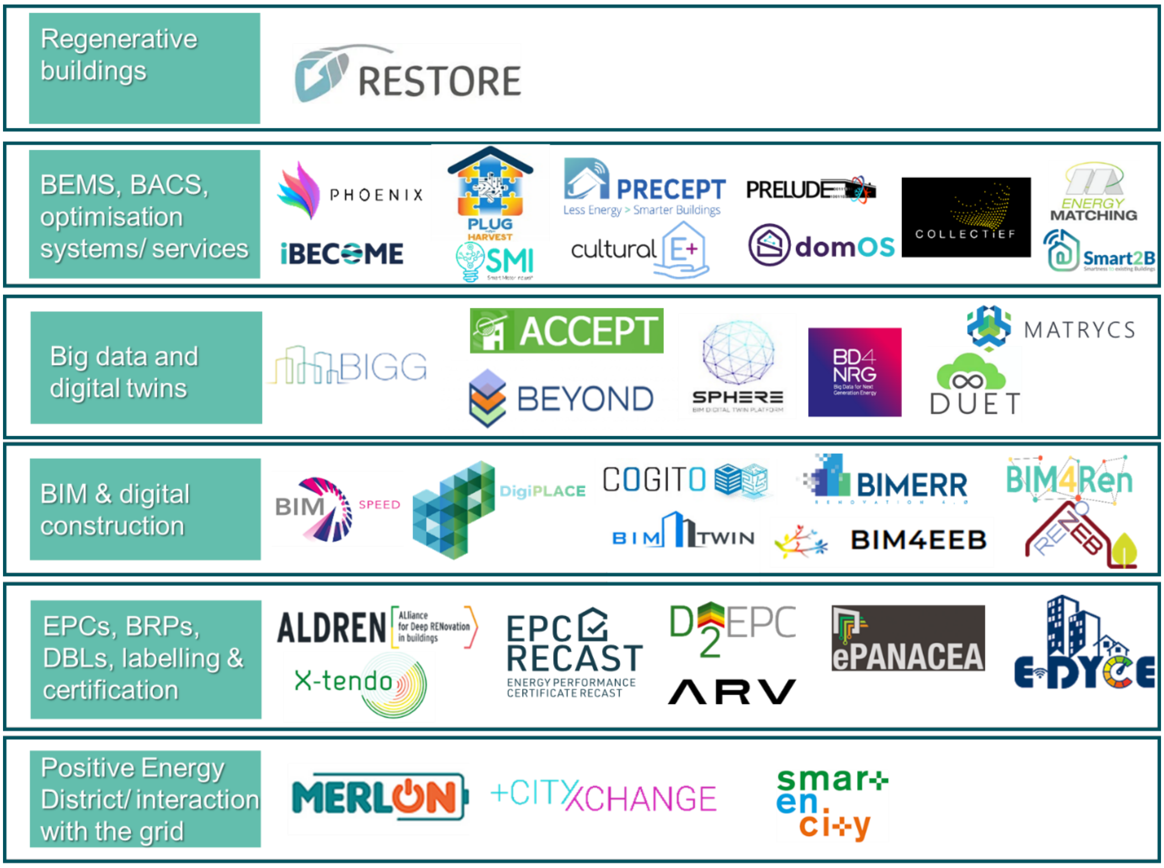


Figure 15: Relevant EU-funded projects identified by the Task Force members

Findings from some of these projects have already been presented in the state of the art. Lessons learnt from recent projects RESTORE, SPHERE and domOS are presented below.

3.2.2 Lessons learnt from the RESTORE COST ACTION

RESTORE (REthinking Sustainability TOwards a Regenerative Economy), concluded in 2021 and part of the COST programme, was aimed at advocating, mentoring and influencing for a restorative built environment sustainability through working groups, training schools (including learning design competitions) and Short Term Scientific Missions.

Working Group 4 "Rethinking Technology" explored the potential for further implementation of restorative interactive systems and technologies in new and existing buildings. It aimed at defining the aspects that determine a regenerative indoor environment, so that all the technologies and their characteristics that provide this "regenerativeness" may be defined.

Lessons learned include:

Key technologies can promote a paradigmatic shift in building design from "less bad" to "more regenerative". A regenerative environment that will both restore and improve the natural environment (and humans likewise), as perfectly integrated within a built environment (building and surrounding), by enhancing the quality of life for biotic (living) and abiotic (chemical) elements. Building smartness increases awareness and the transformation of collected data into useful information can support further investments to transform existing building stocks.

However, proper technologies need a dedicated evaluation framework for aware selection within a comprehensive decision-making process. A list of KPIs was therefore prepared as a step towards the achievement of a better indoor environment and reconnection with natural elements, as presented in Figure 16 (Lollini and Pasut, 2020).

Environmental aspect	Sub-aspect	KPI	Regenerative values
Air Quality Environment	*Contaminants*	Formaldehyde	≤ 0.1 mg m^{-3} [30 min]
	Outdoor/Indoor	Particulate matter: PM_{10} $PM_{2.5}$	< 150 µg m^{-3} [24h] < 12 µg m^{-3} [1yr]
	Occupant satisfaction	% satisfied people	80 %*
Hygro-Thermal Environment	*Temperature/ humidity/air speed*	Implementation of ASHRAE 55	ASHRAE 55 + evaluation of air movement
	Occupant satisfaction	% satisfied people	80 % *
Visual Environment	*Daylight*	Useful Daylight Illuminance	300 – 3000 lux
	Circadian Rhythms	Equivalent Melanopic Lux	≥ 200 (9am-1pm) **
	Occupant satisfaction	% satisfied people	80 % *
Acoustic Environment	*Background noise level*	Noise criteria	≤ 30 / ≤ 40 ***
	Occupant satisfaction	% satisfied people	80 % *
Human Nature Environment	*Right to light*	% with windows access to daylight	100 % of inhabitants
	Connectivity to Nature (Biophilia)	Intentional interior design interventions that bridge the gap between natural and built environments.	1. Biophilic Design Workshop held prior to design. 2. Biophilic Interventions in-corporated: 7/14 Biophilic Patterns [Browning et al. 2014]. 3. POE *Connectivity with Nature* satisfaction.

* response rate representing at least one quarter of the total number of building/indoor environment users. Although a value of 100% is desirable, and in some cases like hygro-thermal comfort is achievable with the use of personal comfort systems [Pasut et al. 2015], we are aware that there will always be a percentage of people that despite all efforts may never be satisfied. For this reason, we aim at a value that is 80% or higher.

** for 75 % or more workstations.

*** enclosed / open offices.

Figure 16: Final list of KPIs and values proposed by RESTORE COST Action (WG4)[5]

3.2.3 Lessons learnt from the SPHERE project

The goal of SPHERE's project is the improvement and optimisation of buildings' energy design, construction, performance, and management, reducing construction costs and their environmental impact while increasing overall energy performance. SPHERE will help boosts a building's energy performance throughout its lifecycle and reduce time, costs & the environmental impact of the construction process. The use of digital twin during any phase of the building's lifecycle, allows different stakeholders to interact with this BIM Digital Twin model, based on the building's information and a scalable set of different software tools, and make predictions and calculations and saving time and energy.

Key results:
The project is developing a platform where tools and services are integrated, and it can also manage sensors and actuators, providing a powerful tool for the building control. The platform can include different services and thus follow the building lifecycle, also helping management and building maintenance. Amongst these services, we can find the following:

- Human Thermal Model for individual control of heating/cooling in buildings based on temperature and humidity optimised for energy saving.
- IMAN + iPredict: The Facility Manager finds in this predictive maintenance tool a useful support to know on a daily basis if the HVAC thermal energy consumption was in line with the predicted value.
- SIL libraries (Software in the Loop Libraries) which are a set of components created by experienced simulation engineers with the aim of making it easier for EcosimPro simulation software users to build exportable simulations of complete HVAC systems, saving them from having to create from scratch components such as piping, equipment...
- SIMBOT (Simulation Bot): A standalone HVAC simulation software of a building created with EcosimPro software and SIL libraries. The main objective is to create a HVAC digital twin to analyse the historical data of the real system, validate the current data of sensors and equipment and anticipate the future to improve energy management. It can be exported in web service format (to be used by other programs exchanging JSON files) or Excel spreadsheet (to be used directly by engineers)

Lessons learned so far include:
The implementation of sensors and controllers, integrated with different software services and tools helped reducing significantly energy consumption for heating, cooling and ventilation. The digital model was useful for the decision-making aspects that led to the definition of HVAC and IoT systems. The benefits of implementing these solutions highly exceed the extra costs of implementing/installing the necessary hardware.
Communication among different building stakeholders should be facilitated through the use of all possible channels, digital and conventional, in renovation processes specially where misunderstandings can happen while carrying out the renovation works.

3.2.4 Lessons learnt from the domOS project

[5] ASHRAE Standard 55 specifies conditions for acceptable thermal environments

Smart services to reduce the environmental impact of buildings are many: energy dashboard for occupants, energy management system to orchestrate flexible energy components, optimisation of heat generation and distribution… As of today, smart services are deployed as silo solutions, typically provided by appliance manufacturers. The multiplicity of parallel systems increases the costs, degrades the user experience, and forbids in practice the deployment of multi-appliance services as required for energy management. In this context, domOS develops a “virtual connector” for buildings, allowing any smart service to interact with any local device or appliance, if permitted. Note that the ecosystem does not require existing or new appliances to conform to a given specification. The specificities of a given appliance model needs only be described in ad hoc document. The domOS ecosystem is based on current and emerging IoT (Internet of Things) standards.

Interoperability requires that appliance types (e.g., heat pump, electrical vehicle charging station…) are modelled in a standard way. The current version of the current vocabulary to define the energy topology and models for appliances and processes in building, the domOS Core Ontology (dCO) is available on-line at https://www.dco.domos-project.eu/. It builds on several ontologies and complements them when and if necessary.

Lessons learned so far

The domOS ecosystem is being implemented in the five domOS demonstration sites, which cover a broad spectrum of use cases and are based on different IoT frameworks. Solutions compliant to the domOS ecosystem specification can run either as stand-alone systems hosted by a building gateway or as hybrid gateway-cloud distributed systems.

The definition of models that are at the same time expressive for services and adaptable to multiple appliance models is a challenging task and a key issue for a rollout of the domOS ecosystem specification.

3.3 Other initiatives related to smartness to reduce environmental impacts

Name of initiative	Relevant inputs
Level(s) framework	EU Level(s) provides a common language for assessing and reporting on the sustainability performance of buildings. It is a simple entry point for applying circular economy principles in our built environment. Level(s) offers an extensively tested system for measuring and supporting improvements, from design to end of life. It can be applied to residential buildings or offices.
Green building certifications	DGNB, BREEAM, LEED and EDGE type of green building certifications are now well mature, however communities certifications are also needed. LEED ND and BREEAM Communities are not used widely in EU for many reasons. It is important to move on from building to community scale: tools need improvements.
Aspern Smart City Research	aspern Seestadt in Vienna is one of the largest urban development areas in Europe. The basic objective of ASCR is to develop market-oriented, scalable, and economical solutions for the energy future in urban areas and to make the energy system more efficient and more climate-friendly.

4 Barriers and drivers

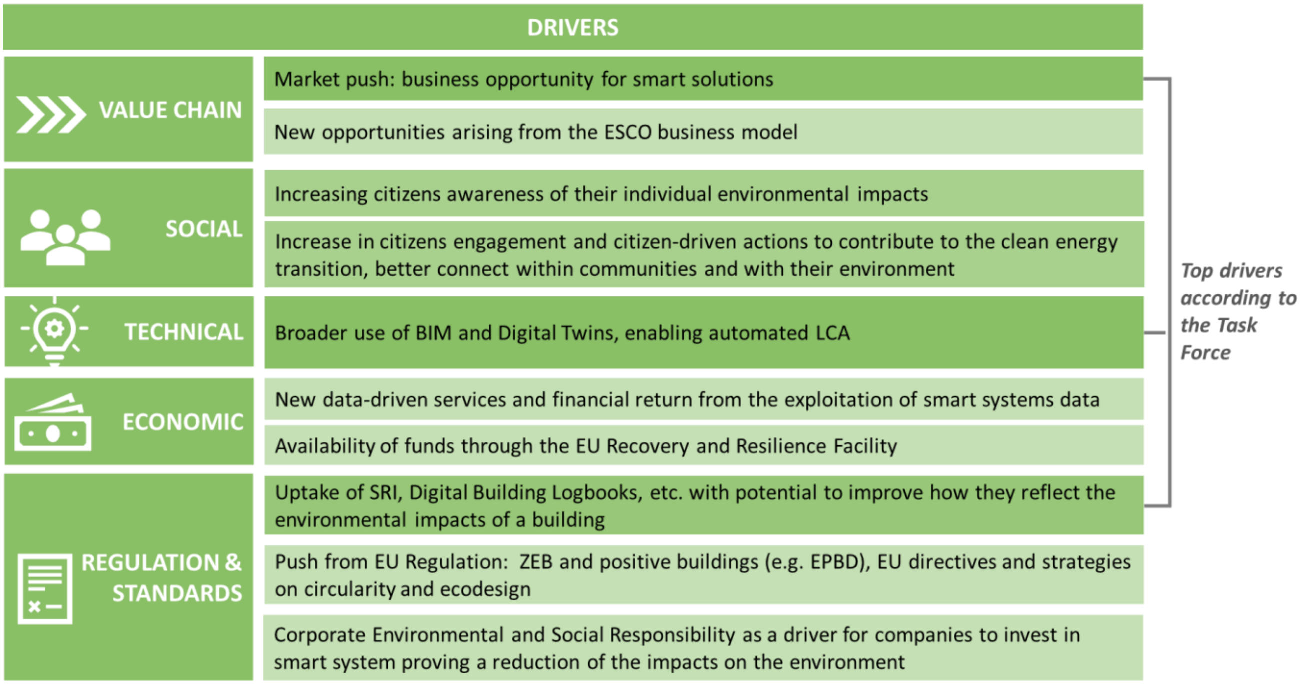
4.1 Barriers

Barriers to the reduction of environmental impacts thanks to building smartness were reviewed and prioritised by the Task Force. The top barriers are highlighted below.

BARRIERS		
VALUE CHAIN	Fragmentation of the construction sector with no flow of information between the different players and across the different phases of the building life	Top barriers according to the Task Force
	Lack of skills and awareness from the construction sector with regard to energy efficiency and more generally environmental impacts	Top barriers according to the Task Force
SOCIAL	Lack of awareness and knowledge from building owners of environmental impacts of buildings and how they can be alleviated by smart technologies	Top barriers according to the Task Force
	Low acceptance and lack of commitment from users, leading to an inefficient use of smart systems limiting the environmental impacts	Top barriers according to the Task Force
	Unclear responsibility with regard to decision-making and investment in smartness, especially in condominiums	Top barriers according to the Task Force
TECHNICAL	Integration challenges across solutions and sectors, with interoperability issues	Top barriers according to the Task Force
	Lack of information on the environmental impacts of smart devices themselves (with a life-cycle approach)	
	Lack of unified LCA tool and lack of standardised life-cycle approach using Digital Twins	
ECONOMIC	Lack of financial incentives targeting smart systems that limit the impacts on the environment	
	Unattractive Return on Investment and Cost Benefit calculations (partly because those to do not integrate externalities such as environmental impacts)	
	Recent increase in prices of building material and equipment	
REGULATION & STANDARDS	Lack of standardisation for smart devices and smart buildings	
	Lack of compatibility of EU and national network codes with latest digital tools	
	Slow transposition and/or implementation of EU Directives (EPBD in particular)	

4.2 Drivers

The drivers identified by the Task Force are as illustrated below.



5 Gaps

Various activities required to overcome the barriers and leverage the drivers related to the optimisation of building costs were suggested and prioritised by the Task Force members and are presented in Table 1. The priority ones according to the Task Force are in bold.

Table 1: Suggested R&I and go-to-market activities

Type of activity	Activities
R&D	- **Develop common LCA methodologies and indicators tailored to smart systems and their environmental impacts, in cooperation with the industry** - Expand research on social acceptance, building upon Post Occupancy Evaluation methodology - Innovate in interoperable smart systems that allow to minimise environmental impacts, beyond energy (e.g. in the fields of water, waste)
Demo	- **Run experiments and demonstration activities in pilot buildings to show the usefulness, effectiveness and optimal conditions of use of new smart systems minimising environmental impacts, in line with needs from the industry, and with shared assessment metrics** - Share results as open datasets, using building data semantics - Demonstrate how Digital Twins used throughout the lifecycle of a building can support the minimisation of environmental impacts (including using simulation to define best scenarios)
Scaling up & industrialisation	- **Use lighthouse buildings to showcase good practices and provide long-term datasets to support replication & scaling up**

	- Improve knowledge transfer from EU funded & research projects to industrials through e.g. industry associations - Support the roll-out of smart systems with business models such as Energy Performance Contracting and ESCO models
Certification & standardisation	- Expand the use of well-established building certification schemes, e.g. LEED, BREEAM, DGNB, and streamline the use of dynamic sensor data as proof of performance - Activate more widely the EN ISO 52120-1 standard (Energy performance of buildings — Contribution of building automation, controls and building management)
Regulation & legal framework	- Enlarge the SRI to include broader environmental impacts as well as resilience and include the SRI score as part of EPC - Use data from smart systems as evidence of 'green' activities to support claims related to the EU Taxonomy, and to steer policy development - Set up minimum requirements for repairability and recyclability of smart sensors and actuators

6 Conclusion

This document formalises the collaborative work performed by the members of SmartBuilt4EU task force 2, on a voluntary basis, during the period May 2022 – October 2022. It also integrates the feedback collected during 1) a peer review conducted by VITO in September 2022, and 2) an open consultation process in October 2022.

Based on an analysis of the state of the art and the identification of barriers and drivers, the main objective of this paper is to detect some research and innovation gaps that still need to be addressed in the coming years in order to ensure an adequate education and upskilling opportunities to the workforce of the whole construction value chain in relation to smart buildings.

This white paper will feed the elaboration of the Strategic Research and Innovation Agenda that the SmartBuilt4EU consortium will present to the European Commission.

To receive the updates on the SmartBuil4EU task forces, white papers and events, please register here: https://smartbuilt4eu.eu/join-our-community/

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8 Annex 1: list of H2020 projects reviewed

Table 2: list of relevant EU projects

Project	Status	Contact in TF	Weblink	Relevant inputs
accept	Ongoing	Ismini Dimitriadou	https://www.accept-project.eu/	Integrated ACCEPT tool-chain to bootstrap the transition of energy communities to fullplayers of the energy & flexibility markets and offering value-adding services to customer
ALDREN	Ended	Graziano Salvalai (poliMI)	https://aldren.eu/	BRP+Renovation roadmap
SMARTER FINANCE FOR FAMILIES	Ended	Steven Borncamp	https://cordis.europa.eu/project/id/847141	Bringing banks and developers together into lower interest mortgage for green homes
ARV	starting	Mohamed Hamdy (NTNU)	https://greendeal-arv.eu/	Automated use of LCA, digital logbooks and material banks
BIM4Ren	ongoing	/	https://bim4ren.eu/	exploitation of BIM potential for the energy renovation of existing buildings for the whole construction value chain

BIM SPEED	ongoing	Sofía Mulero (CARTIF)	https://www.bim-speed.eu/en	BIM integration and BIM passports for renovation scenarios
BD4 NRG	Ongoing	Sofía Mulero (CARTIF)	https://www.bd4nrg.eu/	Big Data solutions for increasing the efficiency and comfort of buildings, and de-risking investments in energy efficiency
BIM TWIN	Ongoing	/	https://bim2twin.eu/	Digital Building Twin (DBT) platform for construction management implementing lean principles to reduce operational waste, shortening schedules, reducing costs, enhancing quality and safety and reducing carbon footprint.
BIM4EEB	Ongoing	/	https://www.bim4eeb-project.eu/	BIM4EEB develops a BIM-based toolset – BIMMS - which offers a set of functionalities that meet the stakeholders' needs during the renovation work. BIMMS can integrate tools and enable the data interoperability through data exchange services.
BIMERR	ongoing	/	https://bimerr.eu/	Seamless BIM creation and information exchange among the three phases of the AEC/ renovation value chain.
BIGG	ongoing	/	https://www.bigg-project.eu/	Building Information aGGregation, harmonization and analytics platform
BEYOND	ongoing	John Avramidis	https://beyond-h2020.eu	BEYOND introduces a reference big data platform implementation for collecting, processing and analyzing building data, while transforming them into a tradeable commodity through the development of appropriate data sharing mechanisms for data sharing between different stakeholders.
+CITYXCHANGE	ongoing	/	https://cityxchange.eu/	Positive energy blocks and districts with balancing and optimisation of energy in the PEB
COGITO	ongoing	Giorgos Giannakis	https://cogito-project.eu/	digitalisation of Construction Phase using Digital Twin Digital Construction 4.0 toolbox that harmonises Digital Twins with the Building Information Model concept
COLLECTiEF	ongoing	NTNU- Mohamed Hamdy	https://collectief-project.eu/	Implement an interoperable and scalable energy management system to smart up buildings and their legacy equipment on large scale
cultural E+	ongoing	EURAC + ADVANTICSYS	https://www.cultural-e.eu/	IoT+ML+cloud for positive energy buildings LCC tool
D2EPC	Ongoing	/	https://www.d2epc.eu/	dynamic EPCs

DigiPLACE	Ongoing	Alexis David	www.digiplaceproject.eu	DigiPLACE is a framework allowing the development of future digital platforms as common ecosystems of digital services that will support innovation, commerce, etc. It will define a Reference Architecture Framework for digital construction platform based on an EU-wide consensus involving a large community of stakeholders, resulting in a strategic roadmap for successful implementation of this architecture.
domOS	ongoing	Dominique Gabioud	http://www.domos-project.eu/	Operating System for smart building: Any in-building infrastructure available for any monitoring / control / optimisation application, if permitted
DUET	ongoing	/	https://www.digitalurbantwins.com/	Developing and validating the use of Digital Twins for better policy making
EDYCE	ongoing		https://edyce.eu/	EDYCE provides Energy flexible DYnamic building Certification. It aims to create a technology-neutral methodology for dynamic labelling, based on maximizing the free running potential of the building and promoting the use of passive and low-cost solutions, instead of mechanical systems.
ENERGY MATCHING	ongoing	/	https://www.energymatching.eu/project/	Developing and demonstrating cost-effective active building skin solutions as part of an optimised building energy system, being connected into local energy grid and managed by a district energy hub implementing optimised control strategies within a comprehensive economic rationale balancing objectives
ePANACEA	ongoing			ePANACEA develops a holistic methodology for energy performance assessment and certification of buildings. Its platform makes use of the most advanced techniques in dynamic and automated simulation modelling, big data analysis and machine learning, inverse modelling for the estimation of potential energy savings and economic viability check.
EPC RECAST ENERGY PERFORMANCE CERTIFICATE RECAST	ongoing	Graziano Salvalai (PoliMI)	https://epcrecast.wordpress.com/ https://epc-recast.eu/	New generation of EPCS House owners' considerations about usefulness of the EPC are central as owners decide whether to implement energy conservation opportunities provided by the EPC. EPC RECAST is a decisive decision-supporting tool for tenants and potential buyers. It provides guidance on cost-optimal building renovation for building owners, covering as well IEQ, wellbeing and smartness.
iBECOME	ongoing	/	https://ibecome-project.eu/	In small enough so as to not be equipped with BMS, the deployment of the iBECOME solution will allow essential energy savings and comfort

				improvements at very low cost but also provide the ability to tap into the emerging markets of additional services.
MATRYCS	ongoing	Sofía Mulero	https://matrycs.eu/	AI-powered framework for decision-support models, data analytics and visualisations in real-life applications
MERLON	ongoing	Katerina Valalaki	https://www.merlon-project.eu	optimisation at different levels / optimal interaction of buildings with the grid / optimal flexibility valorisation
PHOENIX	ongoing	Dimitra Georgakaki	https://eu-phoenix.eu/	The aspiration of PHOENIX project is to change the role of buildings from unorganized energy consumers to active agents orchestrating and optimizing their energy consumption, production and storage, with the goal of increasing energy performance, maximizing occupants' benefit, and facilitating grid operation.
PRECEPT Less Energy > Smarter Buildings	Ongoing	/	https://www.precept-project.eu	Proactive and Predictive Building Management System (PP-BMS) based on devices/systems interoperability and innovative technologies such as digital twins, artificial intelligence, etc.
PRELUDE	Ongoing	/	https://prelude-project.eu/	The project is focused on assessing the right level of smartness necessary for any given household and then providing the optimal tools according to the needs of the user. Combination of smart and low cost solutions into a proactive optimization service.
RENOZEB	ended	Focchi - a.pracucci@focchi.it	https://renozeb.eu/	RenoZEB aims to unlock the nearly Zero Energy Building (nZEB) renovation market by increasing property value through a new systemic approach to retrofitting. A more collaborative environment through a Building Information Modeling (BIM) based collaboration platform
RESTORE	ended		https://www.eurestore.eu/	Pan-European Network of 150 researchers and industry representatives from 40 countries. Networking, publishing and operating through Working Groups, Training Schools and Short Term Scientific Missions on the topic of regenerative buildings.
Smart2B Smartness to existing Buildings	ongoing		https://cordis.europa.eu/project/id/101023666	Development of non-intrusive Internet of Things sensors and actuators to control equipment, while improving indoor comfort and energy efficiency. The project will allow for coordinated control of legacy equipment and smart appliances and integrate two existing cloud-based platforms into a single building management platform.
smart en city	ongoing	José L. Hernández (CARTIF)	https://smartencity.eu/	Smart Cities project where AI techniques are applied for energy forecasting and cost prediction of energy resources for heating

SMI	ongoing	/	https://www.smi.uha.fr/en/	Artificial intelligence to support the proactive management of energy consumption by end users
SPHERE	Ongoing		https://sphere-project.eu/	Digital Twins + ICT Systems of Systems infrastructure based on Platform as a Service (PaaS) service to allow large scale data, information and knowledge integration and synchronization, to improve energy efficiency across buildings' entire lifecyle
X-tendo	Ongoing		https://x-tendo.eu/	X-tendo and its toolbox introduce ten features of the next generation of energy performance certificates. It aims to ensure that the developed features and overall guidelines for improving EPCs are in line with four cross-cutting criteria: more reliable and high quality EPCs, user friendliness, economic feasibility of EPCs, and consistency with CEN/ISO standards.