Machine Learning algorithms for Urban Building Energy Modeling

European Commission

12th International Conference on Improving Energy Efficiency in Commercial Buildings and Smart Communities

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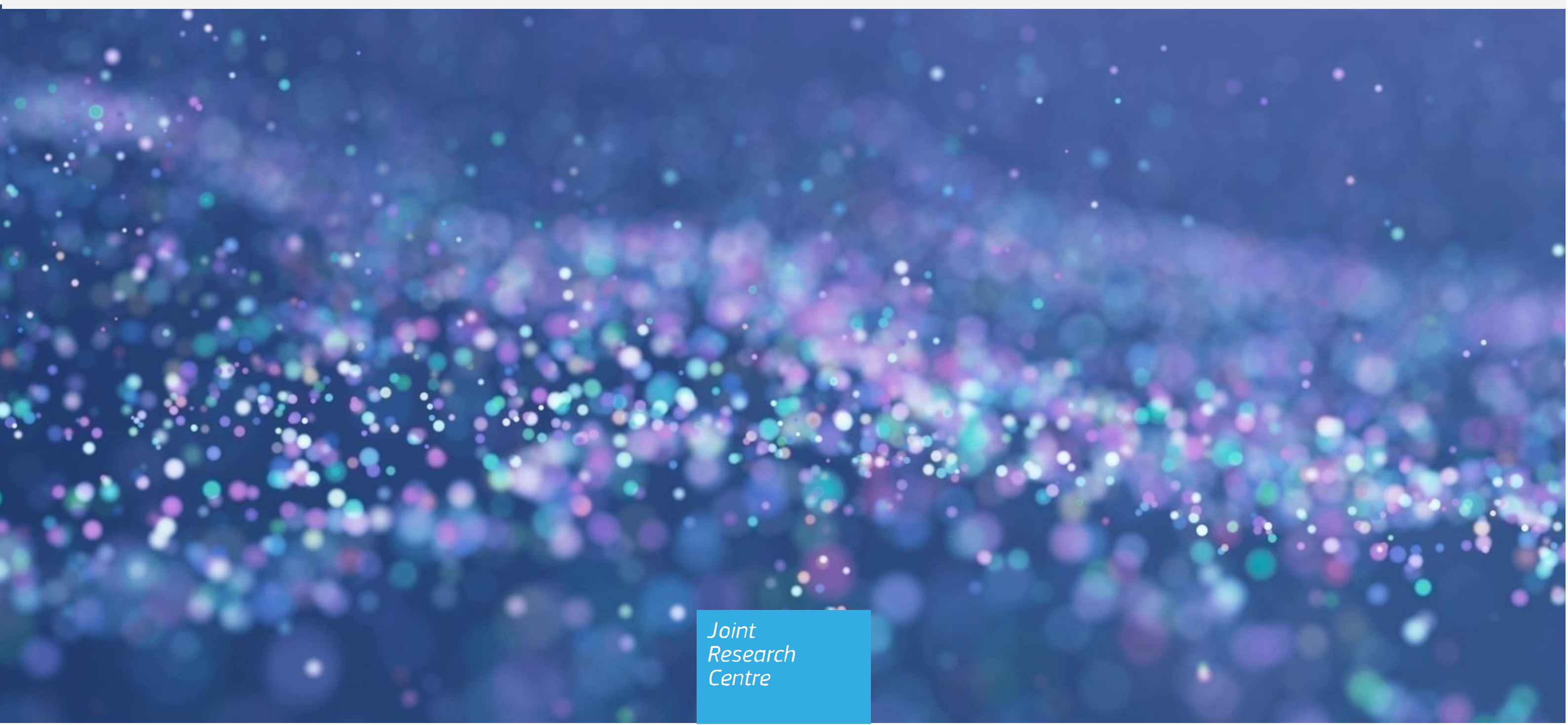

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Abstract

The IEECB&SC'24 and the European ESCO conference, held in Frankfurt on 6 and 7 March 2024, brought together all the key players in energy efficiency and decarbonisation of commercial buildings and district, such as investors and property managers, academia and experts, equipment manufacturers, service providers (ESCOs), utilities, facilities management companies, data centre operators, urban planners and local and national policy makers, with a view to exchange information. In particular the conference aimed to attract property owner, investors, architects, local authorities and urban planners to present and discuss synergies and cooperation in removing existing barriers to energy efficiency, renewable energy and smart and NZE buildings and districts, on the role of ESCOs and on the impact of digitalisation and AI.

Its objective was attracting high level presentations showing new technologies, techniques, services, policies, programmes and strategies to increase energy efficiency, renewable energy sources and to reduce greenhouse gases emissions in non-residential buildings, ICT and data centres and district/communities and cities.

The Proceedings contains articles based on the presentations.

1 Analysis of a novel compact integrated thermal energy storage system (MiniStor) in European sites

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Abstract

The stock of buildings in the EU has a great deal of potential to improve energy efficiency by incorporating solutions into their current structures in a variety of ways. One such solution involves optimizing the use and management of thermal energy by levelling demand peaks and increasing the utilization of intermittent renewable energy as for example solar-based heating and cooling, integrating medium-term storage systems. To this end, during the Horizon project MiniStor, a novel, compact integrated thermal storage system was designed, installed, and tested at the premises of Centre for Research and Technology Hellas (CERTH) Smart Home. Both existing residential and commercial buildings can be retrofitted with this technology. For flexibility and year-round use, it is based on a high-performing thermochemical material reaction of calcium chloride/ammonia (CaCl2/NH3) combined with parallel hot and cold phase-change materials (PCMs). The total heat energy storage density exceeds 200 kWh/m3. Additionally, the system stores electrical energy in a Li-ion battery with a capacity of 7.68 kWh able to respond to grid signals and provide excess energy to the electrical grid. The input heat is generated from a solar field comprising of hybrid PV/T and typical flat plate solar collectors with a total installed capacity of 16kWth. The entire system is managed by a smart Building Energy Management System. This paper presents preliminary results from the installation and system testing, including the average coverage of thermal loads per charging/discharging with the simulation results from a dynamic model of the MiniStor system including the solar field, developed in Aspen Plus Dynamics and integrated with Matlab/Simulink. On average the system can cover 63% of the buildings daily thermal load.

Introduction

One of the fundamental strategies for reducing EU building energy demand, which accounts for around 40% of EU final energy demands [1], is to increase the use of renewable energy sources (RES) for covering heating/cooling demands in buildings. Solar energy systems either in the form of solar thermal systems or in the form of photovoltaics are currently the most widely used RES systems in buildings [2]. Solar thermal and photovoltaic systems are now a competitive alternative to fossil fuel systems, and they are predicted to become even more so in the future due to the high yearly solar radiation and temperatures in southern Europe. [3]. However, as the behaviour of solar conversion systems is stochastic, their wide application relies on long-term seasonal thermal storage in order to store excess energy and use it when needed [4].

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Thermal energy storage (TES) systems are grouped into three main categories: sensible heat, latent heat and thermochemical (TCM) storage. While the sensible heat storage is the most used storage option, its energy density (20-30 kWh/m3) is quite small in comparison to thermochemical storage (100-600 kWh/m3) [5]. Thus, the overall volume of these systems is quite large for either water-based systems or rock-based ones [6]. Also, phase change materials (PCM), which use latent heat, have higher energy density (40-80 kWh/m3), however their volume is still considered large in comparison to the thermochemical storage [7].

TCM storage has been a relatively new technology that provides a very high energy density leading to more compact storage solutions, which may easily fit in modern residential single- or multi- family houses. They can enable long-term seasonal heat storage, addressing the intermittent nature of RES and therefore provide heat supply over extended periods [8]. Another advantage is the lower heat losses during the storage period in comparison to other typical heat storage methods [9]. On the other hand, the higher cost of implementation and maintenance and the need for specialized materials are the most important disadvantages. In addition, the kinetics of thermochemical reactions may also be a limiting factor, with some reactions occurring slowly, affecting the rate at which heat can be stored or released. Material compatibility issues, corrosion, and degradation can pose challenges and affect long term system efficiency [6].

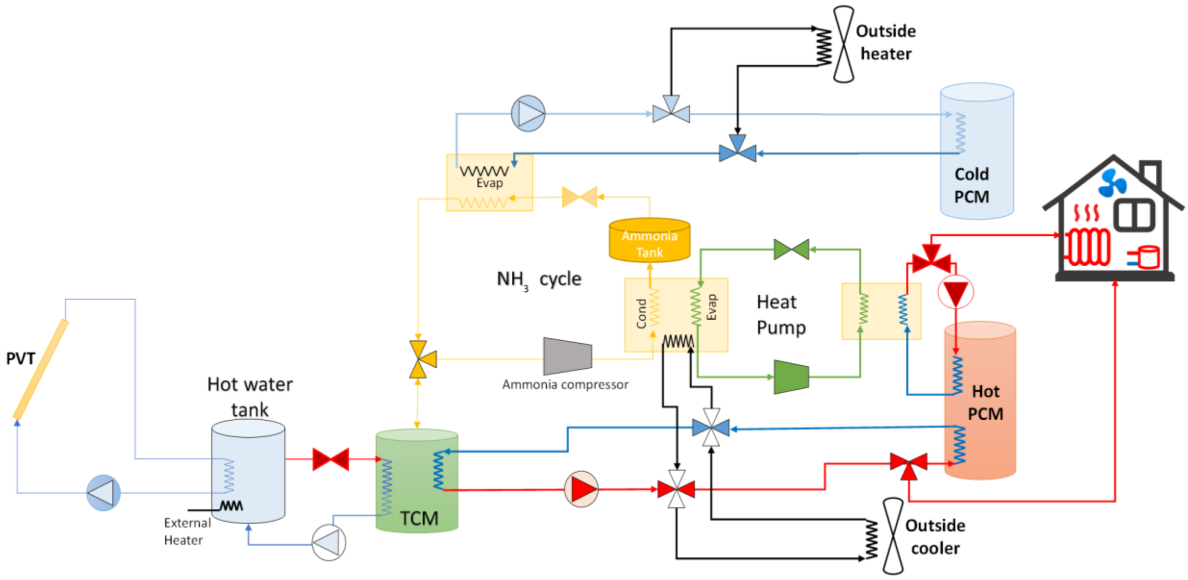
Research on TCM storage is ongoing, and several numerical and experimental studies that aim to address the aforementioned limitations and enhance their feasibility and effectiveness are available in the literature. Experimental studies regarding the working pair of CaCl2–NH3 include the works of Van der Pal et al. [10], Oliveira et al. [11] and Wang et al. [12]. It should be noted that these works are for prototypes that were developed in laboratories without testing them in real world applications. There are also many papers with numerical models that simulate the reaction kinetics in steady state [13] or combine them with other system components in 1D models [14]. A numerical model was developed to simulate the novel, compact integrated thermal storage system called MiniStor [5] by CERTH. The model was developed in Aspen Plus Dynamics, integrated with Matlab/Simulink. In addition to the simulation model and during the Horizon project MiniStor [15], a working prototype of the innovative system has been deployed. It is installed at the premises of CERTH's Smart Home [16] and it covers the heating and cooling loads of an office inside the Smart Home.

In this paper, the integration of the prototype MiniStor system in CERTH's Smart Home in Thessaloniki is presented. MiniStor combines TCM and PCM for year-round energy storage. Its energy storage density is exceptionally high, more than 10.6 times higher than that of comparable water based systems. Flat plate solar thermal collectors (FPC) and hybrid photovoltaic thermal (PVT) panels supply the required energy input, however it can be connected to other systems for heat generation, such as waste heat or biomass boilers if required. All the MiniStor system components as well as its operation are described in Section 2. Preliminary results from the dynamic model of the MiniStor system are provided in Section 3. The average coverage of thermal loads per charging/discharging cycle is presented for the system in Thessaloniki.

1.1 MiniStor system description

The MiniStor system consists of four main sub-systems: 1) the PVT and solar thermal collectors including the buffer tank for heat generation, 2) the TCM reactor with its corresponding ammonia cycle, 3) the heat pump and the PCM storages (Hot and Cold PCM) and 4) a battery that receives electricity from the PVTs through an inverter that covers the electrical needs of the MiniStor system, e.g., pumps and compressors. The overview of the MiniStor thermal system components (sub-systems 1-3) and its integration with the building's HVAC systems is depicted in Figure 1 [17].

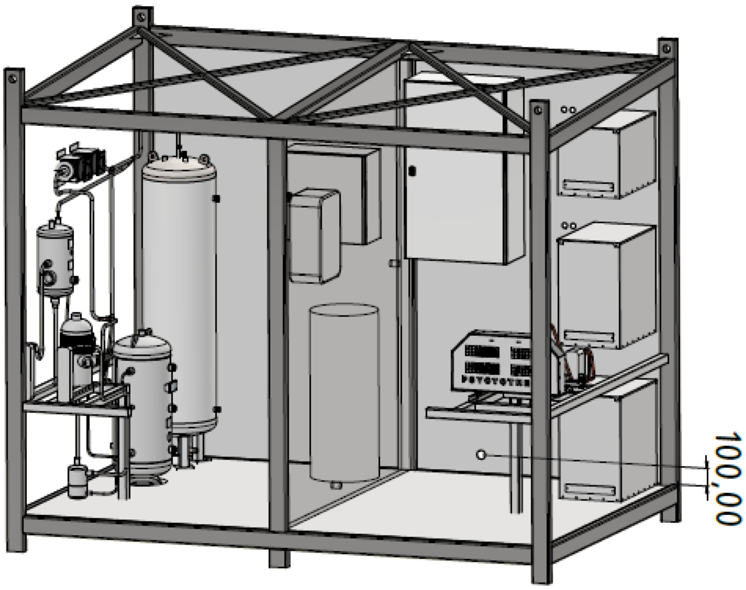
Figure 1: Overview of MiniStor thermal system components



During the winter period, the system can provide heat in two ways. During the charging mode, the required heat for the salts' desorption comes from the solar field with the complimentary use of the 2kW electrical back-up heater when required. Having provided heat to the TCM reactor, the decomposition reactions start with the increased reactor pressure which results in the production of gaseous NH3 according to the endothermic decomposition reactions. Then, the gaseous NH3 is compressed, condensed and stored in a tank. Next, the condensation heat is elevated by the heat pump up to a temperature of 336 K in order to cover the heating demands of the building.

The second way is during the discharging mode, which occurs in summer and winter nights as well as during cloudy winter days. After completing the charging mode, the NH3 is in liquid form and stored in the tank. As long as the reactor equilibrium pressure is lower than the evaporation pressure, the material flows into the evaporator and evaporates at a temperature set by the surrounding environment. The exothermic synthesis reaction occurs in the reactor once the gaseous NH3 enters it, and this causes the TCM reactor to emit heat at a temperature of 330–336 K. The excess heat can be stored in the heated PCM since the processes are exothermic. In the summer period the MiniStor system can cover part of the cooling demand by exploiting the NH3 evaporation cooling load, which is formed during the discharging phase. The output from the NH3 evaporation is stored in the cold PCM, which is characterized by a melting temperature of 284 K. All parts of the MiniStor system are installed in a container with a volume of 17.3 m3 with all the necessary safety equipment as seen in Figure 2.

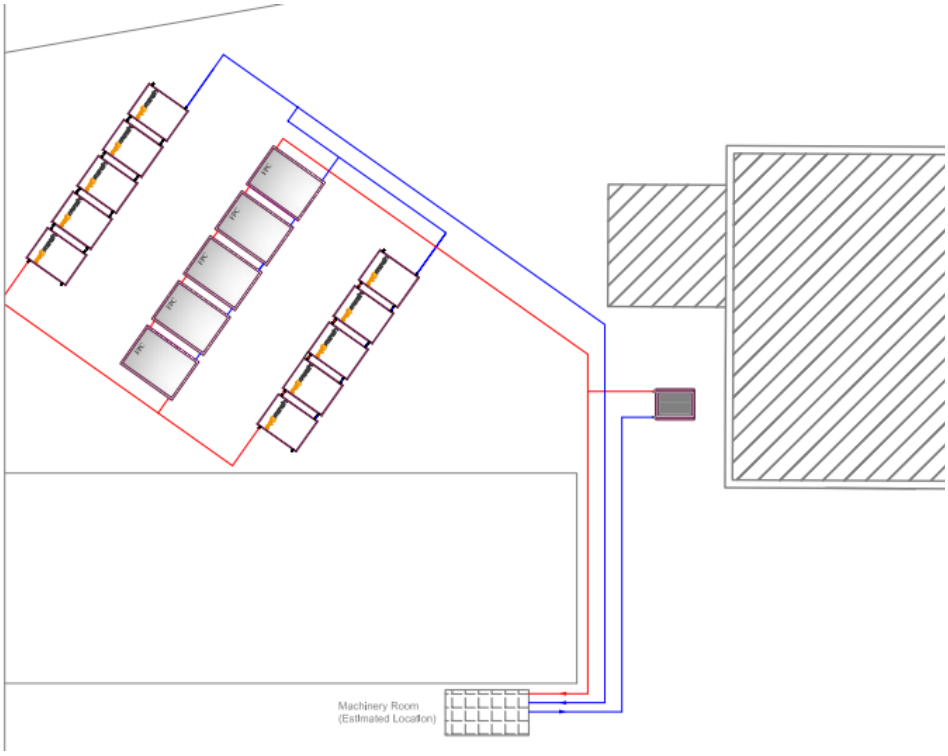
Figure 2: MiniStor system



1.1.1 PVT and solar thermal collectors

The necessary heat input to the system is provided by a solar array consisting of ten PVTs and five FPCs with an inclination of 37° due south. The PVT model consists of a high-efficiency monocrystalline silicon cell laminate coupled with thermally fastened tubes that act as an absorber, which removes the excess heat with an aperture area of 1.55 m2, an optical efficiency of 0.51, heat loss coefficients α1=4.93 (W/m2K) and α2=0.021 (W/m2K) and a maximum electrical power of 260 W. The solar thermal collectors array consists of five FPC's with a gross area of 2.37 m2 each, an optical efficiency of 0.823 and heat loss coefficients α1=3.36 (W/m2K) and α2=0.013 (W/m2K) respectively. The layout of the solar array is provided in Figure 3. To avoid overheating, an external heat exchanger is used that cools the heat removal fluid when necessary.

Figure 3: Solar array layout in the field



Moreover, in the MiniStor system a small buffer water tank is incorporated along with a 2kW electrical back up heater. The TCM prerequisite for heat input at a temperature over 329 K necessitates an automation system that measures the solar field's output temperature and controls the operation of the thermal heat fluid recirculation pump accordingly. Therefore, the utilization of the water tank temperature for controlling the hot water supply to the TCM leads to a stable heat provision to the latter. The storage of electricity in the lithium-ion batteries is managed by the solar hybrid inverter. It depends on the electrical demand of the MiniStor thermal system and the building and whether there is a surplus in the electrical production that may be sent to the electrical grid. A smart meter is installed right after the inverter. The main characteristics of the hybrid solar inverter and the lithium-ion batteries are presented in Table 1.

Table 1: Characteristics of the inverter and the batteries

Hybrid solar inverter	
Maximum input power	5 kW
Direct current (DC) input voltage range	150V to 1000V
European efficiency	96%
Lithium-ion batteries	
Storage capacity	7.68 kWh
Round-trip efficiency	96%
Maximum Depth of Discharge (DOD)	90%

1.1.2 Thermochemical Reactor and ammonia cycle operation

The main innovation of MiniStor is the TCM reactor which is a process unit for solid-gas sorption that stores heat energy efficiently and at a high density. Equations (1) and (2) provide the basis for the TCM sorption process, which is based on a reversible chemical reaction between a liquid/gas phase change refrigerant (NH_3) and a reactive solid ($CaCl_2$). The TCM material is used in the form of salt, i.e. $CaCl_2$*4NH_3. Ammonia reacts with calcium chloride to form calcium chloride complexes that produce heat per kg adsorbed sorbate but also absorb a considerable amount of sorbate per kg of sorbent, compared to zeolites [18].

$$CaCl_2 \bullet 8NH_3 + Heat \leftrightarrow CaCl_2 \bullet 4NH_3 + 4NH_3 \quad (1)$$

$$CaCl_2 \bullet 4NH_3 + Heat \leftrightarrow CaCl_2 \bullet 2NH_3 + 2NH_3 \quad (2)$$

The TCM reactor consists of 7 tubes with a length of 1.25 m each and diameter of 114.3 mm, filled in such a way to form 2 sub-reactors leading to 17.5 kWh of thermal storage. In Table 2, the characteristics of the TCM reactor are presented.

Table 2: Characteristics of the TCM reactor

Volume of reactive compound	82 liters
Mass of salt	35.5 kg
Mass of graphite	6.2 kg
Mass of compound	41.7 kg
Total length of tube reactors	8.82 m with a diameter of 114.3 mm
Cycled ammonia mass	23.7 kg
Total Mass of cycled ammonia	32 kg

There are two distinct phases that occur inside the TCM reactor.

The TCM reactor uses the heat input during the charging phase to produce a gaseous ammonia stream in accordance with the endothermic breakdown reactions described in reactions (1-2). The 1st reaction is performed for temperatures above 317 K and the 2nd reaction for temperatures above 329 K due to the different reaction rates for the operating pressure of 200 kPa and within 317-343 K for the pressure of 300 kPa. The produced gaseous NH_3 stream is compressed at 1100/1600 kPa and condensed at 1100 kPa /301 K or 1600 kPa /313 K. The NH3 compression up to 1100/1600 kPa allows for a reasonable condensing temperature of 301/313 K to be achieved. After the NH_3 is condensed, it is stored in a tank in liquid form.

The second distinct phase is the discharging phase, where the NH_3 is chemically absorbed by the salt. This phase takes place mainly during summer and winter nights. When the gaseous ammonia enters the reactor, the following exothermic reaction occurs:

$$CaCl_2 \bullet 4NH_3 + 4NH_3 \leftrightarrow CaCl_2 \bullet 8NH_3 + Heat \quad (3)$$

$$CaCl_2 \bullet 2NH_3 + 2NH_3 \leftrightarrow CaCl_2 \bullet 4NH_3 + Heat \quad (4)$$

The liquid NH_3 is converted into gaseous form in the evaporator at 273-283 K and 400-600 kPa. As a result, the TCM reactor releases heat at a temperature between 330 and 336 K. The heat generated by the TCM synthesis is either used directly to heat the building's loads during the winter or stored in the hot PCM. Similarly, in the summer, 400–600 kPa is the equivalent evaporation pressure produced by ammonia evaporating at temperatures between 273-283 K. By using the heat generated in the evaporator, the cold PCM may be charged, or the cooling demands of the building may be directly covered.

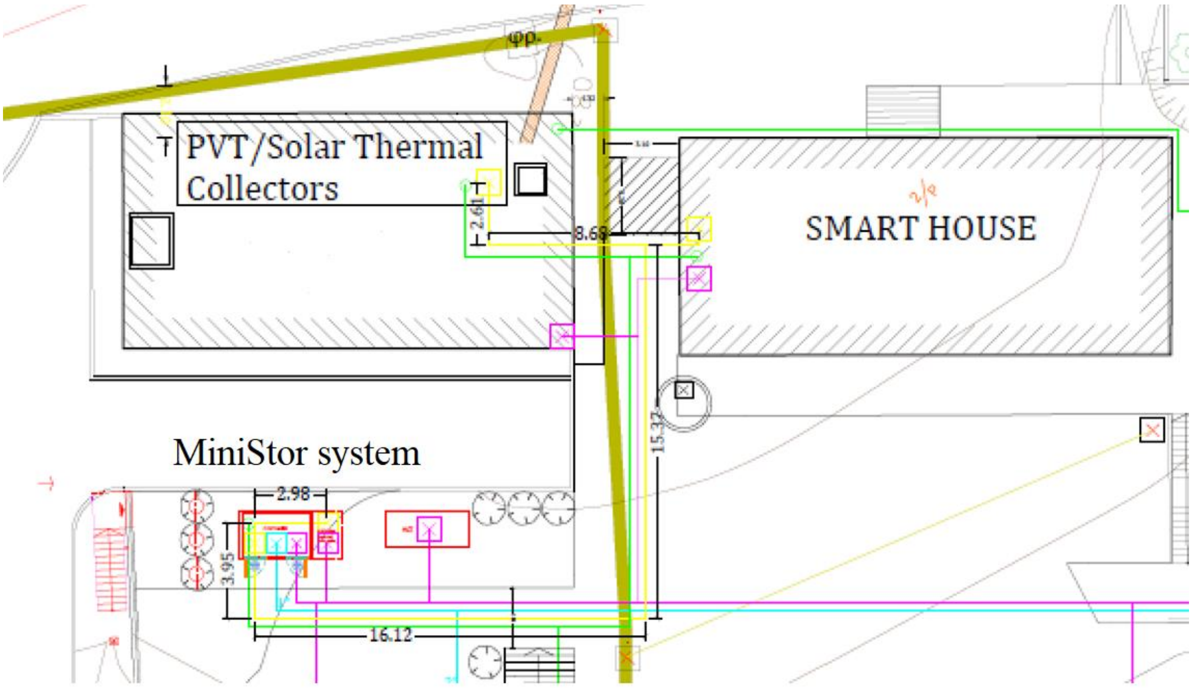
1.1.3 Heat Pump and Phase Change Material storage

To increase the released heat of the NH3 condenser from 301 K up to 336 K and store the heat in the PCM storage or use it in conventional HVAC systems, a custom heat pump (HP) unit with R410A is utilized. The heat from the HP is mainly used in the winter, however heat release from the HP condenser may also be used in the summer for domestic hot water production. Furthermore, the condensation heat is sent to the HP evaporator via a closed water circuit. The heat pump runs on a standard refrigerant cycle, where heat is transferred from the water circuit (NH_3 Condenser-Heat Pump Evaporator) to the refrigerant in the evaporator. The refrigerant is then compressed in the compressor at 4200 kPa after being evaporated at 294 K/1400 kPa. The compressed, evaporated refrigerant is then condensed to liquid in the condenser, which operates at 337 K/4200 kPa, delivering heat to the hot PCM where it is stored. The high-pressure liquid refrigerant is expanded to a lower pressure through the expansion valve to complete the typical refrigeration cycle. The heat pump has a COP of 3.61.

Next, the heat from the HP is stored in a hot PCM tank at 331 K. For the heat storage charging and discharging operation modes, respectively, the hot PCM is connected to the TCM reactor and the heat pump via separate water circuits. From the hot PCM, the heat is transferred to the HVAC system of the office building through insulated PPA pipes. The hot PCM tank has a storage capacity of 3.5 kWh and a volume of 0.09 m3. The system also includes a PCM tank that stores heat at 284 K. This cold PCM is exclusively connected to the evaporator of NH3 through a chilled water circuit. Its primary function is to hold the extra cooling capacity produced by the NH3 evaporator's discharging operation mode at 273-283 K. The cold PCM has a storage capacity of 6 kWh and a volume of 0.22 m^3.

MiniStor is demonstrated in the premises of CERTH in Thessaloniki, Greece (40.56, 22.99) and more specifically in the Smart Home of CERTH/ITI. The building has two floors with a total habitable area of 317.7 m^2, of which 182.7 m^2 are on the ground floor and 135 m^2 are on the 1st floor. The occupancy of the building is limited to the working hours of the week since it is currently used as offices for CERTH's personnel. In Figure 4 the location of the solar field and the Ministor system is also presented. All pipes between the solar field and the container of the Ministor System, and between the container and the Smart Home are insulated and installed underground to minimize heat losses. MiniStor provides heating/cooling only to a large room (labelled as "Control Room West") of the building. The gross area of the room is around 49 m^2 and it is located in the western side of Smart Home's ground floor. The supply of heated or chilled water-propylene glycol mixture is done by directly connecting the hot and cold PCM vessels to an indoor fan coil unit according to Figure 4. The fan coil unit has a heating capacity of 6 kW and a cooling capacity of 4 kW.

Figure 4: Location of MiniStor in the Thessaloniki site



1.1.4 Safety Equipment

The system is designed according to EN 378 [19] and is installed in an outdoor area more than 2 m from any buildings. The NH3 stored is below the charge limit of 50kg rendering it safe for operation. According to EN378 (EC based) the following measures have been undertaken:

- The installation of an emergency exhaust ventilation with anti-sparkling motor, Normal ventilation of >4 ACH when the room is occupied.
- Emergency ventilation of >15 ACH (ATEX anti-sparkling motor of the fan)
- The installation of a drain pan below the NH3 circuit (with blocked drainage)
- Pharmacy box with an eyewash bottle
- Installation of an emergency stop and electrical isolation of the NH3 compartment
- Installation of an emergency alarm with buzzer and flashing lamp, powered by UPS
- Furthermore, detectors required for systems with more than 50 kg of NH3, have also been installed:
- 350 mg/m^3 for pre-alarm which triggers mechanical ventilation and provides an alarm
- 21,200 mg/m^3 for main alarm that sets the emergency stop and at the same time the power supply on the NH3 apartment is turned OFF (except alarm systems and ventilation)

Finally, additional safety measurements to minimize the risks have been implemented:

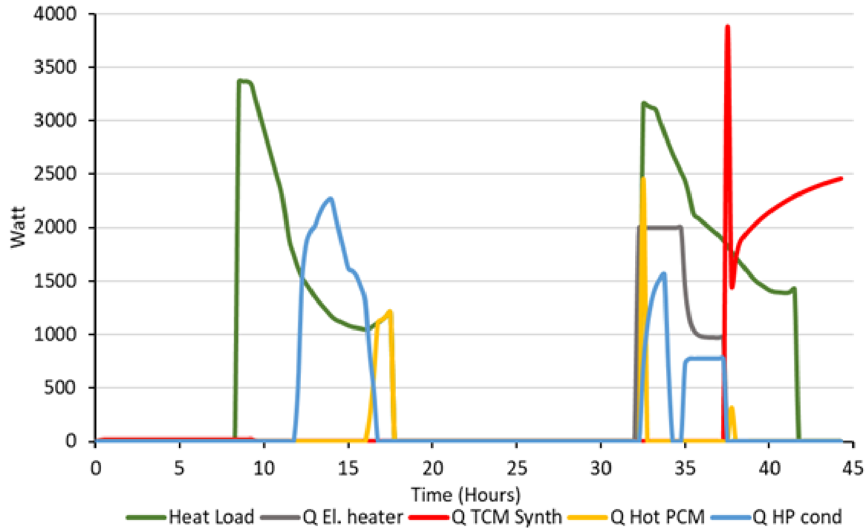
- Ammonia is installed in a separate compartment of the container with its own door.
- Access is restricted to this compartment.
- Open (naked) flames are not permitted, except for maintenance purposes by certified personnel and by ensuring adequate ventilation.
- A remote emergency switch for the TCM plant is in the control panel.
- All piping passes are sealed.
- Emergency lighting.
- The door opens directly to the outside air.
- Alarm buzzer and flashing lamp outside the door, prevents entering in case of a leakage alarm.

1.2 Simulation results and discussion

As the system has just been integrated into the Smart Home, numerical results are provided for the operation of the MiniStor system in Thessaloniki for a full cycle of charging/discharging in winter and summer, representing heating and cooling operation. A full cycle is usually completed in two to three days and therefore a typical winter and summer period is defined (11th to 13th of March for winter and 11th to 13th of June for summer) to accurately capture the behaviour of the system. TMY data for Thessaloniki are used while the heating and cooling needs are estimated according to the EN 12381 and ASHRAE CLTD / CFL / SCL method accordingly for the Smart Home. More info can be found in previous work [5] [17].

The TCM reactor is always considered empty at the start of each simulation. First, the numerical results during the typical winter period are presented. In Figure 5, the heating load, the electric heater load, the heat from the HP condenser, the heat from the synthesis reaction and the heat from the hot PCM are presented over time for the average winter period. Since the building is an office building heating load is required only from 9 am to 5 pm with its maximum value appearing early in the morning. Due to low solar radiation, the 1st stage of decomposition is achieved later in the day and the heat load from the heat pump condenser covers the demands, while later it charges the hot PCM tank.

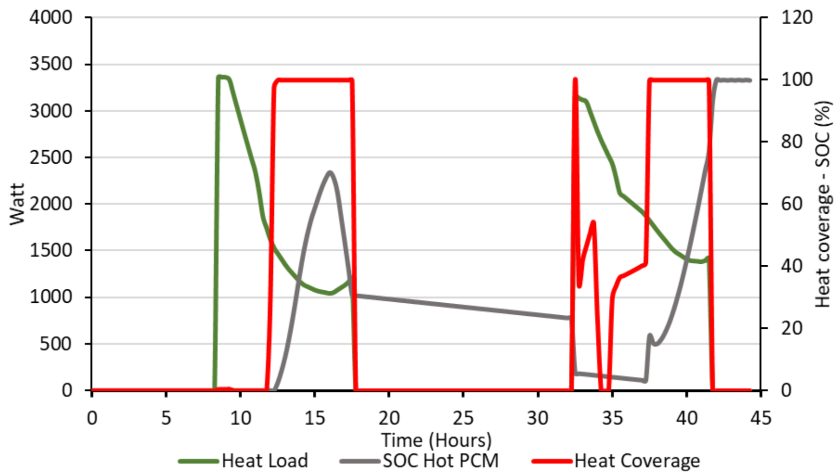
Figure 5: Heating load (W), electric heater load (W), heat from the HP condenser (W), heat from the synthesis reaction (W) and heat from the hot PCM (W) over time (hours) for the average winter period



Source: Authors' elaboration

On the next day, the heat from the hot PCM tank briefly covers the demand and the electric heater is enabled to help the hot water inside the TCM reactor reach the activation temperature of the 2nd stage of the decomposition and supply heat to the fan-coil unit from the heat pump

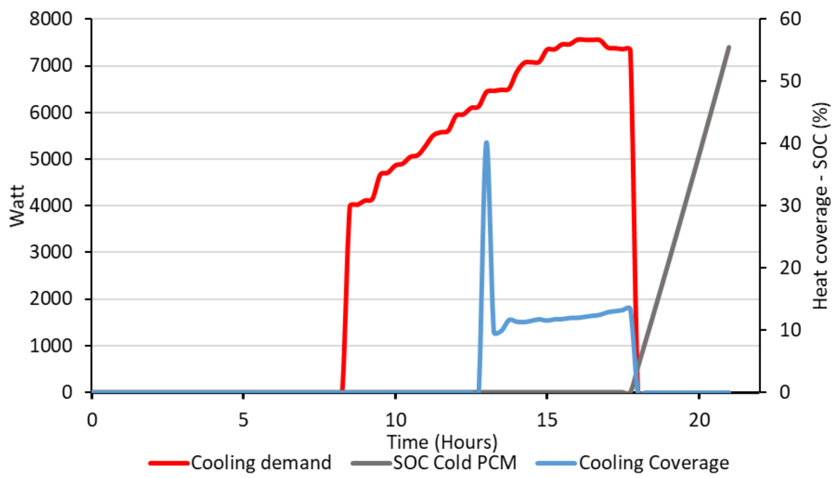
Figure 6: Heating load (W), state of charge of PCM (%) and heat load coverage (%) over time (hours) for the average winter period



When the decomposition ends, the discharging phase begins to supply heat from the synthesis reaction to cover the load and charge the hot PCM tank. The simulation is completed in less than two days, i.e., when a full cycle of charging/discharging is complete.

In Figure 6, the heating load (W), the state of charge of PCM (%) and the heat load coverage (%) are presented over time for the average winter period. The heat load coverage is calculated by dividing the heat from the heat pump, the heat from synthesis and the heat from the hot PCM tank over the heating load. Any surplus from the heat pump or the synthesis reaction is stored into the hot PCM tank. Here, it is seen that the heat load coverage follows the behaviour of the heat from the heat pump and the synthesis reaction. When there is heat from one of these operations, part of the heating load is covered. On the 1st day, not only the load is covered after 11am but also the charging phase has surplus heat that is given to the hot PCM tank. Thus, the state of charge of the hot PCM tank is increased. The next day, the heating load is covered briefly from the hot PCM tank. The coverage of the load is also decreased in these early hours. However, when the discharging phase begins, both the coverage and the state of charge of the hot PCM tank are increased leading to a charged hot PCM tank ready for the next day. In addition, the system manages to fully cover the heating needs for 10 hours during the two days and in total presents an average heating coverage of 63%. Also, on the first day, the decomposition reaction takes place utilizing only solar radiation and covers the demand of the building by 97% for 5.75 hours, while also charging the PCM up to a SOC value of 31%. The PCM supports the system to maintain the coverage of the demand 2.25 hours in total and at the end of the simulation it has a SOC value of 100%.

Figure 7: Cooling load (W), state of charge of PCM (%) and cooling load coverage (%) over time (hours)



Source: Authors' elaboration

In Figure 7, the cooling load (W), the state of charge of PCM (%) and the cooling load coverage (%) are presented over time for the average summer period. The cooling load is significant, and it is difficult to cover it with only the NH_3 evaporator output of the MiniStor system. The operating cycle of the system is one day, dedicated for the decomposition and for the synthesis reactions, since the different imposed operating conditions (mass flow of heat transfer fluid, TCM thermal inertia, operating TCM pressure etc.) as well as the high solar radiation available in the summer reduced the cycle duration of the system. The TCM is easily charged due to the high solar radiation available in the summer, then the discharging phase needed to evaporate the liquid NH_3 from the reservoir is enabled, during which time the cooling load coverage is rapidly increased to around 12%. Since the synthesis reaction continues even when there is no cooling demand, the state of charge of the cold PCM tank is increased and it reaches a high value of 56%. In the next day, the cold PCM tank will cover 3kW of the total cooling loads.

Conclusions

The MiniStor system is a novel compact integrated thermal energy storage system. The thermal storage of MiniStor is based on $CaCl_2/NH_3$ (calcium chloride/ammonia) TCM material reaction combined with parallel hot and cold phase-change materials (PCMs). The compactness of MiniStor is seen in its heat energy storage density which is 213 kWh/m3. MiniStor can be adapted easily for integration into existing residential and commercial buildings in order to cover their heating/cooling demand. The simulation results from a dynamic model of the MiniStor system including the solar field, which is developed in Aspen Plus Dynamics and integrated with Matlab/Simulink, demonstrate that MiniStor manages to fully cover the heating needs for 10 hours during the two days for the average winter scenario presenting an average heating coverage of 63%. The use of the backup electrical heater is mandatory to help the solar field increase the hot water temperature to the activation temperature of the 2nd reaction of the decomposition. The cycle of charging/discharging is two days in the average winter scenario. In the summer operation, the cycle is one day, and the cooling load coverage is around 12%. Also, the state of charge of the cold PCM tank is charged up to 56% at the end of the cycle. As the system has just been installed and commissioned, the actual operation of the system will be monitored, and the simulation results will be validated.

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2 NABERS Nearly 25 years on - Program Overview

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Abstract

In 2024, the National Australian Built Environment Rating Scheme (NABERS) will be celebrating 25 years since the launch of its first rating in 1999. This paper provides an overview of the scheme's development, achievements, and future plans.

NABERS is one of few rating schemes internationally that focusses entirely on the measured in-use performance of existing buildings rather than design features. Buildings are rated based on their performance (e.g. energy use, water use from bills) relative to empirically derived benchmarks for an equivalent median building. Ratings range from 1 star to 6 stars with average performance being approximately 3 stars. A 1-star NABERS Energy rating uses approximately 6 times more energy than one achieving a 6-star rating. NABERS also has a Commitment Agreement process for new buildings, which enables new building projects to commit to a post-construction NABERS rating.

In the financial year 2022-23, NABERS certified over 2000 office buildings in Australia, covering over 23 million m^2 of office space. Over the life of the program, over 4000 unique office buildings have been rated, representing the great majority of the office sector in Australia. The average emission reduction for offices that have been rated 14 years running is 55% (energy 42%) and for shopping centres rated for 10 years is 50% (energy 42%). This represents an unprecedented scale of savings and appears significantly attributable to the influence of NABERS.

The success of NABERS is based on its simplicity, quality and relatively low cost, which make it well suited to the property industry and its ability to create a commoditization of energy efficiency performance between building owners and tenants, and between portfolios and shareholders.

2.1 Background

2.1.1 Building Energy Efficiency and Rating Schemes

Internationally, it is well recognized that energy efficiency in the built environment represents a significant economic and environmental opportunity. Notionally, around 40% of the world's emissions are attributed to the broader buildings sector, although energy use in buildings (as opposed to construction) has been identified as 28% of global emissions in 2019, comprising residential (17%) and non-residential (11%). [1]

Achieving energy efficiency is typically seen through the lens of improved building design, with most countries having energy efficiency requirements in building codes that dictate minimum standards for (nor example) insulation, glazing, HVAC equipment and lighting. These design-led approaches are also reflected in many sustainability rating tools, such as LEED, BREEAM and GreenStar, and form a natural point of intervention for new construction.

However, for operating buildings, the relationship between these design features and actual energy use is less clear. Indeed, assessment by Cohen et al [2] showed that the design-based UK Energy

Performance Certificate grade had a very limited relationship to how much energy a building would use in operations. This problem is more generally referred to as the "performance gap", i.e. the difference between expected (simulated) and actual energy performance in the real world. The causes of the performance gap are various [3], including errors of prediction and differences in operating conditions, but of greatest interest from an efficiency perspective is the possibility that the commissioning, control and operation of buildings may be a significant determinant of performance. This conclusion was supported by work by Bannister et al [4], which showed that a wide range of management and non-technical had an influence at least as strong as major technical features.

In this context, therefore, the measurement of operational performance as a separate metric from design performance has significant real-world value because theoretical benefits do not reliably deliver actual emissions reductions. Measurements to compare the operational energy performance of buildings, while simple in theory, are complicated by operational and external parameters that affect a building's energy use but that are unrelated to efficiency. Examples of parameters that can make two buildings difficult to compare include differences in their respective climates, hours of operation and density of occupants, among several others. For individual buildings these factors can be accounted for using complex methodologies such as IPMVP Option C [5], but from a broader building-to-building perspective, a different approach using external benchmarks is required. Such benchmark systems are less common than design-based alternatives, but the leading examples are Energy Star Portfolio Manager in the United States [6] and the National Australian Building Environment Rating Scheme (NABERS) in Australia [7], both of which commenced operation in the late 1990s.

In assessing operational building performance, it is useful to understand the balance between behavioural influences and technical management influences. For an office building, for instance, the whole building energy use is a combination of these effects, where loads such as computer use are heavily influenced by the occupants, while HVAC energy use is largely driven by technical management. However, for most residential applications behavioural factors are dominant, as the decision whether to heat or cool is generally more discretionary than in non-residential buildings. As a result, where the intent of measuring operational performance is primarily to assess technical management, non-residential buildings are a more obvious operating domain. This is reflected in the non-residential focus of both Energy Star Portfolio Manager and NABERS.

2.2 What is NABERS?

2.2.1 History

NABERS was originally called the Building Greenhouse Rating (BGR) and was developed in 1998 and launched in 1999 for the New South Wales (NSW) Sustainable Development Authority by the lead author of this paper in collaboration with the Building Research Association of New Zealand. Coverage at the time was limited to energy use in office buildings. BGR was extended to national coverage in 2000 and renamed the Australian Building Greenhouse Rating (ABGR). Over the period 2000 to 2005, a number of updates were undertaken to customize benchmarks for individual states.

In 2005, the Australian Government Department of Environment started developing a separate rating system with coverage of broader environmental issues, including water, waste and indoor environment quality. The scheme was named the National Australian Built Environment Rating Scheme (NABERS) and was subsequently transferred from the Australian Government to the NSW Government, who operated the existing ABGR scheme. As part of this process, ABGR ratings were rebranded as NABERS Energy ratings, and three additional performance-based ratings were developed: NABERS Water, NABERS Waste and NABERS Indoor Environment. Legislation in 2010 made the public disclosure of NABERS Energy ratings mandatory for most office buildings; this requirement continues in 2024.

NABERS Energy and Water ratings were developed for hotels and shopping centres (2007-08), data centres (2012, energy only), public hospitals (2017), apartment buildings (2018), retirement living and residential aged care (2021) and warehouses and cool/cold stores (2022, energy only). At the time of writing, energy and water ratings are also being developed for schools and retail stores.

NABERS development has also expanded to other countries, with NABERS ratings now available for offices buildings and public hospitals in New Zealand (2013), and for office buildings in the United Kingdom (2020).

2.2.2 Rating types

The rating tools cover four separate areas of performance, being:

- Energy/emissions: Energy efficiency, with emissions-based weighting of fuels and electricity, based on measured operational energy use.
- Water: Water efficiency, based on operational water use.
- Indoor environment: Indoor environment quality based on measurements of thermal comfort, indoor air quality, lighting and acoustics.
- Waste: Waste production and recycling, based on measurements of waste streams.

Availability of ratings in different sectors is summarized in Table 1.

Table 1.Availability of NABERS ratings for different sectors.

Sector	Energy	Water	Indoor Environment	Waste
Offices	Y	Y	Y	Y
Shopping Centres	Y	Y	N	N
Hotels	Y	Y	N	N
Data Centres	Y	N	N	N
Public Hospitals	Y	Y	N	Y
Apartment buildings	Y	Y	N	N
Residential Aged Care and Retirement Living	Y	Y	N	N
Warehouses and Cool/Cold stores	Y	N	N	N
Schools	2024 release	2024 release	N	N
Shops	2024 release	2024 release	N	N

NABERS does not aggregate ratings for an individual building; thus a building obtaining both an energy and water rating will get two ratings rather than a single aggregated rating. This is designed to reflect that a building can perform well in one area in sustainability (e.g. energy efficiency) and poorly in another (e.g. water efficiency).

Discussions in this paper refer only to energy or water ratings unless otherwise noted.

2.2.3 Rating Methodology

A 0-6 star rating scale used in NABERS across all rating types, with 1 star representing poor performance, 3 stars average performance and 6 star excellent performance. The rating scale is set so that, typically, at least 80% of buildings in the benchmark data set rate between 1 and 6 stars, thereby ensuring that the rating is broadly inclusive of the sector. Ratings have one year validity and are based on a one-year measurement period.

The rating scale for each rating type and coverage was developed based on a benchmark dataset assembled specifically for the rating development process, in consultation with the relevant industry sector. This benchmark dataset would include energy and water use but also cover key operational variables that may be considered as potential adjustments. This is done to ensure that, as far as possible, a building receives a high rating because it is efficient compared to similar buildings, rather than because of factors such as being in a mild climate zone or operating shorter hours than other buildings in the same market.

Based on this data, regression analyses are used to determine a benchmark equation of the form[1] $B = f(A_1, A_2 \dots A_n)$ where B is the expected emissions/water use for a building with operational parameters A_1 to A_n being factors such as climate or hours operation. The equation is used to represent the real-world average energy use of a building under the operational conditions described by factors A_1 to A_n. The ratio of actual emissions/water use to this benchmark is calculated, and linearly translated into the star rating. The rating scale from 1 stars to 6 stars covers a factor of 6 in site energy/water use[2].

2.2.4 Coverage

As an empirically based system, the data used to develop NABERS benchmarks reflects the data available from the market. In Australian office buildings, electricity metering has traditionally been configured around a base building/ tenant split, whereby the tenant has a utility-owned electricity meter that covers only the lighting and general power within the tenancy (including supplementary, but not primary, air-conditioning systems), and the base building electricity meter covers everything else (primary air-conditioning to tenancies, common area services, lifts, etc.). As a result, NABERS Energy for offices has separate ratings for base buildings, tenancies and whole buildings. This has been fortuitous, as these boundaries align with first-order control boundaries: that is to say, the building owner can rate their base building with first-order independence from the activities of tenants, and vice versa. This assisted considerably in the roll out of the rating as it made it possible for the base building rating to be used as a procurement parameter in leasing discussions[3].

This type of metering demarcation also affects the coverage of three other energy/emissions ratings:

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[1] The "custom benchmark" described here holds true for all ratings other than NABERS Energy for Offices, which was developed using fixed benchmarks with adjusted energy consumption. The two methodologies produce similar results, but the custom benchmark approach is preferred because it is simpler overall.

[2] For more recently developed ratings, this factor of 6 is fixed and a linear scale is used across the entire range. Earlier developed ratings use customised ranges and are generally bi-linear, with the change in slope occurring at the 5 star mark.

[3] State, territory and the Federal government all introduced minimum NABERS base building ratings into leasing requirements in the period 2000-2009.

- Shopping centres: The shopping centre rating is framed from a “base building” perspective, with the complication that in practice some shops provide part or all of their own air-conditioning within their own metering. The rating has parameters to separately assess base building-serviced and tenant-serviced shops as a result.

- Apartment buildings: The apartment building rating is also a “base building” rating that assesses energy used in the shared services and spaces in the building. The benchmark was designed to adapt to the many service combinations which exist in practice, such as the fact that some apartment buildings provide central HVAC services to residents, while in others this is provides by the residents themselves.

- Data Centres: The data centre rating offers three rating types, being an infrastructure rating (analogous to base building, in this case covering everything other than IT equipment), an IT rating (covering the IT equipment only), and a whole facility rating (all services plus IT). The infrastructure rating is based on calculations similar to the widely used PUE measure but has an emissions base and has more tightly defined rules of measurement.

The indoor environment and waste ratings also have separate benchmarks for base building, tenancy and whole building. All other energy and water ratings are whole building ratings. Details of all ratings can be found on the NABERS website [7].

2.2.5 NABERS NZ

NABERSNZ Energy for offices was launched in 2013/14 and is operated by the New Zealand Green Building Council on behalf of the NZ Government [8]. The rating is very similarly structured to NABERS Energy for Offices in Australia, but with adaptations reflecting differences in the measurement of floor area and some metering coverage issues.

NABERS NZ for Hospitals will be launched in 2024 and is operated by the New Zealand Government.

2.2.6 NABERS UK

NABERS UK Energy for offices was launched in 2020 after an extensive development process that was funded and facilitated by the Better Buildings Partnership [9]. The rating is based on the same principles as the equivalent Australian rating but uses a relative primary energy metric rather than an emissions-based metric. As UK office buildings tend to have a split of primary air-conditioning equipment between tenants and base building, the rating includes a number of methodologies not present (or needed) in the Australian rating to facilitate ratings in the absence of metering to match the base building/tenancy split assumed in the rating. The primary emphasis in initial roll-out has been on new-build under the title “Design for Performance”, as this can be metered correctly from day one. The scheme has now been expanded to also be able to certify whole buildings, to allow office buildings that do not have sufficient metering to separate owners from tenants to obtain a joint assessment for the entire building.

NABERS UK Energy for Offices is currently operated by BRE, who have announced they will be stepping down and are expecting to be replaced by a new administrator early in 2024.

2.2.7 NABERS and New Buildings

As the NABERS Energy rating is based on historical energy data of existing buildings, it is not always obvious how this could be applied to new buildings. However, NABERS in Australia has had a Commitment Agreement process[4] available for new buildings for over 20 years [10]. This process enables new building developers to commit to a future NABERS target in operation while subjecting the building design to formalized peer review and simulation processes to test the viability of the proposed target. Developers are then contractually obliged to undertake a NABERS rating once they reach 12-months of building operation, to demonstrate achievement of the target rating in practice.

2.3 NABERS Operations

2.3.1 Governance

NABERS is a national government program administered by the NSW Government as the National Administrator). The operation of NABERS is overseen by a national Steering Committee comprised of all State and Territory representatives, and the Australian Federal Government. These government members have voting rights within the Committee.

The NABERS Steering Committee is also made up of non-voting stakeholder members from bodies representing the wide range of NABERS stakeholders. These industry bodies participate in all major discussions about the direction of the program and are refreshed every 3 years. Industry bodies that were part of the Steering Committee in the 2021 and 2023 period are: Aged Care Industry Association, Australian Institute of Architects, Australian Institute of Refrigeration Air Conditioning and Heating, Australian Property Institute, Australian Sustainable Built Environment Council, Chartered Institution of Building Services Engineers, Council of Capital City Lord Mayors, Energy Efficiency Council, Facility Management Association of Australia, Green Building Council of Australia, Indoor Air Quality Association Australia, International Building Performance Simulation Association Australasia, Property Council of Australia and the Strata Community Association.

2.3.2 Operations

Each rating has a set of rules specific to the individual rating that provides detailed parameters and procedures for the evaluation of each of the inputs to the rating. There is also a common set of rules covering the assessment of energy data. Rules documents are available on the NABERS website [7].

All ratings other than hospitals (and in 2024, schools) must be obtained via the use of an accredited assessor. Accredited assessors are required to visit the site, collect and verify data, calculate rating inputs and submit the rating to NABERS. Accredited assessors are trained in the rules associated with ratings (primary accreditation is based around offices ratings, additional training modules are used for additional ratings). To become accredited, assessors undertake the relevant training, pass an exam with a minimum 80% mark and undertake two supervised ratings, where their work is subject to scrutiny by an appointed supervisor (an experienced NABERS assessor). All ratings are subject to an audit process upon submission to NABERS. Furthermore, approximately 5% of ratings are

[4] Also operating in the UK as Design for Performance.

retrospectively audited in greater detail to reconstruct the rating from primary data. Disciplinary and retraining procedures are available where an accredited assessor has performed poorly.

Hospital ratings (and schools in 2024) are conducted in bulk by the relevant state/territory agency based on bulk data parameters (no site inspection) and subject to desk audit by the NABERS team before acceptance.

All ratings have one year of currency, after which the rating can no longer be publicized. Many sites choose to re-rate annually.

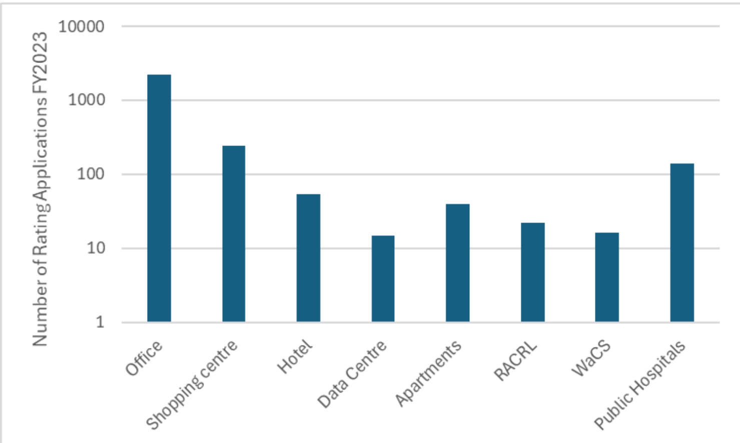
For ratings other than hospitals and schools, a rating administration fee is charged by NABERS [11]. For most ratings this is currently $AUD1410, except for small offices below 2000m² for which it is $AUD705. Discounts are provided where multiple ratings are simultaneously conducted on a single site. Accredited assessor consulting fees are charge in addition to these rating fees and range from $2,500-$9,000 depending on the scale and complexity of the site[5].

2.4 Uptake of NABERS[6]

2.4.1 Australia: Energy/emissions Ratings FY 2023

In financial year 2023, a total of 2712 energy/emissions rating applications were received, dominated by office energy ratings[7] (2187), shopping centres (242) and public hospitals (138), as shown in Figure 1.

Figure 1. Total energy/emissions rating applications received in Financial Year 2023. Note that a logarithmic scale has been used to enable data to be seen more clearly. In practice, rating applications are dominated by office ratings.



NABERS estimates that 4186 office buildings have been rated at least once in the life of the program, corresponding to 77% of the market floor area. Shopping centre market penetration is not specifically

[5] This range is relevant to energy and water ratings only.

[6] The NABERS Annual report [14] provides a wide range of statistics about the program.

[7] Includes base building (60%), tenancy (19%) and whole building (21%).

calculated but is also high given that the original target market[8] for the rating comprises regional and subregional shopping centres of which there are 369 nationally [12].

Public hospital ratings are undertaken within the health agencies of each state and territory. There are approximately 697 public hospitals in Australia [13], the majority of which should be ratable under NABERS.

Uptake of the hotel rating has been more limited, with a total of 156 individual sites rated over the lifetime of the rating. A significant number of sites have rated for multiple years, however.

Data centre ratings operate within a small market of around 112 significant sites [15]; 24 unique sites have been rated in the lifetime of the rating thus far. Again, many sites that have used the ratings have obtained repeat ratings over multiple years.

The apartment buildings rating has had limited uptake at this stage relative to the large scale of the market.

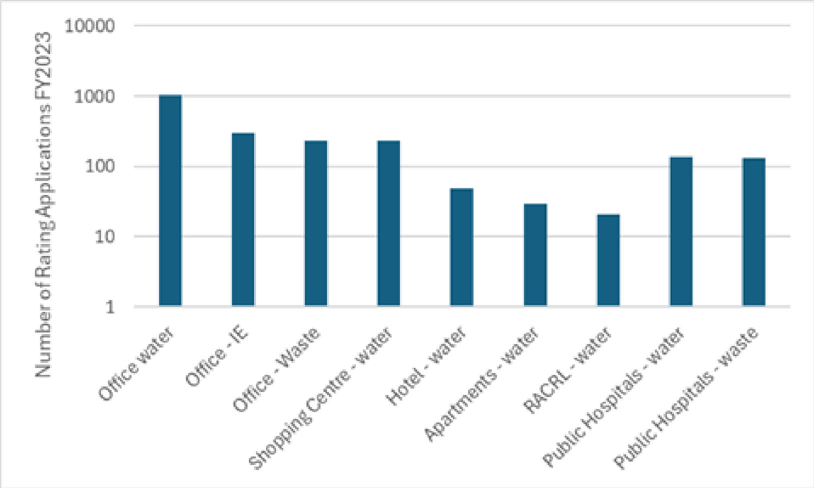
The Residential Aged Care and Retirement Living rating (RACRL) and the Warehouse and Cool/Cold Storage rating (WaCS) are recently launched and so numbers are expected to be low.

Australia – Water/Indoor environment/Waste ratings

In financial year 2023, a total of 2156 water, indoor environment and waste ratings were undertaken, dominated by offices water (1023), offices waste (328), offices indoor environment (401) and shopping centres water (232), as shown in Figure 2. Rating numbers for other sectors follow the same patterns as for energy/emissions.

[8] The rating has latterly been expanded to include smaller shopping centres (of which there are a further 1120) but the rating statistics show an average floor area of over 42000m², indicating that the rating are heavily dominated by the larger end of the market. NABERS ratings in FY2023 cover just over 10.1 million m², which is 38% of the total sector floor area as estimated by the Shopping Centre Council of Australia [12]

Figure 2. Total non-energy/emissions rating applications received in financial year 2023. Note that a logarithmic scale has been used to enable data to be seen more clearly. In practice, rating applications are dominated by office water ratings.



2.4.2 Australia – Commitment Agreements

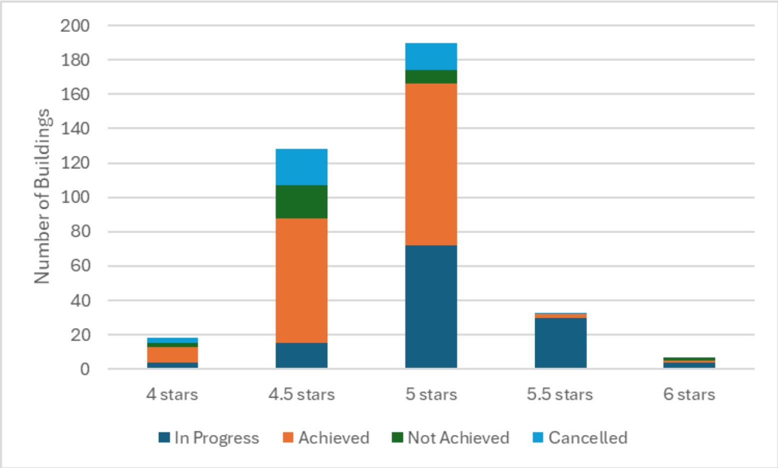
As shown in Figure 3, there has been a total of 387 Commitment Agreements over the duration of the program, dominated by offices (341 Base building, 22 Tenancy, 8 Whole Building), with minor activity in apartments, data centres, hotels and shopping centres[9]. Historically, the majority of Commitment Agreements have been signed for 4.5 or 5 star ratings, but 85% of the 154 commitment agreements starting 2018 onwards are for ratings of 5 stars or higher. Achievement rates are high for sites where the process has had the time to complete. A number of the sites listed as “Not Achieved” have subsequently achieved their target rating outside the Commitment Agreement process.

2.5 NABERSNZ

Program statistics for NABERS NZ are not readily available, but the NABERSNZ website lists 48 office buildings as having current ratings, with 72 buildings having been rated at least once.

[9] The Commitment Agreement Process was only opened to sectors beyond offices in 2019.

Figure 3. NABERS Commitment Agreement statistics – whole of program lifespan.



2.6 NABERS UK

As noted earlier, the primary emphasis in the UK has been on new buildings via the Design for Performance process, which is the equivalent of NABERS Commitment Agreements in Australia. There are 80 current Design for Performance agreements in place, and 5 current NABERS Energy for Offices ratings.

2.7 Impact of NABERS

The longevity of the NABERS program provides a unique opportunity to see the impact on building performance; this is particularly true in Australia where there are few other major programs driving energy efficiency in commercial buildings[10]. The most insightful data can be achieved by looking at the average emissions and energy intensity of buildings that have been rated across multiple years. This is illustrated in Figure 4.

It can be seen in the figure that sites with multiple ratings have shown a consistent trend to lowering emissions and energy intensity, with long term involvement in the NABERS program being correlated with emissions reductions of around 50% on average and energy intensity reductions of around 40%.

While not all of these savings can be attributed exclusively to NABERS, the scale of the benefit is substantial. There are two pieces of evidence indicating that this benefit is additional to general trends, such as improved lighting efficiency:

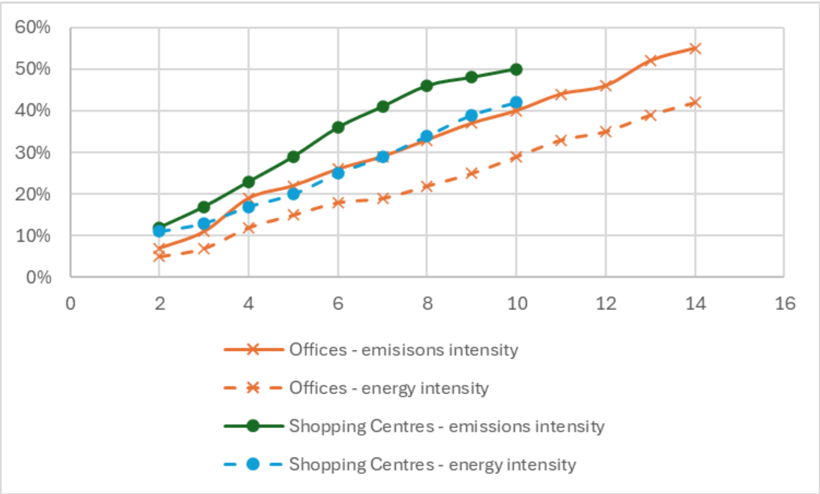
1. There has been a substantial amount of activity by building owners, particularly in larger portfolios, towards the programmed upgrade of buildings to higher NABERS ratings. This activity has moved through multiple phases, starting with resolution of metering and data

[10] The National Construction Code introduced energy efficiency requirements for commercial buildings in 2006, and these were significantly updated in 2019; however these apply only to new building and major refurbishments.

issues, followed by building controls, tuning and plant upgrades, and latterly by the addition of on-site solar power[11].

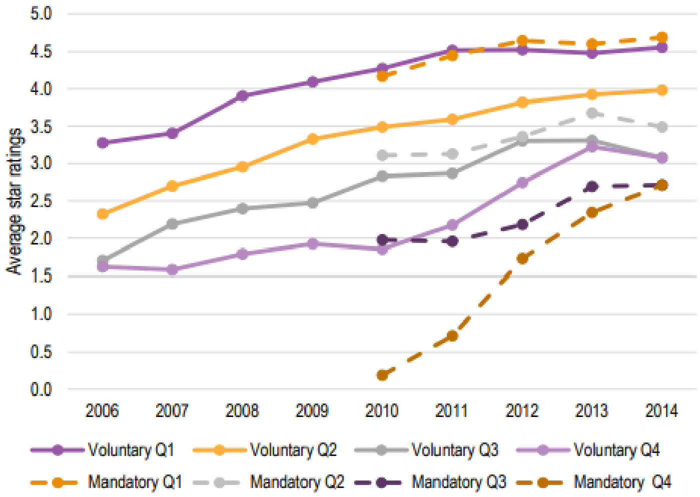
2. In 2015, consultants ACIL Allen were engaged by the Federal Government to review the impact of the mandatory disclosure regime [18]. As part of this work, they examined the changes in rating of buildings that had already been rating their buildings versus those mandatorily brought into the scheme upon the commencement of mandatory disclosure, as shown in Figure 5. What is striking in this figure is that the poorest performing quartile of buildings under the mandatory category improves rapidly to match that of the equivalent quartile of voluntarily rating buildings. This indicates that the process of measurement and declaration of NABERS rating has a direct impact upon efficiency related activities at least for the worst buildings.

Figure 4. Reduction in emissions and energy intensity for buildings rated multiple times.



[11] For example, see [16] and [17].

Figure 5. Impact of mandatory disclosure on NABERS ratings as published in [18]. "Voluntary" refers to buildings that were already rating their buildings prior to the introduction of mandatory disclosure; "Mandatory" refers to the buildings that only started rating after the introduction of mandatory disclosure. Q1, Q2, Q3 and Q4 refer to the quartiles of the relevant group of buildings as arranged by NABERS rating.



2.8 Discussion

2.8.1 Success Factors

It is of course difficult to empirically determine success factors in a real-world program. However, it is possible to consider the anecdotal experience of those involved in the program, including the authors, as to what appears to have resonated well or otherwise. Key factors that appear to have contributed to NABERS success are as follows:

1. Industry engagement. Each NABERS rating has been developed with extensive industry engagement. This is in some ways inevitable, as the starting process for each rating involves a large-scale data collection exercise. However, ongoing engagement through the lifetime of the ratings has enabled feedback to be received and incorporated into rating updates, establishing confidence in the star rating results.

2. Market drivers. Over the past 20 years, much emphasis has been placed on creating market drivers for the use of NABERS, and for the improvement of star ratings over time. This was particularly well matched to the office sector, where the base building rating could be cited as a procurement requirement by tenants[12]. Furthermore, in the office and shopping centre sectors, the availability of a high-quality and low-cost metric to demonstrate climate action at an individual-building and portfolio-level has been used to attract investment.

3. Measurement, not theory. A key element of the design of all NABERS ratings has been that they are based on measured outcomes rather than design inputs. This feature has driven the

[12] The incorporation of minimum NABERS Energy Base Building requirements into leasing guidelines for state, territory and federal government leases was particularly crucial in the early phases of the rating.

Australian industry to focus sharply on building upgrades and better management techniques that deliver actual reductions on energy use and emissions.

4. Quality, repeatability. All NABERS ratings have adopted strong rules to ensure that ratings are repeatable. This is particularly important given the wide range of interpretation of key input variables (e.g. floor area, hours) which could otherwise undermine the usefulness of the rating.

5. Market comparison. NABERS is designed to be relevant to the entire building stock, with the rating scale designed to ensure at least 80% of buildings within a sector can get a rating of between 1-6 stars, with the remainder receiving a zero-star rating. This means that poorly performing buildings can identify their starting point and chart a path to improvement on an annual basis[13].

6. Mandatory disclosure. The introduction of mandatory disclosure of NABERS ratings in 2011 was transformational for the scheme (and the market) in many ways and has been successful in driving improved performance in the market overall. The fact that NABERS had been operating for 12 years at that stage and already had significant uptake made the process of creating a mandatory process far easier, as there had been opportunity to refine the rating and build industry acceptance.

7. Integration with other initiatives. NABERS ratings have been integrated with many other initiatives, which have proved to have a symbiotic impact on NABERS as well as the other initiatives. Those initiatives use NABERS ratings as a robust metric to verify environmental achievement, without having to set up their own complex measurement and verification systems. While in return, those initiatives create additional incentives to encourage building owners to improve their NABERS ratings. Examples include the integration of NABERS targets in green loans with major Australian banks, state planning policies, government procurement policies and standard green lease templates, among many others, many of which would not be possible without NABERS ratings.

2.8.2 Issues, Challenges and Lessons Learnt

The operation of NABERS has of course had to face many issues and challenges over time, and a number of key lessons have been learnt. The following are some key issues and challenges.

1. Sectors with weak market drivers. While the office and shopping centre markets have strong internal and external drivers to undertake and improve NABERS ratings, such drivers are somewhat less potent in many other sectors. For hotels it is possible that this may be able to be addressed via government procurement[14] , but sectors where the building space itself is often not rented or sold (such as for schools, hospitals or universities), the naming and shaming incentives of mandatory disclosure of energy performance policies may be needed.

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[13] This is in contrast to single “best practice” benchmark systems, which were available prior to NABERS/ABGR but tended to alienate building owners because of their seeming impossibility.

[14] The Australian Federal Government Net Zero Government strategy includes a measure to publish the NABERS rating of hotels on their internal hotel booking system in 2024, with a view to possibly introducing a minimum NABERS rating requirement in 2026-27. [19]

2. **Sectors that don't rate easily**. There are some sectors for which a performance-based rating is challenging simply because there is a lack of comparable buildings. This holds true for some uncommon building types, but also for some significant sectors such as buildings that host manufacturing processes.

3. Complexity of analysis. As NABERS has expanded to new sectors, the tendency has been for the sectors both to be more complex (i.e. driven by a wider range of not necessarily well measured operational factors) and for the expectation of the market generally for the rating to be more nuanced. However, it has been found possible to develop benchmarks for every sector assessed thus far, even where there were significant initial concerns about the feasibility of creating a working benchmark.

On the positive side, there are some powerful lessons learnt:

1. Efficiency keeps getting better. When the office rating was designed in 1999, it was set with 2.5 stars as average performance, 4 stars as market leading and ratings beyond 4.5 star essentially a theoretical proposition only. In 2023, the average office rating is 4.9 stars [14] (half of the emissions of 2.5 stars) and the top of the market is 6 stars (~34% of the emissions of 4 stars). There was no expectation in 1999 that such radical improvements were possible, let alone able to be achieved across the entire office sector.

2. A rough rating scale is better than no rating scale. Although the benchmarking process has been as thorough as possible for each rating, there have been cases where the consequent real-life ratings were not 100% aligned with what was expected during the design phase of the rating tool. However, experience has shown that this is not a major impediment for industry acceptance of the rating, and that rating tools can be improved once more data is available.

3. Performance ratings can be transformational. NABERS has had a transformational influence on the operation of Australia's office and shopping sectors. This has led to changes in design practice, the creation and growth of an energy efficiency industry, the mainstreaming of the use of building simulation in design processes and the enthusiastic adoption of energy efficiency as a KPI in facilities management and corporate reporting. Australia is today a significant exporter of building sustainability technology and expertise to much larger OECD countries in Europe and North America, with products that were originally built to satisfy the need from Australian building owners to rapidly improve their NABERS ratings.

2.9 Moving Forward

Key current and future initiatives include:

1. Response to the decarbonization of the Australian electricity grid. Australia's grid is going through a rapid decarbonization process. Furthermore, Australia also has a mature industry of Power Purchase Agreements (PPAs) which permit renewable energy to be sold directly from a renewable energy generator to a customer. As a result, NABERS has recently changed how it reports the use of renewable energy and is reviewing options for how to compare buildings once the domestic electricity grid reaches 100% renewable energy.

2. Expansion of sectors. NABERS is conducting feasibility work regarding the expansion of the scheme to cover universities, medical centres, private hospitals, supermarkets, TAFE, built-to-rent apartment buildings and student accommodation.

3. NABERS is also seeking to expand its capabilities to help many more countries adapt NABERS to create their own energy-performance rating tools tailored to their countries. The program is expected to release an International Strategy towards this goal later in 2024.

Conclusions

The NABERS program celebrates its 25th anniversary in 2024. In 25 years of operation, it has shown that a measured performance-based rating system is viable across a large part of the commercial buildings sector, with potential for transformational impacts and very substantial reduction in achieved emissions and energy intensity.

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3 Commercial Building Energy Efficiency Measures for the Australian National Construction Code: Preliminary Results

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Abstract

The Australian National Construction Code (NCC) is the primary technical document determining building standards for new construction in Australia. This paper provides an overview of the preliminary results of investigations into potential stringency increases for the 2025 update of Section J Energy Efficiency of the NCC.

Core analyses focused on four areas:

- Building envelope: Solar admittance, wall and roof insulation
- HVAC Equipment. Efficiency requirements for chiller plant, unitary air-conditioning, heat pumps, four pipe chillers, outside air control/preconditioning, economy cycle, variable speed drives for fans and pumps, fan efficiency.
- Electrification. Provisions for immediate or future electrification were investigated.
- Roof-top solar. The potential for roof-top solar was investigated and found to be economically attractive.

Overall results indicate significant potential emissions savings (up to 30% without solar, and approaching 100% for low rise buildings with roof-top solar) from aggregated measures. The work reported here has been used as a basis for development of revised NCC measures, but is not necessarily the same as the final efficiency requirements which are undergoing a codification and consultation process throughout 2024.

Introduction

The Australian National Construction Code (NCC) [1], managed by the Australian Building Codes Board (ABCB) on behalf of the federal, state and territory governments of Australia, is the primary technical document determining building standards for new construction in Australia. This paper provides an overview of the preliminary results of investigations into potential stringency increases for the 2025 update of Section J Energy Efficiency of the NCC (Volume 1 - Commercial buildings).

Section J of the NCC Volume 1 was significantly updated in 2019, with predicted savings in the range of 31-49% relative to the 2016 edition of the Code [2]; only minor amendments have been made to efficiency measures since. The 2019 update captured many of the more obvious improvement opportunities, leaving the current update with an arguably more challenging task. However, although the overriding economic parameters for the analysis are identical to 2019, some of the input costs, particularly carbon costs, have increased significantly. Furthermore, greater recognition of climate change provides added impetus to tackle measures that were not addressed previously.

Each section of the NCC is structured around three statements of requirements:

1. Performance Requirements, which set out the performance goals for the Section. These are the only legally enforceable components of the Code. Any solution that can be shown to meet these requirements by any method, including but not limited to a Verification Method or a Deemed-to-Satisfy pathway, is deemed sufficient for compliance.
2. Verification Methods. These are defined calculation/simulation-based methods that enable a project that does not meet the deemed-to-satisfy requirements to demonstrate that it still meets the performance requirements.
3. Deemed-to-satisfy Requirements. These are specific prescriptive measures which are deemed to comply with the Performance Requirements without further verification.

This paper sets out a summary of the process and results of investigations leading to recommendation for updates to Section J of the 2025 edition. The investigations are based on the development of revised deemed-to-satisfy requirements, which can then be relayed though into updated Verification Methods and Performance Requirements as required.

These results presented in this paper are only consultant's recommendations to the ABCB, and indeed include three different stringencies representing significantly different outcomes, whereas Code can only have one stringency level. The recommendations are currently going through a process of codification and stakeholder/public consultation which will result in the actual final measures for NCC 2025.

3.1 Australian Climate Zones

The eight climate zones referred to in this paper are those used in the NCC. These are as listed in Table 1.

Table 1. Climate zones [1]

Climate Zone	Representative location	Climate
1	Darwin	Hot and humid summer warm winter
2	Brisbane	Warm and humid summer mild winter
3	Alice Springs	Hot and dry summer, warm winter
4	Wagga Wagga	Hot and dry summer cool winter
5	Sydney	Warm temperate
6	Melbourne	Mild temperate
7	Canberra	Cold temperate
8	Thredbo	Alpine

3.2 Outline Analysis Process

3.2.1 Stringency levels

The brief for the project required three different stringencies to be assessed, being:

- Stringency 1: Energy efficiency measure updates only, not consideration of rooftop PV

- Stringency 2: Stringency 1 plus rooftop PV
- Stringency 3: Stringency 2 plus electrification[1]

These were developed in parallel via the processes described in the next section.

3.2.2 Analysis process

The analysis process for a project of this nature was necessarily complex. A four-stage approach was used, being:

1. Definition of key analysis parameters. In this stage, the key economic and technical parameters for the project were determined.

    (a) From an economic perspective this included identification of the current and future costs of electricity and gas, carbon pricing and emissions intensity. US recommendations for Social Cost of Carbon were used [3], and Australian Federal government projections were used for future electricity emissions figures.

    (b) From a technical perspective, ten building archetypes (small, medium and large office buildings; small and large hospital buildings; school; strip retail shops; large standalone retail outlet; motel and hotel) were developed and preliminary simulations conducted to assess comparative heating and cooling loads. Based on these results, four archetypes (medium and large office; small and large hospital) were selected as being the core archetypes for use in the analysis process, with the balance being retained as check calculations at the end of the process.

2. Initial Measures development. In this stage, 18 separate streams of work were undertaken to assess the stand-alone economic feasibility of measures related to the following: Chillers; unitary air-conditioning; heat pumps; 4 pipe chillers; economy cycle; indirect evaporative cooling; glazing; roof insulation; wall insulation; rooftop PV and batteries; VSDs for cooling tower fans, ventilation fans and pumps; cool roofs; HVAC zoning; HVAC fans; lighting controls; peak demand management; EV charging; and electrification.

    Notable scope exclusions were lighting power density (deemed unviable after the major stringency increase implemented in NCC2019), boilers (already specified at fairly high efficiency and potentially becoming redundant given electrification analysis) and floor insulation (not considered likely to yield worthwhile benefits relative to existing provisions). EV charging was evaluated on a functional/projected needs basis only and is not considered further in this paper.

[1] The full scope for Stringency 3 included additional work to investigate the use of additional PV as a form of balance to continued gas use in dual fuel buildings such that their emissions in the first 14 years is predicted to be the same as for the equivalent all-electric building. This analysis has been excluded from this paper for reasons of space and narrative clarity.

For each measure, the 4 core archetypes from stage 1 were used as required across the 8 climate zones used for building regulation in Australia to define, cost and simulate benefits associated with each measure on a standalone basis. The threshold for acceptance was defined as achieving a benefit cost ratio (BCR) of greater than 1 across the expected lifetime of the equipment/measure.

3. Whole Building Analysis. In this stage, the results of stage 2 were integrated into the four core building archetypes, taking into account the various interactions between measures (particularly as they affected plant sizing). The three stringencies were treated separately in this analysis:

   (a) For stringency 1, the energy efficiency measures were applied and whole-of-building BCRs were calculated. Where these were greater than 1, additional measures that had previously been assessed as uneconomic but of high energy savings were added to bring the whole of building BCR closer to 1. Based on this, an optimised set of stringency 1 measures was developed.

   (b) For stringency 2, the optimized stringency 1 results were integrated with the results of the Stage 2 (Initial Measures Development) PV measures.

   (c) For stringency 3, stringency 2 buildings were tested against electrification scenarios for the two core archetypes that had gas space heating.

4. Expansion of results. In the final stage, the measures derived for the three stringencies were applied to the six remaining archetypes, with energy savings and BCRs being calculated.

The timeline of the project was for approximately 12 months, following (and to some extent in parallel to) which an extensive process of stakeholder and public consultation was and is being undertaken to refine the measures and determine finally agreed Code text.

3.3 Summary of Key Analyses and Recommendations

3.3.1 Glazing

The majority of Australia has a sunny temperate climate with the result that measures to limit solar gain are of paramount importance, as commercial buildings are mostly cooling dominated.

Assessment of glazing measures for Code is complicated by the realities that (a) walls are cheaper than windows and (b) in Australia, in general, walls are more energy efficient than windows. A pure cost-benefit analysis would therefore reach the unhelpful conclusion that the best option is to have no windows. In NCC2019, a new methodology was developed for glazing assessment that started with the assertion that the minimum function of a window is to provide acceptable daylighting to a perimeter zone (defined as 5% daylight factor for daytime only building, 3% of overnight operating buildings and assessed with a 3.6m deep perimeter zone) [4]. This, in combination with the recognition that solar and insulation impacts on vertical facade can be treated first-order independently, led to a significant restructuring of the relevant code measures.

The major feedback from industry on the NCC 2019 measures was that daylight factor – being based on a uniform grey sky – is not representative of Australian conditions (which are dominated by sunny rather than overcast conditions). As a result, the analysis for NCC2025 used sDA (specific Daylight Autonomy), set at a threshold of 300 lux for 50% of the time across 85% of a 3.5m deep perimeter floor plate for daytime buildings and 160 lux/50%/85% for overnight operating buildings. These daylight-driven criteria were translated to a solar admittance factor (defined as the product of Solar Heat Gain Coefficient (SHGC) and window wall ratio (WWR) based on the comparative SHGC and visual transmittance properties across a library of glazing selections.

The resultant figures were then tested by simulation to verify that they produced an energy saving. This was found to be the case in all bar Australia's coldest climate zone (climate zone 8, represented by the ski resort village Thredbo in the NSW Snowy Mountains). For this climate zone the solar admittance factors were adjusted upwards to reflect that the lowest combined heating and cooling energy occurred at a higher solar admittance. The resultant glazing recommendations were as follows:

- Daytime buildings: In climate zones 1-7 reduce average maximum solar admittance from 0.13 (range 0.12-0.16 across different climate zones and facades) to 0.975 (range 0.09-0.11), and in climate zone 8 from 0.295 to 0.125.
- Overnight buildings: Reduce average maximum solar admittance from 0.08 (range 0.07-0.1 across different climate zones and facades to a single figure of 0.06.

The estimated energy saving for this measure varied by climate zone and building type but averaged around 10% for daytime buildings and 5% for overnight buildings.

3.3.2 Chillers

Historically, NCC requirements for HVAC equipment efficiencies have been tied to separately legislated Greenhouse Emissions Minimum Standards (GEMS) which regulate the minimum efficiency of equipment allowed to be sold in Australia. This practice has become more problematic as the NCC has become more aspirational while the GEMS program is a minimum, market lagging requirement. A consequence of this situation is that NCC 2019 the chiller efficiency requirements were investigated but ultimately set at ASHRAE 90.1 (2015) levels on the basis that there was an intent – never realised – for this to become the GEMS requirement for chillers. The analysis for the current project found that chillers commonly available in the Australian market outperformed the NCC2019 levels by a significant margin. Thus, a challenge for NCC 2025 development was to create enhanced stringency requirements while not coming into conflict with GEMS.

The approach taken was to step away from regulating the efficiency of individual chillers to that of regulating the efficiency of chiller plant, i.e. generally multiple chillers. This approach avoids the question of individual chiller efficiency but also permits the question of the matching of chiller sizes to load to be addressed. Taking this to its fullest extent, it becomes possible to define an analogue of the AHRI 551/591 Integrated Part Load Value (IPLV)[5] but evaluated for a group of chillers operating together to serve a load in a specific climate zone against a given load profile; furthermore, while such a measure would still need to be assessed separately for air-cooled and water-cooled plant, it would no longer need to provide different performance criteria for different compressor types.

To inform the analysis, a survey of available chillers was conducted, gathering cost and performance data for 57 water cooled chillers and 53 air-cooled chillers across seven manufacturers and a size range of 50-2000kW. Using this data, a conventional cost-benefit analysis was undertaken on chiller selections using the simulation results from two representative building types (large office and large hospital). In each case it was assumed that the site would be served by two chillers each sized at 60% of the design cooling load, representing common redundancy practice in Australia. The lowest cost chiller (on a $/kWr basis) compliant with NCC2019 was selected as the base case for each of the size ranges used in NCC2019. It was found that this lowest cost selection was often mid-range in terms of efficiency, indicating that efficiency is not a strong driver of cost for chillers.

Based on the cost-benefit analysis, the chiller configuration with the optimum performance and BCR was selected for each instance. Resultant selections were typically marginally higher than NCC2019 in terms of full load EER (increase in EER by 0.2-0.5, dependent on size range and climate zone) and somewhat higher in terms of IPLV (increase in IPLV by 0.2-2.1 dependent on size range and climate zone).

The simulation models for these optimised selections were then interrogated to establish the loading factors, condensing/ambient temperatures and chilled water temperatures to be used in the calculation of a climate specific part load value (CSPLV) target for each climate zone and separately for daytime buildings and overnight buildings. The CSPLV is calculated as:

$$\begin{aligned} CSPLV = {} & \alpha_{25} EER_{25}(T_{db,25}, T_{wb,25}, T_{ChW,25}) + \alpha_{50} EER_{50}(T_{db,50}, T_{wb,50}, T_{ChW,50}) \\ & + \alpha_{75} EER_{75}(T_{db,75}, T_{wb,75}, T_{ChW,75}) \\ & + \alpha_{100} EER_{100}(T_{db,100}, T_{wb,100}, T_{ChW,100}) \end{aligned}$$

Where each of the figures α (a dimensionless coefficient), T_{db} (ambient drybulb temperature) and T_{wb} (ambient wetbulb temperature) and T_{ChW} are separately specified for each load step and climate zone. This creates an effective baseline for whole chiller plant performance customized to the climate zone. Furthermore, as the load points are evaluated against the design load for the chillers, the approach aligns with good sizing practices.

3.3.3 Unitary Air-Conditioning

Unitary air-conditioning is similarly affected by the tension between NCC aspirations and GEMS requirements. Current GEMS regulations specify a minimum full load EER of 3.1 from 10-39kW and 2.9 for 39kW and above. While the most recent regulation (issued in 2022) requires publication of a SEER figure, the reality is this is only available for equipment new to the country since the regulation was updated, and thus is not generally available. As a result, this could not be used in the formulation of recommended NCC2025 measures.

In order to circumvent the GEMS conflict, it was proposed that NCC2025 should regulate the capacity-weighted average EER of unitary air-conditioning systems in a building. This then implies that the threshold needs to be set at an average figure rather than a minimum. To establish this average figure, the cost-to-EER relationship for packaged air-conditioning units was investigated, using a database of 54 units across the range 10-100kW. Essentially no relationship was found, so the proposed EER thresholds could be set at the average of available units, which was identified at 3.1 for units above 39kW and 3.3 below.

A similar analysis for VRF systems – previously not differentiated – showed that there was a significant cost-EER relationship for these systems. Furthermore, economic analysis indicated that for systems above 39kW, essentially any subrange of EER was cost-effective against the lowest performing units, while below 39kW the opposite held, with only limited cost-beneficial opportunities available. Based on these results, the decision was made to set the minimum EER requirements at the average efficiency of the available units excluding the poorest performing 20%. This resulted in proposed EER requirements of 4.1 for units under 39kW and 3.7 above.

The inadequacy of EER as a measure for unitary systems was demonstrated via simulation, in which variable speed drive packaged air-conditioners were compared against fixed speed air-conditioners, using manufacturer data for the performance of both. It was found that energy use for the variable speed unit was approximately 50% lower (range 39%-57% across all climate zones for the office archetype and 65% lower (range 38%-75%) for an overnight (aged care) archetype. Cross-checks against the literature showed published figures for 35-50% reductions in considerably warmer climates, so these figures appear reasonable [6,7]. Cost benefit analysis showed that the significant (30%) additional cost of the variable speed units was cost-beneficial in essentially all cases. In the absence of a SEER indicator, the recommended measure was the requirement of a variable capacity compressor plus variable speed evaporator and condenser fans.

3.3.4 PV And Batteries

It had been established in the development of NCC2019 Section J that rooftop PV is economic within the parameters set for Code development, but at the time no measure was adopted. However, for the 2025 update there was some regulatory interest in adopting some form of mandatory minimum use of PV.

From a broader economic perspective, the cost-effectiveness of PV needed to be tested against the alternative of adding grid-scale ground-based PV, as there would be no national benefit if regulations forced the installation rooftop PV where it was more expensive than an off-site alternative. To test this, pricing was obtained for rooftop (up to 100kW) and grid scale (500-10,000kW) ground-mounted PV. Based on this and with allowance for different generation potential (shading reducing rooftop PV output, single axis tracking increasing grid scale output), 20 year $/MWh figures were calculated. It was found that unshaded rooftop installations generated electricity at a cost of $38-$45/MWh; it was found that this price range was only feasible among lower priced grid scale PV installations above 50MW, which are relatively uncommon. This higher cost of grid-scale installations is driven by higher land and connection costs. On this basis it was concluded that a requirement for rooftop PV on unshaded roof areas was justifiable.

Having elected to include such a requirement, it was necessary to also define an upper limit of sizing for cases where the available roof space could potentially over-service the site. For this purpose, a cost-benefit analysis was undertaken, and it was found that if exported electricity gains no revenue (or is prohibited) then the PV installation maintains a BCR of greater than 1 up to around 50% of generated electricity being exported (or unused). This was then converted into a simpler Watts of PV per unit floorspace metric for potential incorporation into the Code.

For batteries, similar considerations of building scale (20-200kWh) versus grid scale (>2000kWh) cost-effectiveness apply. However, in this case, the scale benefit of grid batteries works in their favour, with estimated pricing (including installation) being in the region of $500-850/kWh as opposed to $1000-1400 for building-scale batteries. On this basis, batteries were rejected as a potential code measure.

3.3.5 Other HVAC Measures

The remaining HVAC measures are of a significantly smaller impact than the chiller and unitary air-conditioner measures described above, although their collective impact is significant. In short form, the adopted additional measures were:

1. Heat pumps and 4-pipe chillers. These were previously not regulated. Analysis showed limited efficiency range and little cost/efficiency relationship. Proposed requirements, assessed on a weighted average basis across all such units in a building, were: Minimum heating COP 3.25; minimum cooling COP 3.0, minimum cooling IPLV 4.85.
2. Economy cycle: Minor increases in stringency for two climate zones were recommended; otherwise no changes were made.
3. Outside air control: Requirements for the use of CO2 sensing in systems with the ability to vary outside air were proposed to be extended to several additional climate zones, and airflow thresholds for use were proposed to be lowered.
4. Indirect evaporative cooling: A new requirement was recommended for the use of indirect evaporative cooling for constant flow outside air systems in climate zone 1 and climate zone 3.
5. Fan efficiency: While no new requirement for fan efficiency was proposed[2], a revised framing of the existing requirements was recommended in a manner that is expected to deliver some improvements in overall selection efficiency (while also reducing opportunities for gaming). Most notably the recommended approach moved from regulating the peak efficiency of individual fans to regulating the weighted average efficiency of fans at duty point. This is expected to improve sizing practices.
6. VSDs: NCC2019 had requirements for VSDs on air-conditioning/ventilation system fan motors serving greater than 1000 l/s but no requirements for VSDs on pumps and cooling tower fans. For NCC2025, variable speed drives for fans and pumps have been recommended almost uniformly for fans and pump motors above 750W and cooling tower fan motors above 1kW.
7. HVAC zoning: Requirements for good zoning practices were investigated but with limited success. Resultant proposed changes were limited to a requirement for zones with competing heating and cooling demands not to be served from a single air handler, and for air volume control to be used as the first stage of any zone load modulation (ahead of reheat).

3.3.6 Other Building Envelope Measures

The other building envelope measures investigated were of limited overall impact, and are summarized in short form below:

[2] The underlying efficiency standard used is EN327 [8].

- Roof Insulation: Roof insulation simulations showed that energy savings from roof insulation were minimal, and indeed the existing R-value requirements for roofs (R3.2-R4.8, dependent on climate zone, R3.7 for most climates) were not found to be cost-beneficial, even with allowance for plant size impacts. However, as the brief was to increase stringency, no change was proposed to daytime operating building roof insulation requirements. However, the analysis demonstrated that moderate increases in overnight building roof insulation levels were economically viable; previously these had not been differentiated from daytime buildings. New requirements for overnight buildings were recommended at R3.7-R4.3 with R 4.8 for most climates.
- Wall insulation: Wall insulation simulations similarly showed limited benefits from wall insulation in general, with negative benefits[3] in some cases (mild climates such as Melbourne and Sydney). Cost benefit analysis showed cases both for increase and reduction of R value in different situations. As with roof insulation, though, the brief was to increase stringency, so R value requirements were only reduced if simulation showed an energy benefit from doing so. The net result was a proposed range of moderate upward and downward adjustments. A further change recommended related to the treatment of wall insulation between conditioned and unconditioned spaces; this was made to address the unintended consequence of previous requirements that led to non-cost-beneficial (and indeed, efficiency-neutral) use of insulation in building cores.
- Wall-window U value. The wall R value discussed above is only applied explicitly to walls where the window wall ratio is less than 20%. In other cases, the combined window-wall U-value is regulated, which requires calculation of a figure that reconciles with the glazing measure and the wall insulation measure. Given the larger importance of the solar admittance measure, it was recommended to calculate the wall-window U value targets such that they do not further constrain the maximum permitted window wall ratio. This was achieved by calculating the targets based on a nominal U=2.6 window (which reflected the glazing selections needed to achieve the solar admittance requirements) in combination with the maximum window wall ratio derived from the solar admittance requirements and the wall insulation figures discussed above. The resultant recommended U-values figures were generally lower than the previous requirements, with some exceptions where minor increases in U value were made.

[3] That is, increased energy use at higher insulation levels.

- Roof colour. In NCC2019, a requirement to use lighter coloured (solar reflectance>55%) roof materials was introduced. For the NCC2025 analysis, the use of lighter standard finishes for metal roofs was tested, as well as the use of specialist spectrally selective paints and finishes. Calculations made allowance for the impact of roof microclimate on the efficiency of rooftop plant and the temperature of outside air intakes. It was found that the specialist finishes were not cost-beneficial, but that moderate benefits could be achieved at no cost using the lighter standard finishes. As a result, a new requirement for solar reflectance greater than 75% when there is rooftop plant was proposed. Furthermore, in order to address the use of unpainted zinc-coated roofs (which can have a high solar reflectivity but perform poorly due to low thermal emittance), minimum total emittance requirements were recommended.
- Thermal bridging. NCC has had provisions to address repeating thermal bridging for some time but previously has not dealt with situations such as uninsulated box gutters of exposed slab edges of intermediate floors. Building on unpublished work undertaken for ABCB by the Sustainable Buildings Research Centre of the University of Wollongong, it was proposed that code wording be modified to require mitigation of these instances.

3.3.7 Lighting

Lighting power density targets were significantly revised for NCC2019 reflecting the significant increase in efficiency available from LED lighting [9] (for example, the lighting power density requirement for open office space was set to 4.5W/m², making it one of the most stringent internationally). Given that this reduction was of the order of 50% over previous targets, it was decided not to investigate further stringency increase in NCC2025.

Lighting control, however, was deemed suitable for review and cost-benefit analyses were undertaken around the use of occupancy and motion sensors, which previously had been required in a limited range of specific situations. The analysis for NCC2025 indicated a far broader range of application, so the proposed measure reflects a far more uniform use of occupancy sensing, blended with other types of automated controls directed at ensuring that unoccupied spaces do not remain illuminated. Furthermore, the proposed wording of the requirements was simplified radically, as industry feedback indicated that NCC2019 was overly prescriptive and detailed to the extent that it prevented the introduction of new technologies.

3.3.8 Electrification

Although Australia's commercial buildings are generally cooling dominated, parts of southern Australia have moderate heating requirements. For these areas of the country, reaching into warm temperature areas, it has been traditional for larger buildings to use gas fired hot water systems for space heating. Furthermore, the use of gas fired domestic hot water is commonplace throughout the country.

In 2021, the federal Government announced Australia's commitment to net zero by 2050. Around the same time, it became broadly accepted that, for buildings, this means electrification as the likelihood of a timely broad scale zero emissions replacement for reticulated natural gas appears minimal However, no consistent commitment to degasification has been made, complicating the context for the development of electrification measures for the Code.

For the initial analysis, the base case scenario was set as a dual fuel building[4] that undergoes electrification in 15 years – without any prior planning for electrification. Test cases were set as the same building being all-electric from day one, or undergoing electrification in 15 years having made allowances in original design (e.g. spatial allowances, hot water loop operating temperatures) to ease the transition.

For space heating, the analysis demonstrated that the lowest net present value (cost) of the three scenarios considered (do nothing, prepare for electrification, immediate electrification) was for immediate electrification, with preparation for future electrification being next cheapest and unplanned future electrification the most expensive. For domestic hot water, preparation for electrification was cheapest, followed by immediate electrification and again with unplanned future electrification as the most expensive option.

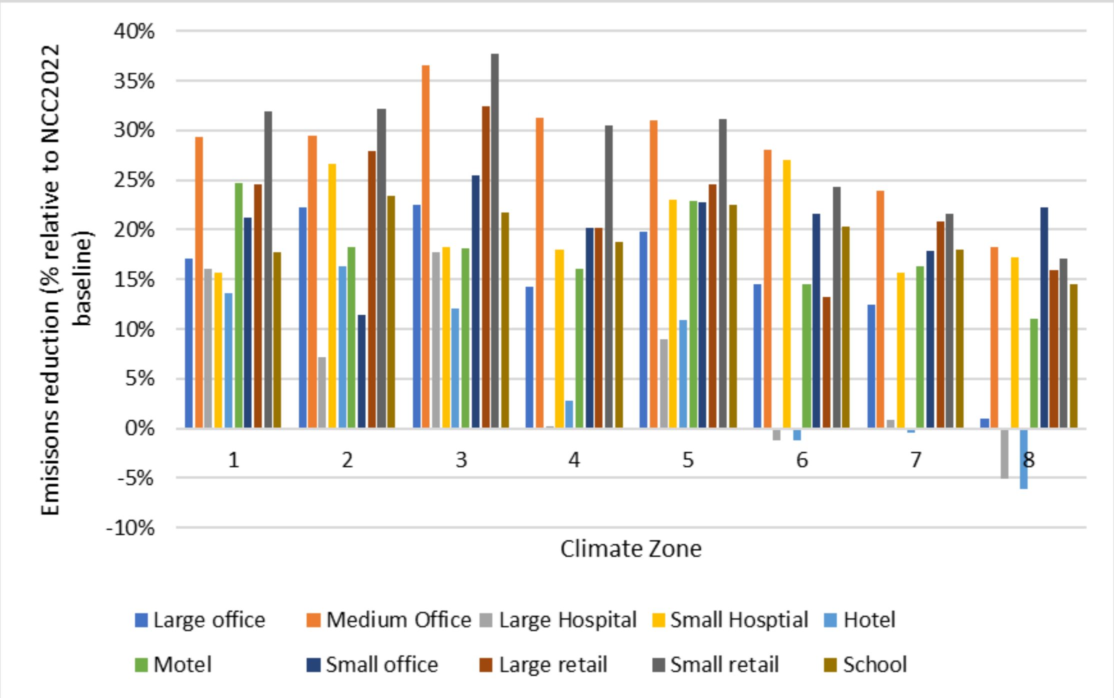
3.4 Whole Building Results

The following section represent the results of the application of the initial measures across the 10 archetype buildings used to represent the building stock.

3.4.1 Stringency 1 – energy efficiency measures only

The projected greenhouse gas emissions reductions from the energy efficiency measures only are as listed in Figure 1.

Figure 1. Stringency 1 emissions reductions results



[4] The large office and large hospital were used as the core archetypes for this analysis.

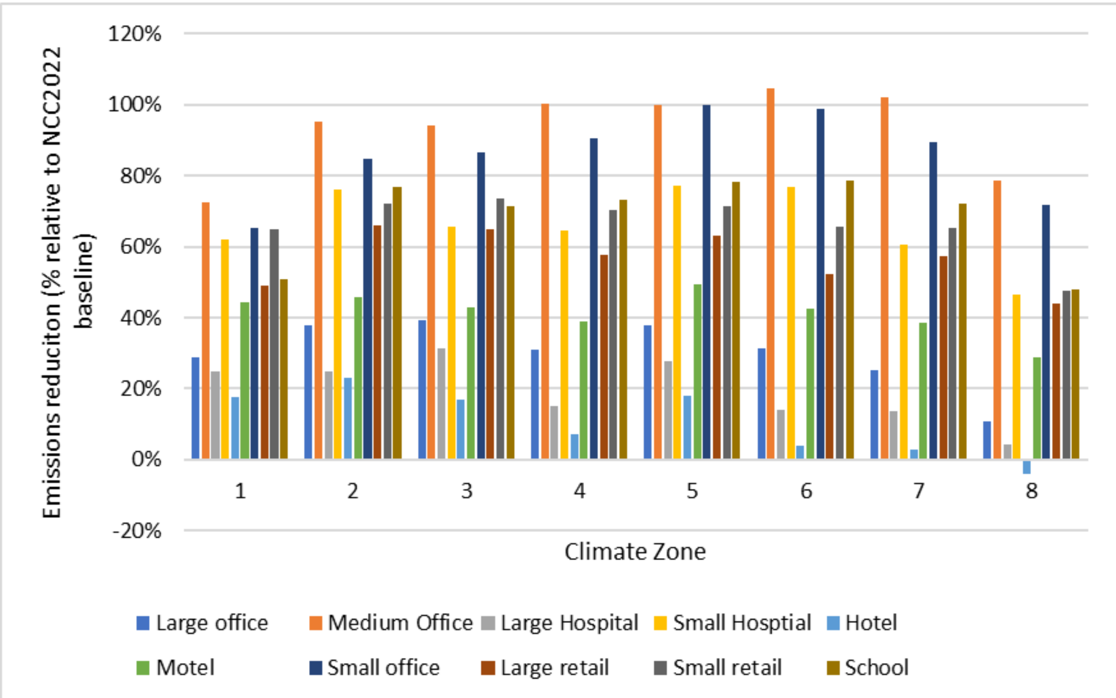
The following notes apply to the results in Figure 1:

- Emissions reductions are expressed based on a 50-year timeframe as a percentage of regulated energy excluding lifts and domestic hot water (neither of which have measures applied). All buildings maintain the same fuel mix for the full analysis period. No emissions credit has been counted for exported electricity.
- Benefit cost ratios were either greater than 1 or had negative capital cost for all cases other than the large hospital and large hotel in climate zone 8.
- Larger savings for the smaller buildings reflect the impact of the unitary air-conditioning measures.
- The chillers used for the baseline were set at the efficiency of the least-cost available chiller, which had a higher efficiency than the NCC2019 minimum requirement, so savings for the large building archetypes, which used chillers, are arguably underestimated relative to worse case compliance.
- The weaker savings for the large hospital and hotel archetypes reflect the limited range of new measures applying to these archetypes, plus the fact that the solar admittance measure was optimized for reverse cycle heating (i.e. heating and cooling weighted equally) as opposed to the gas heating (heating weighted more strongly than cooling) used by these archetypes.

3.4.2 Stringency 2 – Stringency 1 plus rooftop PV

The projected greenhouse gas emissions reductions from the energy efficiency measures plus rooftop PV are as listed in Figure 2.

Figure 2. Stringency 2 emissions reduction summary



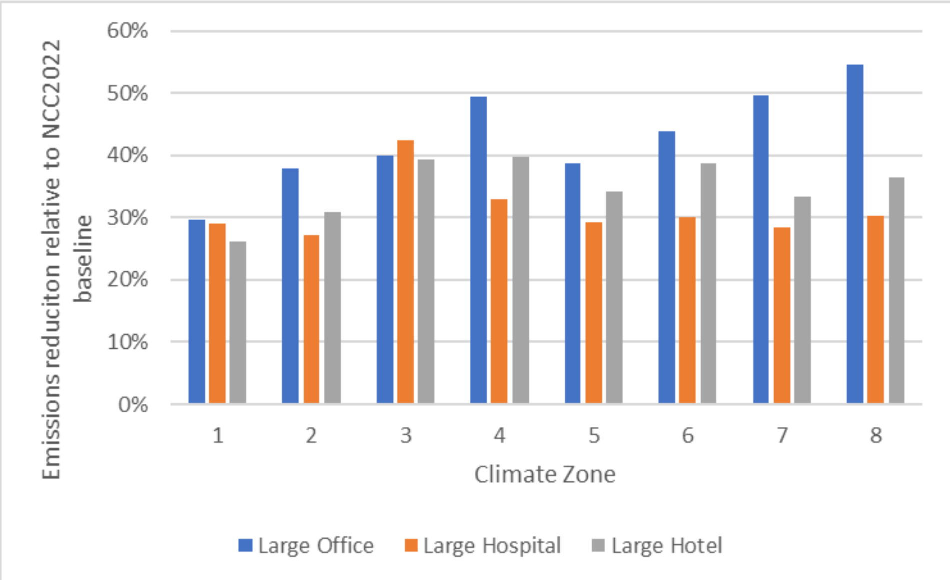
The following notes apply to the results in Figure 2:

- Basis of emissions reductions calculations are the same as for Figure 1.
- Benefit cost ratios were either greater than 1 or had negative capital cost for all cases.
- The higher savings for smaller archetypes reflects the higher roof to floor area ratio of these low-rise buildings and thus the higher impact of rooftop PV.

3.4.3 Stringency 3 – Stringency 2 plus electrification

The projected greenhouse emissions reductions from Stringency 3 for the three archetypes that had gas-fueled space heating are shown in Figure 3.

Figure 3. Stringency 3 emissions reductions, dual fuel archetypes only. Savings for other archetypes are the same as Stringency 2.



The following notes apply to the results in Table 3:

- Emissions reductions are calculated on the same basis as for Figure 1 and Figure 2 except that domestic hot water has been included (assumed to be gas fired in the base case and electrified in the test case). Baseline and test building maintain the same fuel mix for the analysis period.
- Benefit cost ratios were either greater than 1 or had negative capital cost for all cases other than those for the large office and large hospital in climate zone 8; however neither is particularly relevant to buildings likely to be constructed in that climate zone.
- The higher savings relative to Stringency 2 for these archetypes are driven by the introduction of electrification. As the electricity greenhouse intensity is projected to drop from 0.7 in year 1 to 0.16 in year 15 and 0.1 in year 50, electrification delivers substantial greenhouse benefits relative to stringency 2, where no electrification is assumed.

3.5 Discussion and Next Steps

Discussion

Overall results show strong support for the measures at any of the three stringencies. The strongest economic results were obtained in Stringency 2, due to the strong financial performance of the rooftop PV measures. The best and most consistent overall greenhouse savings arise from the stringency 3 electrification measures, as these lock out the increasingly dominant gas emissions into the future; however, the economic return, while still generally above the minimum criterion, is not as good as for Stringency 2 and is below the minimum criterion in a small number of relatively unimportant cases.

The decision as to which stringency will be used as a basis for NCC2025 will be made during 2024 based on consultations between state, territory and federal governments. At this stage no clear direction has emerged.

Next steps

The draft measures have been incorporated into a "public comment draft" of the Code and will be circulated for comment in the first half of 2024, with draft code text for all three stringencies included. Based on feedback from stakeholders, plus consultations with government agencies, the code text will be finalized and published mid-2025. The timing of the adoption of the Code will then be determined by the state and territory governments, each of which will do so on an independent timeframe of typically 0-2 years.

Conclusions

The NCC2025 code development process has investigated three possible stringencies for implementation, being energy efficiency, energy efficiency plus rooftop PV and energy efficiency plus rooftop PV and electrification. The project has identified significant greenhouse savings in each case, with the highest overall greenhouse savings across a 50-year period being offered by the electrification option, albeit at a greater up-front cost than the efficiency plus rooftop PV stringency option without electrification.

The recommendations and findings reported in this paper have been incorporated into a public comment draft of Code, which will be under consultation in 2024. Based on feedback received, state, territory and federal governments will finalise the Code and release it in mid-2025.

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4 Machine Learning algorithms for Urban Building Energy Modeling

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Abstract

Urbanization trends have intensified the focus on predicting building energy consumption within urban areas for sustainable development. Urban Building Energy Modeling (UBEM) offers a valuable approach to simulating and evaluating building energy efficiency within urban contexts, considering various physical and climatic factors.

This paper explores the application of data-driven UBEM in urban energy planning, with the case study of Turin, Italy. It is due to the fact that traditional physics-based UBEM models face limitations in large-scale urban settings, prompting the adoption of data-driven approaches. The study evaluates the effectiveness of Machine Learning (ML) algorithms, particularly Light Gradient-Boosting Machine (LightGBM) and Random Forest (RF), in predicting energy consumption for space heating at both monthly and hourly time steps.

Using a comprehensive dataset of 44,290 buildings and building blocks and the District Heating Network (DHN) in Turin with 6146 connected buildings, the study demonstrates the superior predictive performance of LightGBM over Random Forest, particularly at the urban scale. In the stable operational months from December 2022 to March 2023, LightGBM showed a maximum relative error of 2% for monthly energy consumption prediction, while RF had a maximum relative error of 9%. For buildings' hourly energy consumption profile, despite challenges associated with space heating cut-off during a day, both algorithms exhibit robust performance, with relative errors below ±20% for most of the hours. These results highlight the robustness of both ML models in accurately predicting monthly energy consumption, particularly for urban application.

Keywords: Urban Building Energy Modeling, Data-driven models, Machine Learning (ML), Place-based approach, Geographic Information System (GIS).

Introduction

Predicting Energy consumption of buildings at a larger scale for a substantially large number of buildings within urban areas is gaining a high attention in current years [1]. In Turin, this can be considered as a cause of energy costs for space heating and the necessity to follow the directive for clean energy transition of cities. In such a condition, one of the impactful means to guarantee a sustainable future and achieve a high-quality of living standards is to raise the building's energy efficiency while promoting proper energy supply system according to Renewable Energy Resources (RES) [2]. Zero-carbon emission scenarios become fancy policies to enhance the energy performance of the buildings more specifically for those that are built before energy policies. However, it is a highly complex and demanding process to bring to completion [1].

In achieving clean energy systems, while having Neutral or Active Energy Buildings is crucial, the greatest importance lies in establishing a low-carbon cities. This is particularly vital because integrating RES in certain neighbourhoods encompasses challenges, especially in cultural and historical centers. Consequently, buildings should play an active role, serving as prosumers in supplying energy to end-users who face constraints. Returning to this concept, it is important to gain a thorough understanding of the energy consumptions within a given context at a larger scale (e.g. census section, neighbourhood, or urban scale) to assigning an active role to buildings in the energy-sharing landscape.

Urban Building Energy Modeling (UBEM) is a technique that is capable of simulating and evaluating the energy efficiency of buildings within a larger context [3]. UBEM utilizes place-based methods to simulate and evaluate the energy efficiency of buildings located within urban areas [4]. In a bottom-up approach, UBEM models the energy consumption of each individual building and then combines these findings to comprehend the overall energy requirements on a broader scale. Consequently, within the framework of UBEM, buildings are pivotal in determining final energy consumption estimation. However, while buildings are significant contributors, they are not the only factors at play. Various components of the urban landscape, including urban climate and energy systems, can both impact and be impacted by urban energy consumption [5].

The initial process-driven (physics-based) UBEM models were incorporating Building Energy Modeling (BEM) tools and engage in co-simulation with specialized software for specific topics. However, characterizing buildings at a large scale presents challenges that are not as straightforward as they are for individual buildings [6]. Unlike physical models, data-driven models remove the necessity of constructing thermal balance equations, leading to a decrease or even elimination of dependence on intricate building physical characteristics [7]. The Data-driven Urban Building Energy Modeling framework uses advanced ML techniques to carefully examine and comprehend complex datasets. This allows it to discover complicated patterns, relationships, and connections that traditional models could overlook. This data-driven approach doesn't just make energy predictions more accurate but also provides important insights into what influences energy demand trends in cities. Additionally, the framework is designed to be adaptable and scalable, making it suitable for different urban settings and energy challenges [8].

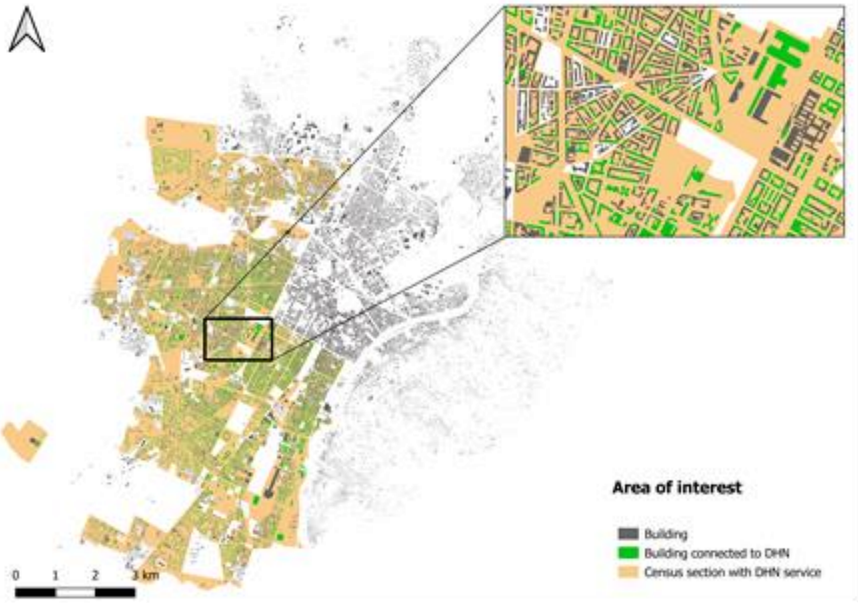
With such robust tools and techniques available, it's crucial to grasp how cities can move toward their objectives of enhancing energy efficiency, mitigating carbon emissions, and improving overall quality of life through the adoption of innovative approaches. Additionally, exploring the potential applications of these techniques within the urban energy planning sector is essential for understanding their scope and impact in the literature.

4.1 Case study

The case study of the current research is the city of Turin with 44,290 (256 Mm^3) buildings and building blocks (the parcels within a utilized geodatabase serve as representations of occasionally individual buildings or a cluster of buildings) and a District Heating Network (DHN) supplying 2500 GWh/year of energy to 73.2 Mm^3 and about 650,000 inhabitants through 726 km of double pipeline (Figure 1). Turin stands out as Italy's foremost district-heated city and one of Europe's most extensively district-heated metropolises, thanks to the combined heat produced by cogeneration plants in south and north of Turin, along with the TRM waste-to-energy plant. These sources serve more than 57% of the total potential heated volume. Impressively, over 90% of the energy injected into the network originates from cogeneration plants, a remarkable achievement facilitated by the installation of heat accumulators in power plants and along the network. The remaining thermal energy is generated through integration and recovery boilers [9].

The monthly space heating consumption of 3866 buildings provided a solid base to train and test energy use model and predict energy consumption for a large number of buildings. From this set of data 49% are residential, 46% are residential mixed with other type of building use, 2% are commercial, and 1% educational. The remaining 2% has various uses which will not be included in the modeling conducted in this study. Regarding their period of construction, 82% of buildings from various types of use were built before 1970. Buildings built between 1971-2005 are 17.8%, while only 1.2% are built after 2005. Further hourly consumption data from 23 residential buildings were utilized to simulate the hourly consumptions of buildings for space heating with similar type of use. Regarding their age, 2 buildings are built before 1945, 12 buildings belong to 1946-1970, 8 buildings to 1971-1990, and only 1 after 1991.

Figure 1. Case Study: Energy Landscape of Turin



4.2 Methodology

The primary approach adopted in this study revolves around a bottom-up method known as Urban Building Energy Modeling. This method employs place-based techniques to simulate and evaluate the energy consumption of urban buildings, taking into account factors such as building types and their period of construction, building materials, number of inhabitants, weather conditions, types of energy usage, and etc. Within this approach, initially advanced data analysis was applied to develop an extensive geodatabase that improves the utilization of different UBEM engines for predicting energy use within a urban scenario. Then attention was directed towards exploring the potential applications and advantages of data-driven with ML algorithms in urban energy simulations.

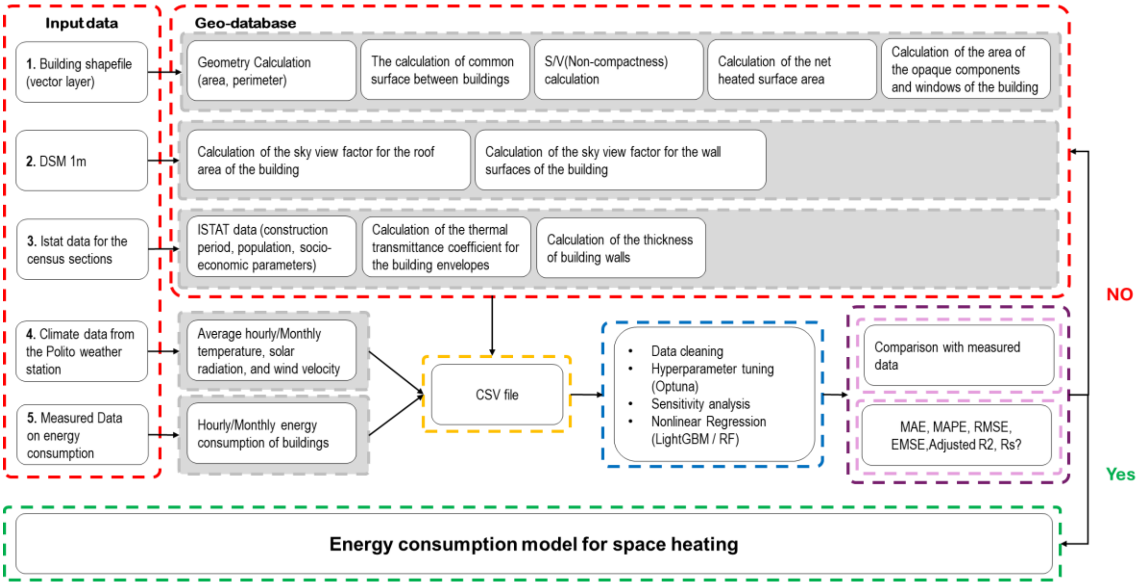
The physical representation of buildings was created using open source QGIS 3.28.15, incorporating buildings' data from the Territorial Reference Database of Institutions (BDTRE[1] in Italian) database promoted by the Piedmont Region, Torino's DSM with a precision of 1 meter, and socio-economic data

[1] https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:da9b12ba-866a-4f0f-8704-5b7b753e4f15

from ISTAT[2]. In greater detail, utilizing the boundaries of buildings and available data features within the BDTRE geo-database, essential physical parameters of buildings such as heat loss surface, gross heated volume, S/V (non-compactness) ratio, along with the surface areas of building envelopes and openings, are computed. The sky view factor of buildings on their roofs and walls is derived from the DSM file. Moreover, based on the buildings' age information from the ISTAT database, variables like heat transmittance coefficient for building envelopes and the efficiency of boilers and DHN are assigned to them. Lastly, socio-economic parameters such as the number of inhabitants, families, strangers, empty flats, and the maintenance level of buildings are obtained from the ISTAT database, which are mainly applicable to residential buildings (Figure 2).

This comprehensive approach facilitated a detailed analysis of energy demands within the studied area. To estimate the heating consumption of buildings, the research utilized monthly and hourly data on space heating consumption from a specific period (November 2022 – April 2023) in the case study. Accordingly, weather data obtained from the Politecnico di Torino weather station for a specific timeframe were integrated into the development of energy model. The collection of all variables is a CSV file make it easy to read and insert in ML model trainings.

Figure 2. Methodology flow chart: Data-driven Urban Building Energy Modeling (UBEM)



The models were developed taking into account the buildings' type of use. To determine these purposes, a statistical analysis was undertaken to ensure an adequate amount of data for the model. Only consumption data from buildings with complete information were used for the models. Then, five heating models were developed, excluding only the "other use" category due to the absence of specific building functions. Given the data available for hourly consumption of buildings, only a model was exclusively developed for residential buildings. Table 1 illustrates the type of use of the buildings for which monthly and hourly consumption data were provided for space heating.

[2] https://www.istat.it/it/archivio/104317#accordions

Table 1. Intended uses of the sample of buildings for which the monthly consumption for "heating" only was provided and used in the model

Type of use	Total buildings number having consumption data	Buildings used in energy modeling	%
Monthly			
Residential	2351	1888	80%
Residential-commercial	1938	1557	80%
Residential-mixed use	275	213	77%
Commercial	119	92	77%
Educational	121	42	35%
Other use (Excluded)	117	74	63%
Total	4921	3866	79%
Hourly			
Residential	30	23	77%

As shown in table 1, almost a quarter of monthly consumption data is not utilized in the data-driven model as data are subjected to the following factors:

1. Buildings with different services than space heating: 618 buildings
2. Missing or negative consumption data (during the 2022-23 heating season): 427 buildings
3. Buildings with abnormal or uncommon consumption patterns: 10 (e.g., continuous heating consumption throughout all 12 months, consumption limited to domestic hot water only during winter months, or buildings with no recorded consumption).

Table 2 provides a breakdown of monitored buildings based on their type of use and period of construction. The majority of monitored buildings fall within the 1961-1970 period, before the implementation of mandatory energy laws and regulations for buildings in the 1976. Following this, the period between 1946-1961 is also represented, indicating a notable proportion of buildings. Overall, newly constructed buildings have a relatively small representation in the training dataset.

Table 2. Typical buildings for which the monthly and hourly consumption for heating has been provided

Type of use	Before 1919	1919-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	2006-2012	2012-2015
Monthly data										
Residential	83	335	538	621	237	51	14	7	0	2
Residential-commercial	50	210	381	616	258	31	5	3	2	1
Residential-mixed use	3	27	65	67	40	8	2	1	0	0
Commercial	5	2	18	42	21	3	1	0	0	0
Educational	2	4	2	32	1	1	0	0	0	0
Hourly data										
Residential	1	1	4	8	6	2	1	0	0	0

To comprehensively assess and compare the performance of ML models in building energy use modeling, two prominent algorithms, LightGBM and RF regression, were utilized. This study aimed to evaluate their appropriateness and efficacy in capturing the intricate relationships between building characteristics and energy consumption patterns. LightGBM is an efficient implementation of the gradient boosting algorithm, which utilizes an ensemble of weak learners, typically decision trees, for regression or classification tasks. RF, on the other hand, is a supervised learning algorithm employed for regression tasks, utilizing a bagging (bootstrap aggregating) approach. It constructs multiple trees to derive average prediction outcomes.

Using the Optuna optimizer, hyperparameters of ML algorithms finely tuned for each energy use model. Throughout the hyperparameter optimization process for models, 5-fold cross-validation is incorporated to ensure the selection of the most optimal set of hyperparameters for ML algorithms to enhance the ML algorithms' ability to generalize while preventing overfitting. Among the LightGBM hyperparameters used in this study (Table 3), "num_leaves" represents the maximum number of leaves in one tree, which controls the complexity of the model. "max_depth" defines the maximum depth of the tree, limiting the growth of individual trees and preventing overfitting. "feature_fraction" specifies the fraction of features to consider for each tree, aiding in the prevention of overfitting and improving model generalization. "bagging_fraction" represents the fraction of data to be randomly sampled and used for training each iteration, contributing to the robustness of the model. "bagging_freq" denotes the frequency of bagging, determining how often bagging is performed. Finally, "lambda_l1" and "lambda_l2" are regularization parameters that control the L1 and L2 regularization terms, respectively, helping to prevent overfitting by penalizing large coefficients. The hyperparameters employed for RF in this study (Table 4) contains "n_estimators" that controls the number of the trees in the forest, 'max_depth' determines the maximum depth of each tree, 'min_samples_split' indicates the minimum number of samples necessary to split an internal node, and 'min_samples_leaf' specifies the minimum number of samples required to form a leaf node.

Table 3. Example of hyperparameters of LightGBM, their tested ranges, and optimized values for the energy consumption modeling of residential buildings

Hyperparameter	Tested interval	Optimized value	Hyperparameter	Tested interval	Optimized value
num_leaves	1 - 200	32	bagging_fraction	0.4 - 1	0.93
max_depth	1 - 10	10	bagging_freq	1 - 10	4
min_data_in_leaf	1 - 10	3	lambda_l1	0 - 0.6	0.42
feature_fraction	0.4 - 1	0.87	lambda_l2	0 - 0.6	0.10

Table 4. Example of hyperparameters of RF, their tested ranges, and optimized values for the energy consumption modeling of residential buildings

Hyperparameter	Tested interval	Optimized value	Hyperparameter	Tested interval	Optimized value
n_estimators	100 - 120	119	min_samples_split	2 - 10	3
max_depth	10 - 15	14	min_samples_leaf	2 - 10	2

Prior to constructing an energy use model using ML algorithms, a thorough sensitivity analysis is conducted on the dependent variables. This analysis is leveraged through the benefits offered by the "feature_importances_" attribute within the "RandomForestRegressor" and "LGBMRegressor" classes. This crucial step enables the identification of influential dependent parameters essential for building precise energy-use models. The process involves selecting the most significant features contributing to the predictive capabilities of the models, thereby improving the overall reliability and significance of the results.

4.3 Discussion and results

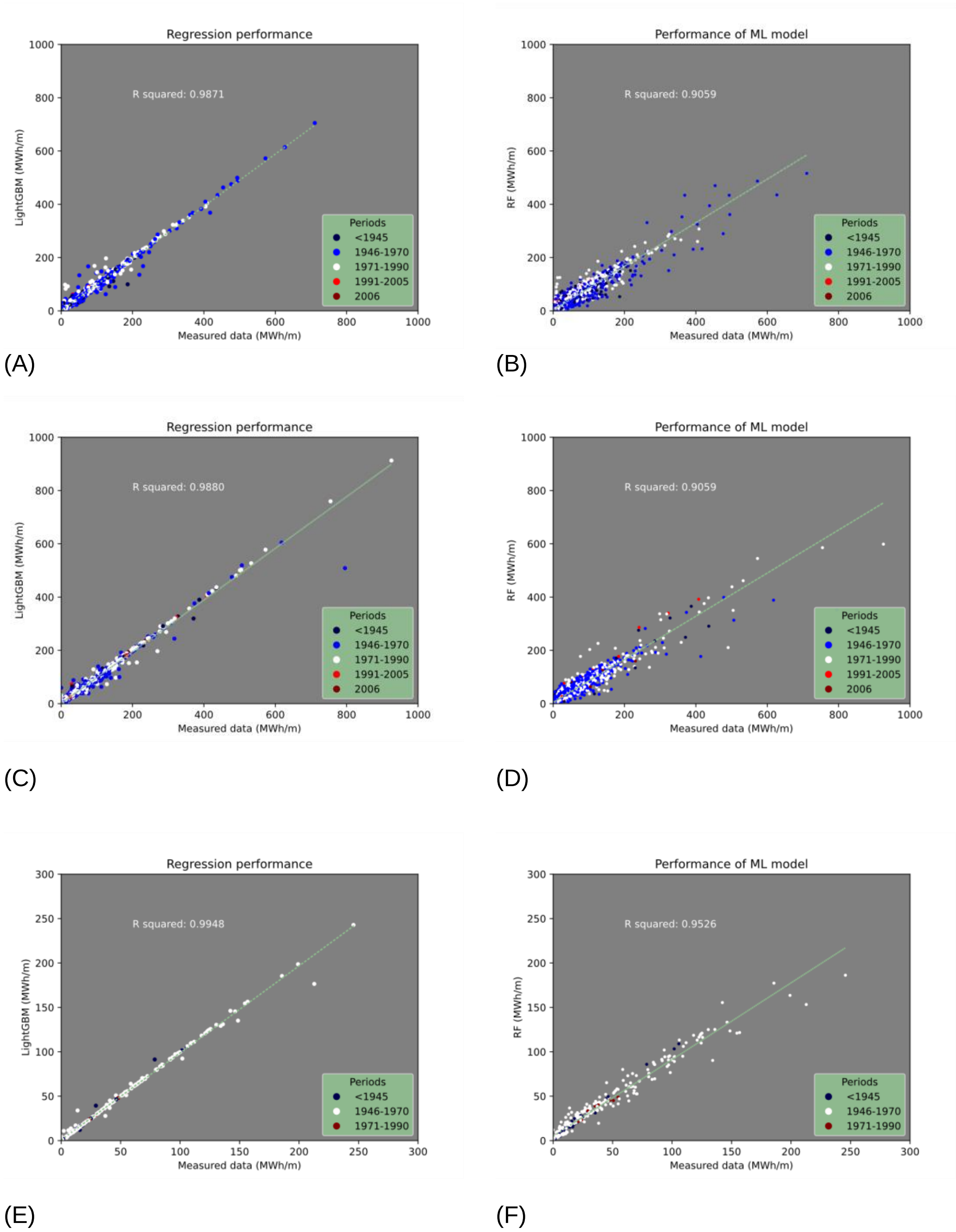
The analysis initialized by finding monthly energy use model of buildings from various types according to Table 1. The focus was on modeling the energy consumption of buildings during the most recent heating season, spanning from November 2022 to April 2023. It should be noted that in the interested heating season, the DHN of Turin was inactive during the October, that is why that specific month was not incorporated in the energy use modeling. For every group of buildings, adjustments were made to hyperparameters, and the energy usage model was developed. This was necessary as the specific hyperparameters define and regulate the structure of each model.

During the hyperparameter tuning process of the ML algorithms, 90% of the datasets were used for training, with the remaining 10% reserved for testing. Additionally, a specific random state of 42 was applied to both the training and testing data. Selecting random state 42 ensures consistency in the division of data into training and testing sets across multiple runs. This consistency aids in reproducibility of results and facilitates fair comparison among various hyperparameter configurations.

It's important to highlight that with a comprehensive database containing monitored energy consumption data from buildings across multiple months, along with diverse climate variables such as average daily air temperature, solar radiation, and wind velocity, it became feasible to consolidate monthly energy consumption into a unified database for training purposes. By incorporating such climatic variables, it is feasible to compute energy consumption across various scenarios such as climate change, energy crises, and similar circumstances. The significance of this approach lies in training just one energy use model for each building category, resulting in significantly enhanced accuracy and predictive capability. This model can accurately forecast energy consumption for unseen buildings throughout the study period in a single iteration.

Referring to the regression performance graphs presented in Figure 3, LightGBM demonstrated slightly superior predictive capabilities for monthly energy consumption across all building clusters, boasting a higher R-squared value. The marginal advantage of LightGBM over RF is further underscored by the Root Mean Square Error (RMSE) values. In this study, RMSE is employed because it offers an error measurement in the same unit as the target variable, facilitating interpretation and comparison. Moreover, RMSE imposes penalties on larger errors, enhancing sensitivity to outliers. Across the various building clusters listed in Table 1, the RMSE values for LightGBM were 3.05, 4.01, 3.15, 2.35, and 3.02, respectively, in the order of building types. In comparison, the corresponding RMSE values for RF followed a higher trend, with values of 9.87, 11.77, 13.17, 7.65, and 9.84, respectively.

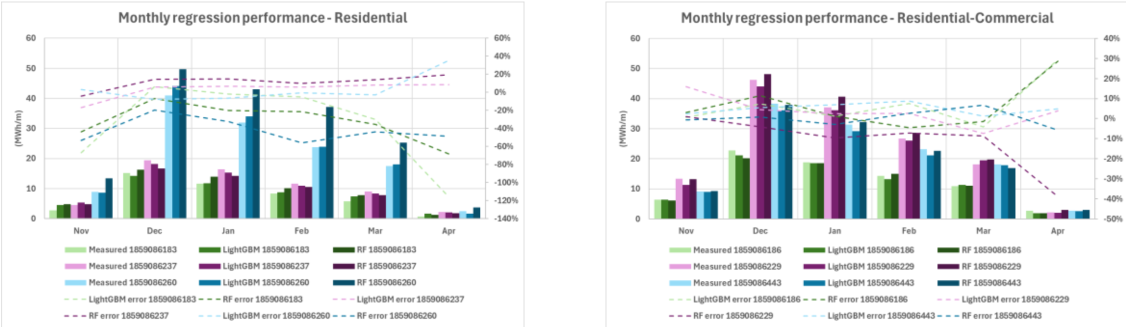
Figure 3. Performance comparison of LightGBM and RF algorithms in predicting monthly energy consumption (MWh/m) for residential (A, B), residential-commercial (C, D), and educational (E, F) buildings respectively at building scale utilizing large, moderate, and small datasets



Furthermore, during the phase of hyperparameter tuning and training the energy use model, LightGBM significantly outperformed RF. To support this statement, when tuning hyperparameters for residential buildings, which comprise the largest group of structures, LightGBM required 151 seconds for optimization and merely 0.6 seconds to train the energy use model. In contrast, the same tasks for RF consumed 3449 and 11 seconds, respectively, before completion.

The efficacy of the ML algorithms in forecasting the monthly energy consumption of buildings is evident from Figure 4 where the relative prediction errors for the majority of the months were within the range of ±20% (at building scale). Notably, their performance appears to be particularly strong during periods of high energy demand (i.e., Dec-Mar). ML algorithms exhibit a heightened capability to predict energy consumption accurately, especially when faced with higher energy-use scenarios.

Figure 4. Performance comparison of LightGBM and RF algorithms in predicting monthly energy consumption (MWh/m) for residential (A) and residential-commercial (B), for 3 typical buildings with different periods of construction



(A) (B)

The energy consumptions of the buildings in Turin for the month of December is shown in Figure 5 and summarized for the heating season in Table 5 for all the city of Turin; it offers valuable insights into the performance reliability of ML models when applied to a larger context. The table reveals that at the urban scale, predictions generated by LightGBM exhibit greater precision compared to RF. Specifically, LightGBM demonstrates exceptionally high performance, with its highest relative error staying below 7%, whereas RF reaches a maximum relative error of 30% under similar conditions.

However, it's important to note that the maximum errors typically occurred during November or April, coinciding with partial operation of the DHN during those months (in October 2022 the heating system was off). This means that during the mentioned months, the DHN of Turin was inactive in some days due to the high outside air temperature, resulting in zero energy consumption during that timeframe. ML models typically exhibit low sensitivity in predicting zero consumption, resulting in marginal difference between predicted and actual consumption. This suggests that the performance of ML models may be affected by the operational status of the DHN, highlighting the need for careful consideration of external factors (e.g., climate conditions). Back to this notion, focusing on the performance analysis of the ML models, a great emphasize was on December 2022 to March 2023.

Focusing instead on the period from December 2022 to March 2023, the maximum relative errors for LightGBM and RF are 2% and 9% respectively. These months, characterized by more stable DHN operations, provide a clearer assessment of the models' performance. Based on these error rates, it's evident that both ML models are robust enough to accurately capture monthly energy consumption across various scales, particularly at the urban level. This underscores the potential of ML algorithms in informing urban energy planning and management strategies with greater precision and reliability.

Figure 5. A 3D model of the monthly energy consumption of buildings within the urban context of Turin

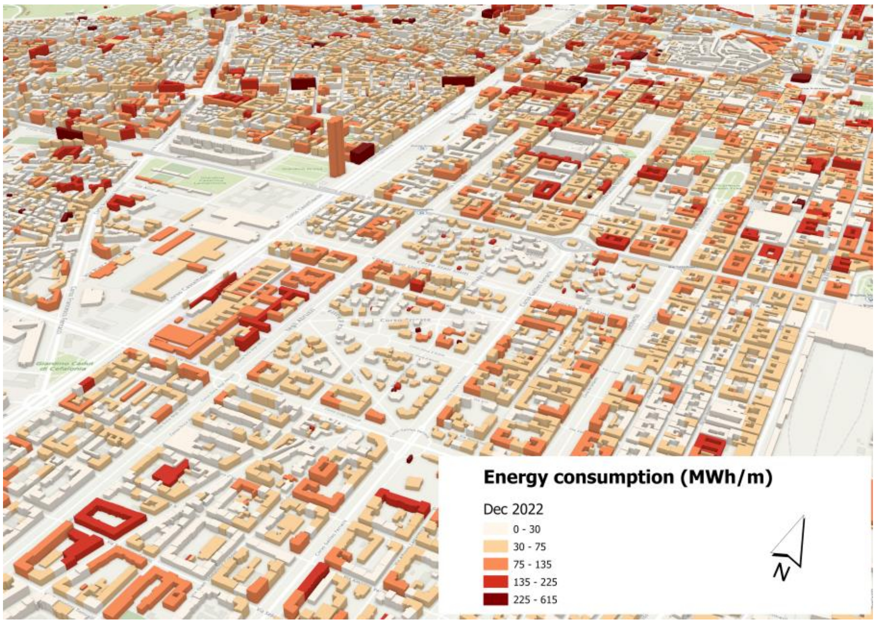


Table 5. LightGBM and RF performance in monthly energy consumption prediction (GWh/m) at urban scale (Relative errors in bracket)

Type of use	Model	Nov 2022	Dec 2022	Jan 2023	Feb 2023	Mar 2023	Apr 2023
Residential	Monitored	21.78	77.92	63.52	47.46	35.8	6.35
	LightGBM	21.45 (-1.5%)	78.25 (+0.4%)	63.53 (+0.2%)	47.4 (-0.13%)	35.77 (-0.8%)	6.69 (+5.35%)
	RF	21.79 (+0.05%)	74.27 (-4.68%)	64.98 (+2.3%)	50 (+5.35%)	36.23 (+1.2%)	6.54 (+2.99%)
Residential-commercial	Monitored	21.63	80.39	65.44	48.46	36.99	6.5
	LightGBM	21.85 (+1.02%)	80.48 (+0.11%)	65.58 (+0.21%)	48.64 (+0.37%)	36.91 (-0.21%)	6.94 (+6.77%)
	RF	21.89 (+1.2%)	76.98 (-4.24%)	67.63 (+3.35%)	50.3 (+3.8%)	37.25 (+0.7%)	6.64 (+2.15%)
Residential-mixed use	Monitored	3.53	12.67	10.33	7.63	5.81	1.02
	LightGBM	3.51 (-0.57%)	12.68 (+0.8%)	10.34 (+0.1%)	7.62 (-0.13%)	5.72 (-1.55%)	1.02 (0%)
	RF	3.78 (+7.08%)	11.51 (-9.16%)	10.17 (-1.55%)	8.16 (+6.95%)	5.67 (-2.41%)	1.33 (+30.39%)
Commercial	Monitored	1.6	5.99	4.84	3.68	2.75	0.43
	LightGBM	1.6 (0%)	6.04 (+0.83%)	4.86 (+0.41%)	3.7 (+0.54%)	2.78 (+1.09%)	0.44 (+2.33%)
	RF	1.68 (+5%)	5.63 (+6.01%)	5.02 (+3.72%)	3.85 (+4.62%)	2.8 (+1.82%)	0.42 (-2.33%)
Educational	Monitored	0.9	3.22	2.81	2.13	1.53	0.23
	LightGBM	0.96 (+6.67%)	3.22 (0%)	2.82 (+0.36%)	2.13 (0%)	1.5 (-1.96%)	0.23 (0%)
	RF	0.93 (+3.34%)	3.05 (+5.28%)	2.83 (+0.71%)	2.29 (+7.51%)	1.5 (-1.96%)	0.29 (+26.09%)

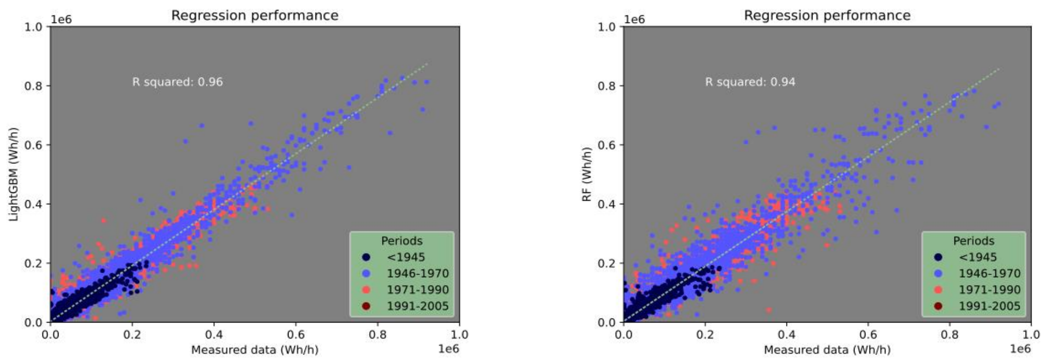
In urban energy planning, it's crucial to grasp the peak consumption of buildings in worst-case scenarios. These scenarios might arise during the initial energy injection into a DHN or occur during the coldest hour of a heating season. Specifically, in this study, which focuses on buildings with hourly energy consumption data, it was observed that the DHN system underwent scheduled shutdowns around twice daily, typically at 9 am and either 13 or 14 pm. Consequently, given that the DHN in

Torino begins operations at 5 or 6 am, it is expected to have three instances of peak consumption each day. This emphasizes the importance of hourly intervals when analysing building energy consumption. Consequently, in this research, there was a keen interest in assessing the performance of ML algorithms in modeling energy consumption at hourly intervals.

The monitored data used for predicting hourly energy consumption corresponds to the previously mentioned heating season. Hourly energy consumption for buildings is predicted for a typical day of each month throughout the heating season, relying on the average daily air temperatures. Those specific dates are: November 14, 2022, December 10, 2022, January 17, 2023, February and March 16, 2023, and April 15, 2023. Just like in modeling monthly energy consumption, climate data was used to combine all monitored data from different months, increasing the size of the training dataset. This resulted in improved predictive performance from the ML models, enabling them to forecast energy consumption even during months when the DHN was only partially operational and therefore had fewer monitored data available.

Concerning the predictive capabilities of the ML algorithms employed in this study, as demonstrated in Figure 6, LightGBM exhibited superior performance in predicting hourly energy consumption. In this particular assignment, the RMSE for LightGBM stood at 13999.83, whereas for RF it was calculated to be 17304.24. The distinction in time for tuning hyperparameters and training energy use models between LightGBM and RF on an hourly basis was slightly better compared to monthly modeling. Nevertheless, there remains a substantial speed difference between LightGBM and RF. Tuning hyperparameters and training the model for hourly consumption with LightGBM required 105 and 0.7 seconds, respectively, while the same tasks for RF took 3062 and 6 seconds. Despite LightGBM requiring less time for tuning and prediction, it showcased superior predictive performance.

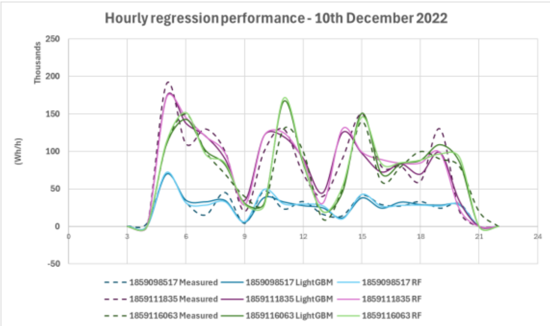
Figure 6. LightGBM performance (A) and RF performance (B) in hourly energy consumption prediction (Wh/h) for residential buildings at building scale



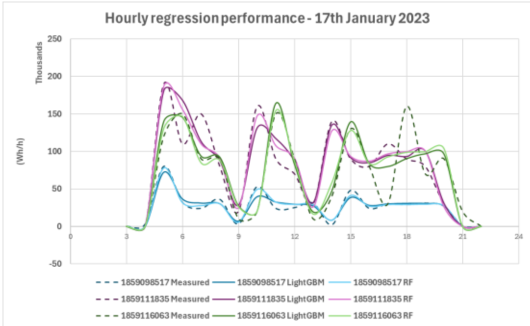
(A) (B)

Overall, as illustrated in Figure 7, both ML algorithms demonstrated reliable performance in forecasting hourly energy consumption patterns of buildings. Across various times of the day, the relative error in energy consumption prediction compared to monitored data typically stayed within a range of ±20%, either for LightGBM and RF, indicating consistent accuracy in capturing consumption trends. However, it is important to note that the ML algorithms encountered challenges during hours when interruptions or shutdowns occurred in the DHN. These instances led to the highest relative errors in energy consumption prediction. During DHN downtime, the ML models struggled to anticipate zero consumption, resulting in discrepancies between predicted and actual energy usage. This phenomenon highlights the sensitivity of the models to external factors such as infrastructure interruptions.

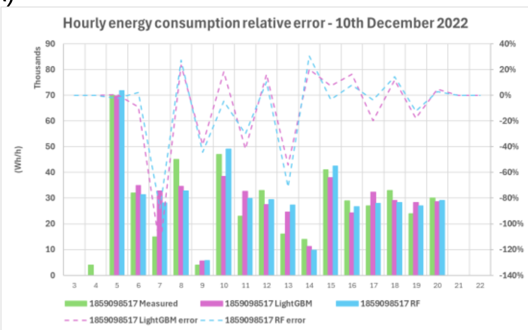
Figure 7. The performance of LightGBM and RF algorithms in predicting hourly energy consumption profile for residential buildings (A, B), and relative error plots for each building (C), (E), (G) for LightGBM and (D), (F), (H) for RF respectively



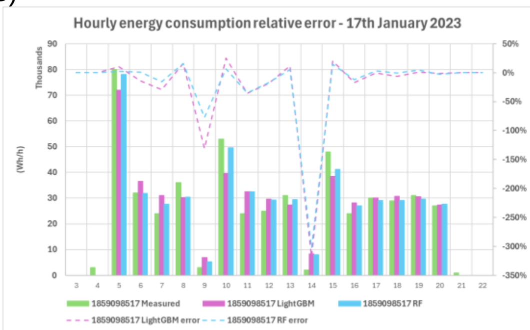
(A)



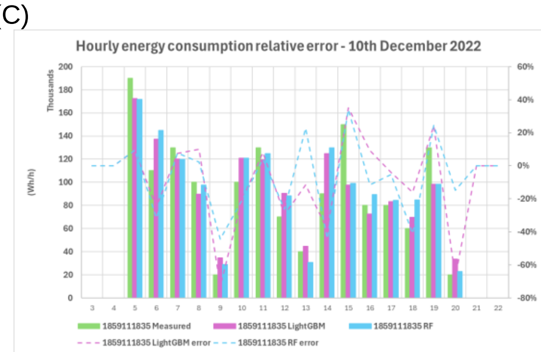
(B)



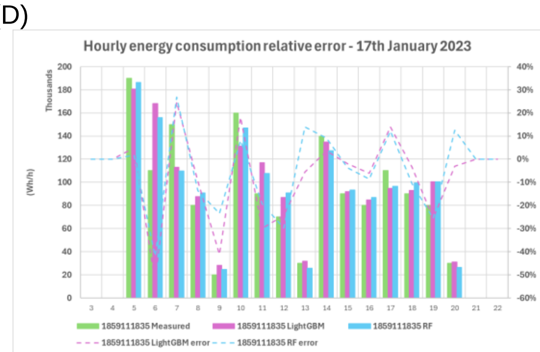
(C)



(D)



(E)



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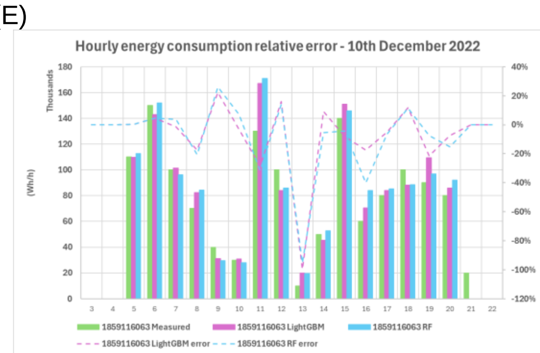
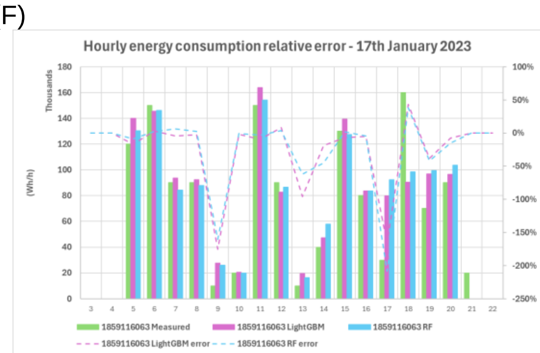


(G)



(H)

Further investigation into these specific instances could provide valuable insights for improving the predictive capabilities of the models in real-world scenarios. By examining the reasons behind interruptions in the DHN and how they influence building energy use, we can gather valuable insights to improve the accuracy of the ML models. Moreover, exploring methods to minimize the impact of infrastructure disruptions on energy consumption predictions could bolster the reliability of the models in practical situations.

In the current study, certain energy-related variables summarized in Table 6, were prominent for predicting energy-use models. Specifically, the average outside air temperature carried significant weight among all other variables. Among building physics variables, the surface-to-volume ratio (S/V), sky view factor, and heat loss surface emerged as particularly influential. Moreover, factors such as the number of empty flats and inhabitants, only typical for residential buildings, played crucial roles in shaping the energy use models.

Table 6. The most consistent energy-related variables (with their respective weights) in predicting energy use models by ML algorithms

Energy model	**Average outside air temperature**	**S/V ratio**	**Sky view factor of roof**	**Building heat loss surface**	**Number of inhabitants**	**Number of empty flats**
Monthly						
Residential	2052	897	906	919	788	700
Residential-commercial	2361	1274	1289	1220	1087	1138
Residential-mixed use	1139	710	745	792	589	513
Commercial	1928	857	999	1056	-	-
Educational	894	568	494	621	-	-
Hourly						
Residential	4915	418	336	1111	236	-

Conclusion

In conclusion, the study embarked on an ambitious journey to explore and implement innovative methodologies for predicting and evaluating energy consumption patterns of buildings within urban contexts. In this context, the research has emphasized the pivotal role of UBEM, employing advanced data-driven techniques, to simulate and evaluate energy efficiency at a larger scale.

Leveraging advanced ML algorithms, specifically LightGBM and RF regression, the study demonstrated significant advancements in accurately predicting energy consumption patterns across various building types and urban scales. The results of the study have shed light on the effectiveness of ML algorithms in capturing complex relationships between building characteristics and energy-use. LightGBM, in particular, showcased superior predictive capabilities, outperforming RF in both monthly and hourly energy consumption predictions. Despite the challenges posed by intermittent district heating network operations, the ML models exhibited remarkable accuracy in forecasting energy consumption, especially during stable operational periods.

However, the study also identified areas for further improvement, such as enhancing model robustness during network cut-off periods and refining algorithms to predict zero consumption instances accurately. Additionally, the research emphasized the significance of ongoing data collection and validation to ensure the reliability and applicability of energy consumption models in real-world settings. Lastly, the paper contributes valuable insights into the evolving field of urban energy modeling and underscores the critical role of data-driven approaches in promoting energy efficiency and sustainability within urban environments.

The results of energy modeling show that the place-based approach can assist in taking into account all energy-related variables from the buildings characteristics and climate conditions to urban context and population features.

In this study, the complete potential of the open-source QGIS platform has not been fully utilized. QGIS possesses significant potential for integrating ML algorithms and combining them with geoprocessing tools to enhance the depth of analysis. Exploring this aspect further could provide a fertile ground to investigate how this capability can be integrated into studies on energy consumption, thereby potentially enhancing the efficiency and precision of relevant analyses.

Acknowledgments

This work was developed as part of the Green District Heating (GDH) research project.

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[9] Gruppo Iren (DH company) available at: https://www.gruppoiren.it/en/our-services/district-heating/our-network.html (accessed on 5/01/2024).

5 Quantifying the Growing Gap Between Brown and Green Buildings

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Abstract

The transition to net-zero emissions presents both a threat and an opportunity for the real estate market. Current valuation methods often overlook transition risks, leading to underestimation of the impact on asset values. This paper examines the growing gap between brown and green properties, driven by factors such as rising capital costs, shifting demand patterns, and environmental risks. Drawing on industry insights and market trends, we quantify the evolving disparity between green premiums and brown discounts, identifying pathways through which decarbonisation efforts influence property values. Our analysis reveals that deep building upgrades are essential for maintaining competitiveness, as green certifications and energy-efficient features become standard expectations. Businesses that embrace deep decarbonisation stand to capture the growing green premium, while investor demand for sustainable buildings intensifies. Valuation standards are evolving to incorporate ESG factors, yet challenges persist in integrating climate change considerations. By comparing conventional green buildings with optimised green developments, we demonstrate the economic benefits of investing in genuine sustainable properties. Our findings underscore the importance of proactive decarbonisation efforts in mitigating risks and maintaining competitiveness in the real estate market.

Introduction

5.1 How big is the threat and opportunity?

In their current state, most buildings are ill-equipped to support the transition to net zero emissions. Currently, formal valuations do not account for transition risks, resulting in a lack of education and information within the market regarding their potential impact. Consequently, property owners may underestimate how these risks can affect asset values, remaining unaware of the challenges, opportunities, and costs associated with decarbonising their holdings.

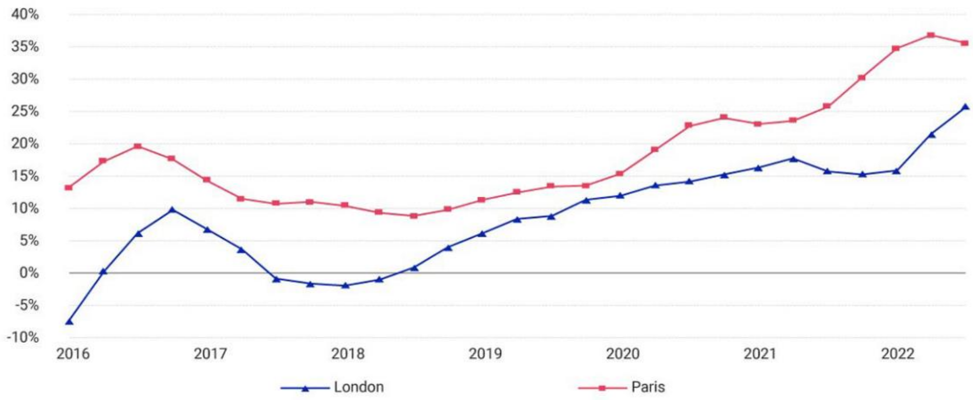
According to ULI, lenders are financing real estate against a value that isn't the real value of an asset. “The value of some buildings is already much lower than its official valuation, as the cost of decarbonisation is not incorporated. We should not be pretending this is not happening”[1]. This poses a challenge as these buildings will become increasingly difficult to let or sell.

The emergence of a significant bifurcation in property values is increasingly apparent in prime markets, a trend that has been amplified by various factors including the rising cost of capital, shifting demand patterns, and environmental risks, particularly in the wake of the pandemic. MSCI's November 2022 report already highlighted a notable green valuation premium of up to 25% in London and 35%

[1] Urban Land Institute (ULI), Transition Risk Assessment, June 2023

in Paris[2]. However, in nascent markets where formal valuations have yet to integrate zero-emission transition risks, a significant portion of these green premiums remain largely speculative. Presently, the disparity between green premiums and brown discounts remains a topic of debate and perspective, with minimal effort devoted to quantifying how this gap might evolve over time and to what extent it is influenced by the green transition.

Figure 1: Sales-price gap between offices that have and don't have sustainable ratings



Source MSCI, London and Paris Offices: Green Premium Emerges, November 2022

Our analysis, drawing from our extensive experience in renovating and developing residential and commercial properties, recent market trends, and reasonable assumptions, indicates that the brown discounts will be substantial enough to warrant investment in comprehensive building upgrades. Investors are increasingly embracing this concept, moving beyond mere reliance on incremental measures, risk mitigation, and compliance. They now view achieving net-zero alignment as a fundamental aspect of investment decision-making, due diligence, and building design, with a focus on data disclosure to showcase its impact. Occupants are also demanding greater energy efficiency, while valuers are increasingly factoring in the costs and opportunities associated with genuinely zero-emission-aligned assets.

A shift is happening in how we define top-tier buildings, driven by changes in carbon footprint, climate concerns, and health priorities. This shift challenges the traditional notion of the "green premium" and emphasises the importance of preserving value and managing risks. Waiting for perfect data or exhaustive research may leave those on the fence too late to embrace these transformative changes.

The fundamental shift in demand for higher-quality buildings is unlikely to be met by the current pipeline of construction projects, presenting significant development opportunities in locations where there is an undersupply of new and refurbished buildings.

[2] MSCI, Tom Leahy, London and Paris Offices: Green Premium Emerges, November 2022

5.2 How time, business models, occupiers, investors, and valuers will drive the growing gap.

We have identified five pathways through which an increasing focus on decarbonisation will lead to a brown discount:

1. Diminishing premiums
2. Business models
3. Occupier Demand
4. Valuations
5. Investor demand

5.2.1 Diminishing premiums

The concept of a green premium, popularised by Bill Gates, describes the ability of energy-efficient buildings to command higher rents, better leasing opportunities, and overall better performance in real estate. Green premiums are already evident in the market, with tenants showing a willingness to pay more for space in climate-friendly buildings. According to a JLL report, green certifications result in a rent premium of 6% and a sales premium of 8%[3]. Cushman & Wakefield found that LEED-certified buildings command a 21.4% higher price-per-square-foot than less sustainable properties[4].

However, as the real estate market transitions toward more sustainable building practices, green buildings will become the norm while those that don't improve will lag. As sustainability becomes widespread, the importance of the green premium may diminish. Instead of paying a premium, tenants and developers will expect lower costs for buildings below the new green standard. Expect the green premium to fade over time, while the brown discount for less sustainable buildings becomes steeper.

The value of specific green features tends to start low and increase as awareness grows, eventually declining as they become standard. For instance, LED lighting, introduced in the early 2000s, initially commanded a premium due to its benefits like longer lifespan and reduced energy costs. However, as LED technology became widespread, the premium decreased as it became a market norm.

Similarly, certifications like LEED and BREEAM initially led to price and rental premiums, but as more properties meet these standards, the premiums are likely to diminish. Looking ahead, as the built environment moves toward a zero-emissions future, properties that stand out in this regard are likely to see increased value for both occupants and investors.

The opportunity to tap into this green premium is therefore ripe now. However, what constitutes a green premium is rapidly evolving. As LED lighting exemplified, that ship has already sailed, and it's no longer a distinguishing feature. Similarly, the market for commercially certified 'green' buildings is rapidly shrinking as the market demands genuine zero-emission buildings. This dichotomy between 'speculative' green buildings (those merely certified for commercial purposes without genuine zero-

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[3] JLL, Return on Sustainability. How the 'value of green' conversation is growing up. January 2022

[4] Cushman & Wakefield, Green is Good, Part 2. Sustainability's Impact on Office Investment Pricing December 2021

emission compliance) and truly sustainable zero-emission buildings is expected to widen rapidly, following the S-curve trajectory of new technology growth. This acceleration is fuelled by the impending Paris Agreement milestone of a 50% reduction in building carbon consumption by 2030.

Today's opportunity lies in going beyond superficial green interventions and viewing ESG as more than mere compliance, integrating sustainability as a core aspect of business operations. Measures that can currently be labelled as 'green' may soon fall out of favour, replaced by genuinely sustainable buildings. Investing in this opportunity ensures that the asset is valued as a first-hand building and enjoys a mid-to-long-term green premium, exceeding average rental prices in the primary market, while also enhancing asset liquidity as net-zero regulations tighten.

In contrast, conventional green buildings—typically certified for commercial purposes and saving less than 30% in energy and carbon—may be valued as first-hand buildings today but may lack the potential for a mid-to-long-term green premium in the primary market. Their asset liquidity is expected to diminish over time as net-zero regulations become more stringent.

5.2.2 Business models

The imperative to decarbonise buildings underscores a broader historical trend: the necessity for businesses to adapt their models as externalities are internalised over time. Viewing this imperative solely as a matter of compliance with slow-moving regulations risks missing its fundamental impact on business models. Failure to recognise this can lead to missed opportunities to capitalise on the green premium, which may erode as net-zero features become commonplace. Moreover, there's a real risk of facing brown discounts and being left behind as the market evolves.

The debate over who bears the costs of decarbonisation is largely moot, as market forces, technological advancements, and regulatory pressures are already propelling the shift towards sustainability. This trajectory mirrors the typical S-curve growth pattern seen in technological markets: initially undervalued, then experiencing rapid growth in demand, and eventually becoming standard.

Consider the abolition of slave labour over two centuries ago: businesses that clung to outdated models faced obsolescence and legal ramifications. Those that innovated, recognising the inefficiency of their old practices, and adapting accordingly, not only thrived but also gained a competitive edge. It is important to clarify that this comparison doesn't equate businesses not adopting green practices with historical injustices. Instead, it emphasises the crucial need for businesses to adapt to changing societal norms and regulations for long-term sustainability.

Similarly, decarbonising buildings is not only technically feasible but also economically viable, with net-zero options now available at comparable costs to conventional development. Forward-thinking asset owners recognise that merely meeting current regulatory requirements is shortsighted. Instead, they view this as an opportunity to eliminate value drains and positioning themselves to capture the growing green premium. By doing so, they not only future-proof their business but also gain a significant market share ahead of the mainstream adoption of net-zero standards. In each scenario, restructuring business models is imperative to establish a stable investment framework for the coming decades.

5.2.3 Occupier Demand

The landscape of occupier demand is undergoing a significant transformation, driven by a confluence of factors ranging from the aftermath of the pandemic to energy and debt crises, and the imperative to achieve net-zero interim milestones by 2030, 2040, and 2050.

In many global markets, rising corporate demand for buildings with sustainability credentials will have an impact on office market dynamics. Across 20 major office markets, including New York, Paris and Singapore, only 34% of future demand for low-carbon workspace will be met in the next several years. In other words, for every 3 square meters of demand, only 1 square meter is in the current pipeline[5].

With an exponentially increasing number of corporates signing up to net-zero targets and an ongoing focus on minimising operating costs, demand for space aligned with these goals is poised to surge.

Historically, green certifications have been the hallmark of a sustainable building, with tenants willingly paying a premium for such spaces. However, the dynamics are changing. Transaction evidence indicates healthy rental premiums for certified buildings across various global office markets, but the significance of green certifications is evolving into more of a requirement than a differentiator.

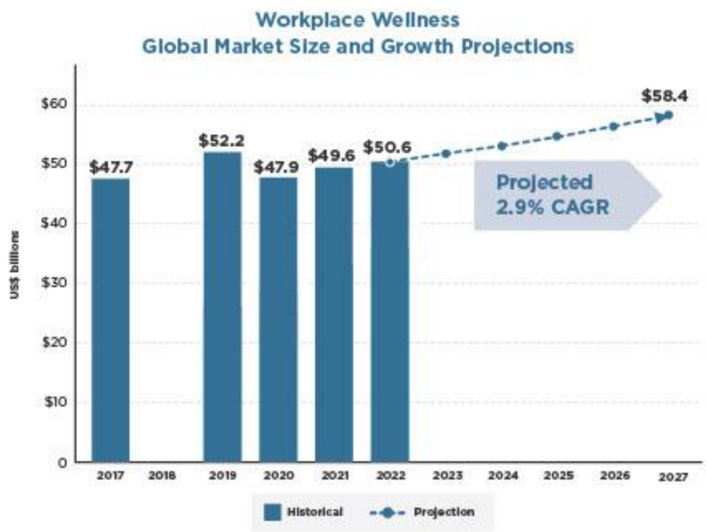
Tenants will increasingly seek environmental performance indicators, such as energy intensity and electrification, on top of green credentials. JLL is already seeing evidence of this in advanced European markets, like London and Paris, where low-carbon prime office spaces are reaching historic rental highs this year, even with an overall slowdown in the sector[5].

In many major markets worldwide, including the U.S., green certifications are becoming commonplace rather than a unique selling point. For instance, 77% of San Francisco's Class A office stock is LEED-certified, compared to 49% in Phoenix, with associated green premiums of 5% and 11%, respectively. Early movers in late-adopter markets like Phoenix may still benefit but established markets like San Francisco pose the risk of a brown discount[5].

Occupiers' focus extends beyond energy, water, and waste usage. The pandemic has shed light on the importance of the "S" in ESG, leading to increased demand for health-related features and amenities. The Global Wellness Institute projects that by 2027, the global workplace wellness market will reach $58.4 billion, with a steady annual compound annual growth rate (CAGR) of 2.9%.

[5] JLL, The Commercial case for making buildings more sustainable, November 2023

Figure 2: Workplace Wellness Global Market Size and Growth Projections



Source: Global Wellness Institute, Global Wellness Economy Monitor, 2023

5.2.4 Investor Demand

Sustainable building demand from tenants is outpacing regulatory changes. As tenants seek spaces aligned with their sustainability objectives, the market is evolving rapidly. However, regulations are catching up, intensifying through stricter building performance standards and corporate disclosure requirements.

As more real estate funds become classified under Article 8 or Article 9 of the EU's Sustainable Finance Disclosure Regulation (SFDR), a building's quality and how it is used will grow in importance.

The limited supply in the market will also contribute to supporting rents and prices of existing buildings, especially those in good condition and with high energy efficiency. These buildings are likely to attract creditworthy tenants who can navigate economic downturns more effectively.

A report from M&G Investments points out: "One of the largest industry shifts will be the focus on climate and achieving net-zero carbon and energy-efficiency targets. Evolving occupier sentiment towards energy use and worker health has also increased the incentive to improve assets to meet these targets." The simple approach will be to buy buildings that are already energy efficient, creating a bigger green premium/brown discount[6].

The Buildings Breakthrough, unveiled during COP28[7] in December 2023, aims to establish low-emission, climate-resilient buildings as the standard by 2030, further fuelling this momentum. Currently supported by 27 countries, the EU commission, and 18 international initiatives, it signals a significant shift. In the years ahead, companies lagging in addressing their carbon footprints, especially across their real estate holdings, will face increasing scrutiny.

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[6] M&G plc: Sustainability Report 2021/22

[7] UNEP Global Alliance for Buildings and Construction (GlobalABC) Breakthrough Agenda

For businesses with operations spanning multiple cities, staying abreast of emerging regulations is crucial to avoid financial penalties and safeguard their reputation. Given the lengthy process of decarbonising operations and upgrading buildings, taking proactive measures now, rather than waiting for new mandates, will enhance their competitiveness and ensure compliance.

Despite widespread recognition of climate risk among investors and occupiers, many companies lack contingency plans[8]. Building a strong case for investing in sustainable buildings involves understanding and mitigating these risks. Integrating short-term resilience measures with broader decarbonisation plans can reduce both short and long-term risks. We believe that 2025 will mark a turning point where investments in genuine sustainable buildings will yield significant returns.

5.2.5 Valuation

Valuation standards and methodologies are evolving rapidly to adapt to the changing landscape of environmental sustainability. Looking ahead, valuers are refining their approaches to incorporate the costs of upgrading buildings to meet net-zero aligned environmental standards and to consider potential carbon taxes. However, despite the growing recognition of the importance of ESG factors in property valuation, current standards set by organisations like the International Valuation Standards Council (IVSC) and the Royal Institution of Chartered Surveyors (RICS) lack explicit mandates regarding climate change considerations.

While sustainability has been acknowledged in some standards, specific guidance on climate change remains limited and non-compulsory. As a result, valuers face challenges in integrating ESG factors into their assessments due to the lack of standardised methodologies and quantitative data. Moreover, the interdisciplinary skills and clear professional guidance needed for effective risk assessment are often lacking among valuers.

The discrepancy between market valuations, which heavily rely on recent transaction evidence, and investment appraisals complicates the integration of ESG considerations into property valuations. Despite increasing demand from investors for green properties as a long-term investment strategy, this surge in demand exposes properties to heightened levels of climate-related risks within a rapidly transitioning global economy.

The growing divide in property values within prime markets serves as an early indicator of broader implications for all property values and markets. In markets not yet impacted, we anticipate a "first mover" effect where buildings undergoing genuine green upgrades aligned with accredited standards will attract higher tenant demand. However, it's crucial to distinguish between superficially "green" properties and those meeting accredited net-zero standards, as the latter are more likely to see sustained value appreciation.

Nevertheless, the transition towards accredited net-zero standards is still in its early stages, with most green building upgrades resulting in modest energy savings. This presents an immediate risk to property values, particularly as current valuations and risk assessments may not adequately address this urgency. To mitigate these risks, we strongly recommend proactive collaboration between property owners and knowledgeable professionals well-versed in evolving environmental standards.

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[8] ECB/ESRB, Towards macroprudential frameworks for managing climate risk, December 2023

By aligning valuations with the latest requirements, stakeholders can better navigate the complexities of sustainable property investment.

5.3 Quantifying the brown discount

The real estate investment landscape is undergoing a significant transformation with two key shifts. Firstly, there's a growing emphasis on optimising the operational aspect of assets, particularly by maximising revenue potential and managing operating expenses to enhance EBITDA. Secondly, there's an increased focus on proactively addressing performance gaps upfront, leading to a reduced risk profile and eliminating the perceived green cost premium.

Carbon reduction begins with early identification of low-carbon design options, considering factors such as building type, location, size, material choices, and structural considerations. By exploring design alternatives and comparing their carbon efficiency very early on, it's possible to find the most optimal solution without at this stage requiring specialised expertise in energy audits, LCA or BIM. Timing is crucial. As a project progresses, the window for green optimisation narrows, with opportunities decreasing by half at each stage.

Against a backdrop of unsustainable emissions, stagnant productivity, and high material and process waste, we can achieve quality improvements, reducing construction defects by 95%, cutting externally sourced energy needed for buildings in use by 75%, and decreasing the materials used in construction by 25%. This transformative process also involves digitalising the entire project workflow, ensuring the creation of a golden thread of information from the outset, even before a single design stroke has been made. The most impactful decisions are made at the investment level during the early-stage due diligence process. UNEPFI research has shown that projects backed by an informed and detailed project brief, supported by an investment mandate, achieve at least 50% more savings[9]. Effective impact coordination, which involves ensuring that project sequencing and decision-making are optimal throughout the end-to-end value chain, can prevent numerous value drains such as split incentives, value-chain bias and performance gaps.

To illustrate the impact of these changes, we'll examine one of our own projects involving the development of 1000 apartments in the UK. Optioneering plays a crucial role in our analysis, where we compare a conventional green development (with an average EPC rating of C or D) against a net-zero energy development (with an EPC rating of A). Additionally, we explored two additional options: one targeting low-hanging fruit with minimal incremental costs, resulting in a significant NPV increase (improving energy performance by around 50%), and another option involving a larger investment, yielding both positive NPV and a 75% reduction in energy consumption. For the sake of clarity we will focus solely on the first two scenarios to facilitate a direct comparison between conventional and optimised green development.

The project spans over 11,280,000 square feet, resulting in a reduction of carbon output by 340,000 tons. With EBITDA improvements of 14%, this translates to over £49.8 million (20%) in extra profit created across 1000 apartments.

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[9] UNEP FI Investor Briefing, Unlocking the energy efficiency retrofit investment opportunity, February 2014

Achievements			
Energy savings	99%	11.8	GWh/year
Economic savings		£3.0	million
Emission savings		5,674	ton/year
Incremental costs		£5.6	million
Pay back		1.8	years
Internal Carbon Price		£16.4	p/ton/carbon

At £16 per ton of CO2, the abatement costs showcase significant efficiency in comparison to the current EU ETS carbon price of £73. This highlights that green optimised decarbonisation can be notably more cost-effective than the prevailing market rate, offering projects risk-adjusted returns and a competitive advantage in carbon emission management.

5.4 Main value drivers

5.4.1 Higher revenue

The following table exemplifies how green optimised properties can command a premium in rent while providing cost savings for tenants, creating a win-win scenario where both asset owner and occupant benefit. The landlord can increase the rent for the green property because the investment in energy-saving measures results in cost savings for the tenant. By offering a property with lower utility costs, the landlord can justify charging a higher rent while still providing value to the tenant.

Tenant investment decision		
	Before	After
Net Effective Rent	£1,755	£1,920
Utilities	£210	£10
Gross Rent	£1,965	£1,930

5.4.2 Lower operating costs

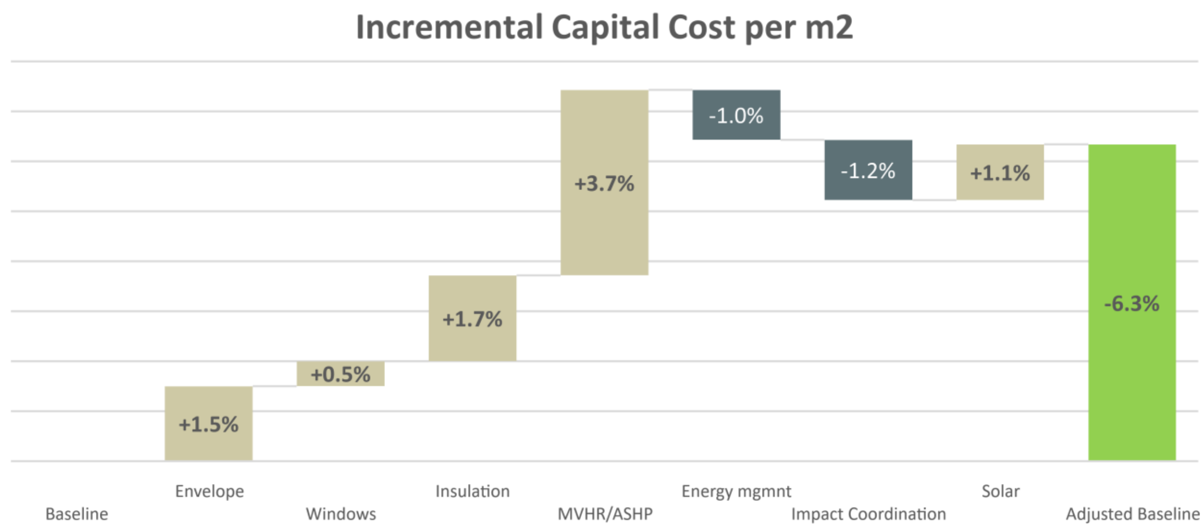
Through optimisation, operating costs are significantly reduced across various metrics. By decreasing the number of active consumption hours per day by 20%, annual energy consumption drops by a substantial 95%. This optimisation also leads to a 30% decrease in annual maintenance costs, with an estimated 25% reduction in annual depreciation. Altogether, these improvements result in a notable reduction of 3.2 percentage points in total operating expenses, showcasing the efficiency gains achieved through optimisation efforts.

	Savings	%
Number of active consumption hours per day	1.5 hours	-20%
Annual energy consumption	11.8 GWh	-95%
Annual maintenance costs	£410 thousand	-30%

Annual depreciation	Estimated reduction of 25%
Total operating expenses	Reduction of 3.2 percentage points

5.5 Impact Coordination

Generally, saving energy is about 4 times cheaper than procuring or generating it. By sequencing green interventions accordingly, investment in energy-saving measures can typically incur an additional cost of up to 15%, which is offset by reduced expenses due to lower capacity needs for mechanical equipment. In this case study, the incremental costs amount to 6.3%, with a payback of less than 2 years.



5.5.1 Cash Flow and Valuations

Let's consider two residential apartment buildings, starting with identical rent and value. Over the past decade, prime rental growth in Europe has averaged 3%. Looking ahead, we anticipate a potential slowdown in rental growth for properties not aligned with decarbonisation targets for 2030, 2040, and 2050. Moreover, investors increasingly prioritise ESG factors, leading to a higher exit yield for brown buildings.

Assumptions	Before	After
Rental growth	0%	3.0%
Initial yield	4%	4%
Exit yield	4.25%	4%
Vacancy period	5%	2%
Inflation	3%	3%
5-year IRR	11.8%	15.2%

For illustration, let's compare green and brown scenarios:

Conventional Green:

- Meets current regulatory and certified green requirements.
- Valued as a first-hand building but lacks a mid to long-term green premium.

- Liquidity may decrease over time as net-zero regulations tighten.

Optimised Green:

- Benefits from a "Low Energy Invoice" upgrade, allowing owners to raise headline rents while offering lower net effective rents.
- Valued as a first-hand building and enjoys a mid to long-term green premium.
- Liquidity is expected to increase over time as net-zero regulations tighten.

Assuming identical rent and asset value at the start, these hypothetical assets yield a 15% internal rate of return over 5 years in the green scenario, compared to 12% in the conventional scenario. By year 5, the difference in exit values amounts to 14%, indicating the potential impact of brown discounts. Realistically, rents could decline for brown buildings, making a 3-percentage point impact on yield a conservative estimate. For lower yields, the effect would be even more pronounced.

Conclusion

The analysis presented in this paper sheds light on the growing gap between brown and green properties in the real estate market, driven by the imperative to transition to net-zero emissions. As the urgency to address climate change accelerates, the traditional valuation methods and market dynamics are undergoing a significant transformation, impacting property values and investment decisions.

Our examination of the evolving landscape reveals several key trends shaping this growing gap. Firstly, the diminishing green premiums underscore the need for deep building upgrades to maintain competitiveness in the market. While green certifications and energy-efficient features once commanded a premium, they are becoming standard expectations rather than differentiators. Instead, genuine zero-emission buildings are emerging as the new benchmark for top-tier properties, offering long-term value appreciation and enhanced asset liquidity.

Secondly, the shift in business models towards sustainability reflects a broader trend of adapting to changing societal norms and regulatory pressures. Businesses that proactively embrace decarbonisation not only mitigate risks but also position themselves to capture the growing green premium, gaining a competitive edge in the market.

Thirdly, occupier demand is driving the market towards low-carbon workspace solutions, with tenants increasingly seeking buildings aligned with their sustainability objectives. As demand outpaces supply, properties with sustainability credentials are poised to command higher rents and attract creditworthy tenants, enhancing their investment appeal.

Fourthly, investor demand for sustainable buildings is intensifying, supported by regulatory changes and evolving market preferences. Buildings that meet net-zero standards are expected to enjoy higher valuations and greater liquidity, while those lagging may face brown discounts and increased scrutiny from stakeholders.

Lastly, valuation standards and methodologies are evolving to incorporate ESG factors and climate change considerations, but challenges remain in integrating these aspects into property valuations. Proactive collaboration between property owners and valuation professionals is essential to navigate the complexities of sustainable property investment and mitigate associated risks.

Our analysis quantifies the gap between brown and green properties by examining the financial implications of decarbonisation efforts. Through a comprehensive comparison of conventional green buildings and optimised green developments, we demonstrate the potential economic benefits of investing in genuine sustainable properties.

The results reveal that optimised green developments, characterised by net-zero energy standards and deep impact measures, outperform conventional green buildings in terms of financial returns and asset value. With higher revenue potential, lower operating costs, and enhanced asset liquidity, optimised green developments offer a compelling investment opportunity, yielding significant returns over time.

Furthermore, our analysis highlights the impact of brown discounts on property values, with brown buildings facing lower rental growth and higher exit yields compared to green properties. This underscores the importance of impact coordinated decarbonisation efforts in maintaining competitiveness and mitigating risks associated with climate change.

In summary, our findings provide empirical evidence of the growing gap between brown and green buildings, emphasising the financial incentives for optimising sustainable interventions.

6 Risk aware resource planning for microgrid connected edge data center with renewable energy production operating under grid power constraints

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Abstract

To meet sustainability goals and decarbonize the network infrastructure, Communication Service Provider (CSP) is considering installing Renewable Energy Sources (RES) at existing or new deployments of 5G and Edge compute nodes. At the same time, new developments are constrained by local conditions such as grid power availability, spacing limitations and restrictions on how installations may affect the local environment, e.g., through heat dissipation from cooling equipment. In this paper, we propose a method for orchestration and planning of resources in relation to the available power from grid and RES. It is based on a probabilistic model of the local power production conditional on the public weather forecast. The model leverages both clear sky models of solar irradiation as well as empirical correlation in power production derived from local weather station observations. Furthermore, as the model is probabilistic in nature it outputs a whole distribution in addition to the expected forecast, and therefore permits planning based on confidence intervals. Hence, we call the approach risk-aware planning. Experiments on a small microgrid connected edge DC with photovoltaic production are conducted to compare the model results with actual observations. Our simulation exercise shows that the set-up can accommodate a 20 Ampere (A) computational load throughout a day, while limiting the grid draw to 16 A during a 12-hour window without exhausting the battery (at 95% confidence). The availability of solar power can thus play an important role and increase the usage of our local power resources, which can improve and extend the usage of services by effective risk-aware resource planning allocation.

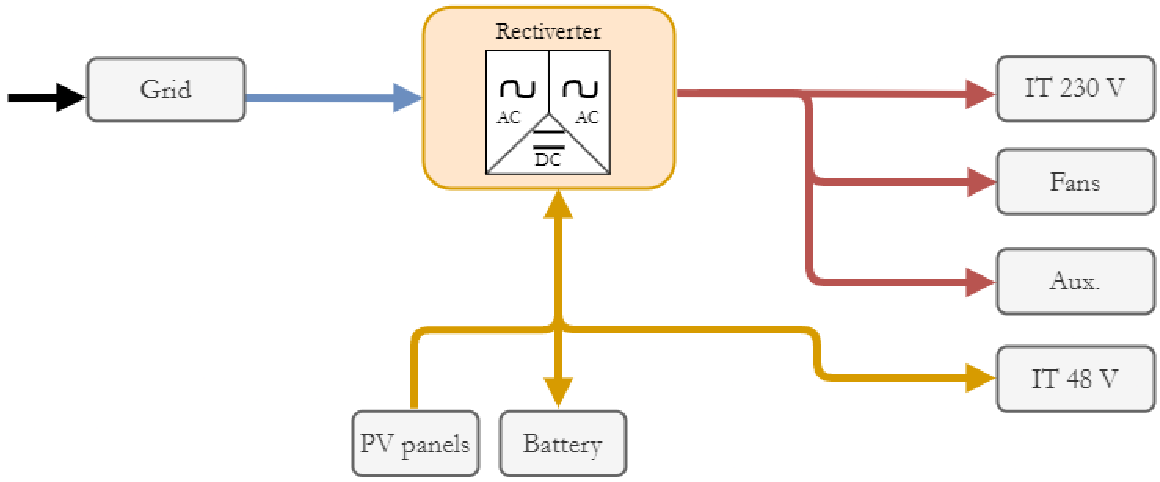
Introduction

Edge computing is a distributed framework which brings compute power and resources for applications closer to the end user. There are many benefits of bringing the compute resource close to the users, such as low latency, high bandwidth, data offloading and device processing capabilities that improve the performance of the service and application [1]. The infrastructure for edge computing may in many cases be hosted on the service providers' facilities, or on different existing deployments of a Telecommunication access network. Edge nodes in the network enhance the local computational power for various use cases and applications. Improving the local Edge node application performance doesn't come without challenges. To fulfil the sustainability targets, local trade-offs considering and managing local constraints need to be solved on the already installed base. Various constraints such as power limitation from grid, energy efficiency and local RES production need to be considered.

One way to solve the problem, given available space, is potentially to install to add RES on existing sites, or when deploying new sites, consider to add RES. Generating local power, from RES, such as photovoltaic systems can provide extra dynamic power to the edge node, that might extend the operation in parallel with the other connected power sources on the Edge. Efficient utilization of all available power sources at an Edge site is important, including grid power, solar power and local energy storage such as batteries. Adding extra power sources will improve the reliability and availability of the edge nodes. At the same time, enabling an energy efficient operation can reduce the operational cost of the Mobile Network Operator (MNO).

A typical Edge node deployment, equipped with Information Technology (IT) equipment, servers, solar panels, batteries, and Uninterrupted Power Supply (UPS) control is illustrated in figure1. Our architecture revolves around the Rectiverter, a versatile UPS component handles both alternating Current (AC) to Direct Current (DC) and DC to AC conversions, allowing flexibility in battery, grid, and photovoltaic usage, as well as managing both alternating current (AC) and Direct Current (DC) loads. The UPS control is essential for power flow management and is operated via a local controller and dedicated Application Programming Interface (API). Additionally, a dashboard and central data collection system are part of the setup.

Fig.1. The architecture of the edge node is centered on the Rectiverter, a versatile UPS component that can handle both AC to DC and DC to AC conversions thus enabling total flexibility in the use of battery, grid and photovoltaic production, as well as both AC and DC loads



6.1 Related Work

There are several papers addressing the problem of energy usage and energy efficiency of microgrid connected Edge compute nodes considering various techniques improving the operation of the Edge node. In Paper [2] the authors propose a model and consider a case where a group of Edge nodes are supplied by local solar power and have limited stored energy on the battery. Solar power charges the battery, and when the battery cannot absorb more energy creates inefficiency. The proposed method includes offloading the node activities to other idling nodes, that consumes less energy to compute the data, and by that using more of the solar power produced. Paper [3] considers a deployment and proposes a unified edge compute system for energy management framework for enabling sustainable edge computing for home energy management and smart home applications. The paper considers renewable energy while reducing electricity bills for households. A prototype is implemented using low-cost and easy-to-get hardware. The results and conclusion is that renewable energy is fully capable of supporting the reliable running of edge computing devices and electricity bills could be cut by up to 85%. Paper [4] considers real-time monitoring of large-scale solar farms considering the reliable and secure deployment of 100% renewable energy-based grids. The paper enables by Machine Learning (ML) determination anomalies on solar panel behaviour during various conditions such as panel damage, electrical errors, monitoring hardware decay, or malicious data injection. The paper presents a design and evaluation of a low-cost edge-based anomaly detection system for remote solar farms using Raspberry Pi and deep learning. They propose a smart edge device to reduce the cost of continuously sending data for anomaly detection by performing analytic on local edge device solar farm, while at the same time the edge device is low consuming.

Paper [5] considers the energy consumption of a Mobile Edge Node, (MEC) network that highly depends on volatile workloads that induces risk for energy demand estimations. The paper considers the problem with the high risk associated with energy supply due to unpredictable energy generation from renewable and non-renewable sources. The paper studies a risk-aware energy scheduling problem for a microgrid-powered MEC network and formulates an optimization problem considering the conditional value-at-risk (CVaR) measurement for both energy consumption and generation. Furthermore, the authors analyse by using multi-agent stochastic game that ensures the joint policy Nash equilibrium, and show the convergence of the proposed model, including and applying a multi-agent deep reinforcement learning (MADRL)-based asynchronous advantage actor-critic (A3C) algorithm with shared neural networks. Paper [6] considers low latency requirements that are expected to increase with 5G telecommunications driving data and compute to EDGE data centers located in cities near to end users. A testbed for such data centers that has been built at RISE ICE Datacenter in northern Sweden in order to perform full stack experiments on load balancing, cooling, micro-grid interactions and the use of renewable energy sources. Furthermore, the paper describes system details on both hardware components and software implementations used for data collection and control. Paper [7] considers and presents a detailed description of two different prototype edge data centers designed to investigate the power performance and thermal dynamics of edge nodes under various applied services. The prototypes were developed and tested at the RISE ICE Datacenter research facility. It presents results of power flow experiments in which input current from the grid was limited while the computational load was maintained using the energy stored in batteries. The paper titled "Rule-Based Control for a Standalone Microgrid" [8] proposes a rule-based power management scheme. The microgrid comprises a solar photovoltaic (PV) array, battery storage (BS), and diesel generator (DG), serving nonlinear loads. The control objectives include ensuring uninterrupted power supply to the loads, maximizing renewable energy utilization, maintaining healthy battery state of charge (SOC), and balancing AC source currents during unbalanced loading.

6.2 Problem formulation

Considering Edge compute nodes deployments that provide various services, an addition of RES capabilities will make an improvement to the Edge node, by increasing the node power availability. At the same time, the operation of an Edge node, need to be more energy efficient related to its operation and therefore there is a need, for a more proactive and on-demand plannable method to orchestrate the workloads. The planner shall consider the input power source availability and capabilities from all connected RES in various time-based operations. In today's systems, planning in many cases does not consider local constraints or how and on what time window, the different power from RES is available, and how it relates to the compute power of the edge nodes.

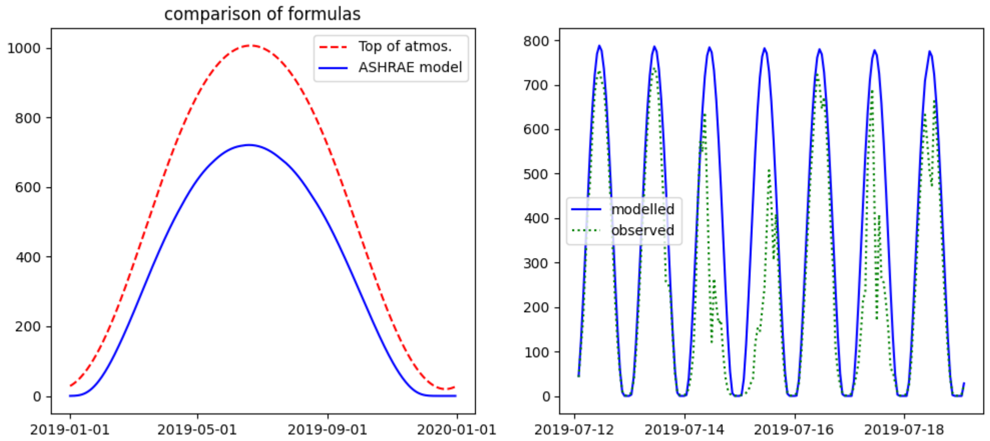
In this paper, we present a method for workload planning, in relation to the input power grid source and RES availability (solar availability) and following constraints, such an input grid power limitation. We propose a method for planning and orchestration that includes various operational states, with objective to minimize of the power grid electricity usage, by provide switching operations, between power grid and solar power availability, for a 24-hour time window. The planning considers and enables an efficient resource planning operation, based on availability of solar power.

6.3 Method

6.3.1 Theoretical models for irradiance

Top-of-atmosphere models for solar irradiance provide a theoretical maximum of solar energy reaching the Earth's surface, accounting for factors such as the (seasonal) distance from the sun and time of day and year, as well as extension that include physical modelling of solar cycle changes. They do not take into account the angle of incidence perpendicular to the earth's surface, the height of the Sun above the horizon, tilt of the measuring surface or other ambient conditions at a specific location on the planet such as atmospheric conditions.

Fig. 2. Comparison of models (left). Comparison with observed (right)



The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) describes a more comprehensive model that additionally differentiates between beam radiation and diffuse radiation incidence, and path length through the atmosphere. The amount of solar energy that is available for conversion to electricity is significantly affected by such conditions, as is exemplified in the left panel of Fig. 2 that compares a Top of the atmosphere model with the ASHRAE model for a specific latitude and longitude (Luleå in Sweden). Appendix A has more details on clear-sky models.

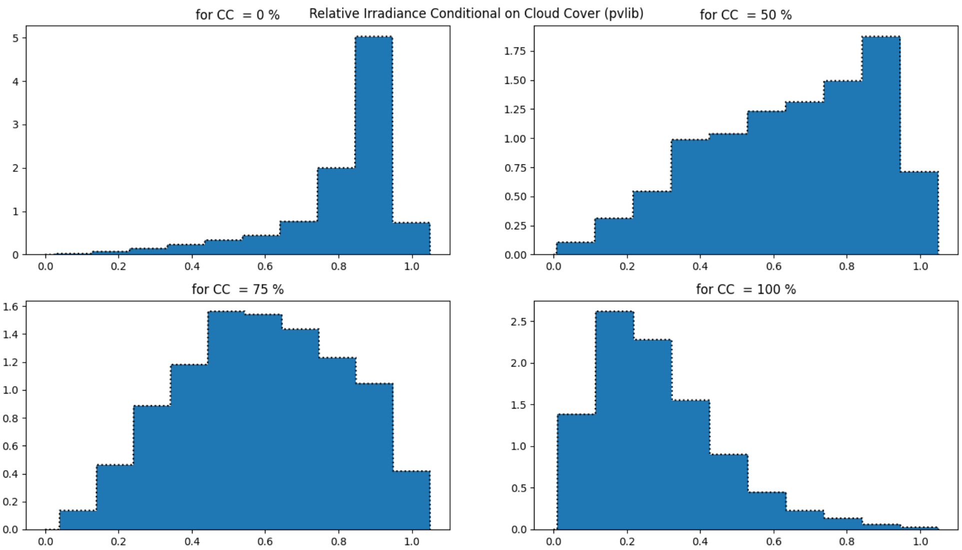
The right panel of Fig. 2 compares the actual irradiance at a measuring station with the modelled values taking into account the above-mentioned atmospheric conditions. It is evident that such a model is not sufficient on its own, as it does not account for local weather conditions such as cloud cover and other intermittent atmospheric conditions. These factors can greatly influence the performance of solar cells, as they can cause fluctuations in solar irradiance. Therefore, accurate modelling of electric production for solar cells requires a comprehensive approach that considers both the theoretical maximum solar energy and the practical limitations imposed by local and intermittent environmental conditions.

6.4 Data sources

The Swedish Meteorological and Hydrological Institute (SMHI) is an expert agency under the Ministry of the Environment in Sweden, with expertise in meteorology, hydrology, oceanography, and climatology. SMHI provides a rich source of data with both forward looking forecasts and historical weather observations that are available on-line through a public API [9]. The STRÅNG dataset [10] is a valuable resource for modeling solar energy generation from photovoltaic (PV) installations. It is curated with support from the Swedish Radiation Protection Authority and the Swedish Environmental Agency. This dataset provides details on two essential parameters: Global Horizontal Irradiance (GHI), representing the total solar radiation received on a horizontal surface (including both direct sunlight and diffuse sky radiation), and Direct Normal Irradiance (DNI), which specifically refers to the solar radiation received directly from the sun when the sunlight is perpendicular to the surface. Researchers and engineers can leverage the STRÅNG data to accurately model solar irradiance for PV installations, aiding in efficient energy production.

In addition to irradiance, meteorological observations on temperature, precipitation, wind speed, humidity, pressure, cloud cover, weather symbol and more. The data is available for all weather stations in Sweden and is updated every 10 minutes. Via the public API, users can extract data for a specific location and time-period. Using this data one can explore empirical relationships between variables that are important for modelling the system, such as:

Fig. 3. Relative irradiation as percentage of clear sky value observed at the Luleå site. Each panel displays an example histogram of measurements co-incident with a specific observed cloud cover

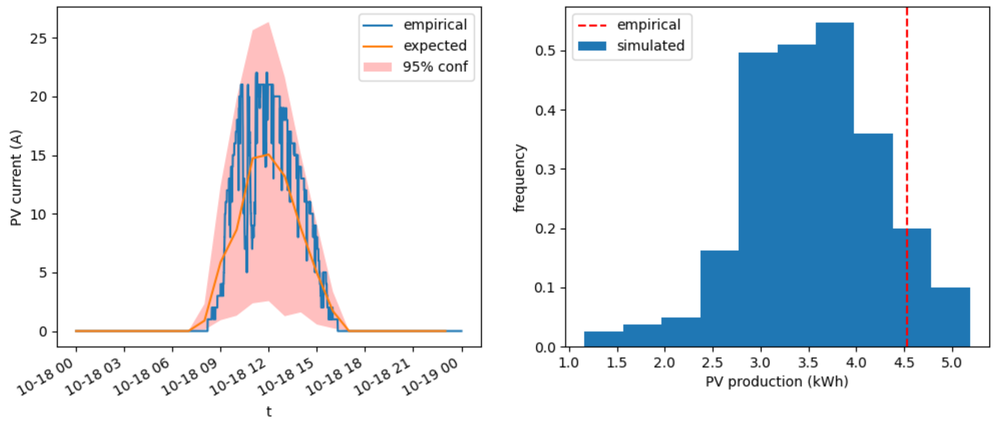


Relative irradiation. We can now look at the fraction of observed radiation to theoretical maximal radiation, which we call relative irradiation. Observed radiation (global irradiation) varies by daily and yearly cycles. By dividing the actual (observed) radiation by the model-based irradiation we get a normalized variable that ranges between 0 and 100 percent.

Irradiation by cloud cover. We can now collect relative irradiation by cloud cover index such that we can approximate its conditional distribution by plotting histograms. Fig. 3 plots histograms of the relative irradiance depends on cloud cover (measured in octaves).

Weather symbol. The weather symbol used on the SMHI Open Data API (Wsymb2) consists of integers ranging from 1 to 27, where each integer represents a different kind of weather situation, such as, rain, snow, clear sky etc. We estimate the empirical distribution of cloud cover conditional on weather symbol, based on the historical forecast data which is available for each specific location.

Fig. 4. Left panel: The local model forecast solar production with confidence bands. Note that the actual solar production is intermittent and may quickly drop as cloud cover changes minute to minute, while model forecast is hourly average. Right panel: Histogram of electric production in kWh over simulated forecast. The actual production over the period is marked a vertical red dashed line.)



Local model. SMHI also provides a probability based multiple scenario prognosis over up to ten days. This data is not supported by the Open Data API but can be downloaded as a json-file from the main ten-day prognosis webpage. It is an experimental beta release and only a subset of the weather variables are available, but fortunately, it includes both temperature and weather symbol. This weather prognosis provides three alternative scenarios for each future projection time and their associated marginal probabilities through time. The marginal probabilities represent the probability of a particular future scenario - that is weather symbol and temperature -- given at the time of the forecast.

We build a model assuming that weather symbols follow a time-inhomogeneous Markov chain and populate it with transition probabilities extracted from the public multi-scenario weather prognosis. The transition probabilities describe the likelihood of transitioning from a state at time t to a state at time t+1. These transition probabilities can be represented as a 3x3 matrix whose columns sum to one. We obtain these probabilities by marginalizing over scenario S_t.

To reflect time-consistency in the transitions, we shrink the solution towards the unit matrix by minimizing the Frobenius norm of the difference between the transition matrix and the identity matrix. This is a problem that is straightforward to solve by convex programming. Appendix B has details on the derivation of transition probabilities for the Markov chain.

With access to transition probabilities, we can simulate weather scenarios. By that we mean a sequence of weather symbols and temperatures. Furthermore, from the SMHI data we can extract the relation between weather symbol, cloud cover and solar irradiance in the form of empirical distributions from which we can sample. Note that the intention of the model is not to predict the weather, but rather to simulate scenarios conditional on the public weather forecast, such that we can model the operating set-up for our edge DC equipped with PV-production and batteries.

We can now put all components together for a generative model for irradiation scenario-paths over the forecast horizon. Algorithm 1 describes the simulation procedure assuming N is the number of simulated paths and T the number of simulation time steps.

Algorithm 1 Simulation algorithm

for $i \leftarrow 1$ to N **do**
    for $j \leftarrow 1$ to T **do**
        Sample the next weather symbol, S_{ij} from the Markov chain transition probabilities at t_j.
        Sample cloud cover, c_{ij}, conditional on weather symbol from its empirical distribution.
        Sample relative irradiation, r_{ij}, conditional on cloud cover from its empirical distribution.
        Calculate the clear-sky irradiation from the theoretical model, $\hat{I}_{ij} = I_{\text{model}}(t_j)$.
        Obtain the predicted (absolute) irradiation by multiplication, $I_{ij} = \hat{I}_{ij} r_{ij}$.
    end for
end for

For clear sky model, we use pvlib [11], a Python library for simulation of photovoltaic systems that also includes models for the microgrid components in addition to support for a wide variety of PV arrays and their physical installation parameters (array size, surface tilt and azimuth, etc.).

6.5 Datacenter model

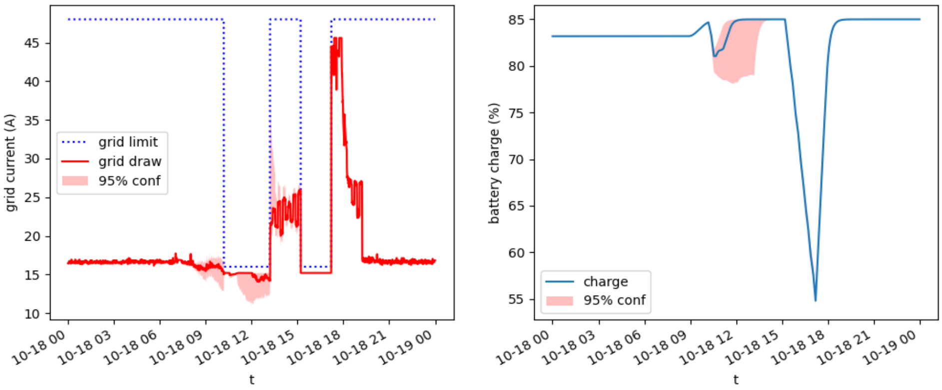
The remaining piece is a model for the data center including microgrid components, battery, inverter and cooling equipment. We take as input variables the computational load (in W) and grid electricity price (in SEK), although the model could be extended to allow also for stochastic modelling of these.

For simplicity, we use a rule-based power management scheme that uses a battery state-of-charge (SOC) to determine the charging and discharging of the battery. The SOC is used to determine the battery's state and the amount of energy that can be stored or discharged. The algorithm determines the charging and discharging of the battery based on the SOC and the available power on the main grid as well as respecting the safe operating range. It's important to consider the long-term health of the battery as overcharging or deep discharging a battery can reduce its lifespan. Appendix C discusses an alternative planning method based on stochastic optimization that is more flexible than the rule-based we employed for the main work. % method employed in producing the results presented in the next section.

6.6 Results

The set of transition probabilities describes a Markov chain for the weather, with up to three weather symbols at each future time. A distribution for cloud cover conditional on weather symbol we already backed out from the SMHI data. We can thus sample cloud cover for each time on our scenario path. The historical data gave us the distributional data (such as moments) for relative irradiation conditional on cloud cover. We can thus sample relative irradiation, which multiplied by the clear sky model prediction of irradiation to give us global irradiation. This can be repeated for as many paths trajectories as we need. Finally, we upsample to hourly time-steps (by interpolation of upsampled missing points separately for each path) to make the forecast plots smoother. An example of the simulated solar production is displayed in the left panel of Fig. 4 that compares the predicted values (expectation with confidence bands) and the actual observed (empirical). We note that this was a day in October that saw relatively clear skies, compared to a forecast that also predicted clouds and rain with some probability. This explains why the actual observed production (empirical) was above the expected. The upsampling also facilitates calculations (in kWh) of path accumulated total production on the solar panels, by taking the simple sum over each trajectory in the Monte Carlo simulation, as in the example of the right panel of Fig. 4.

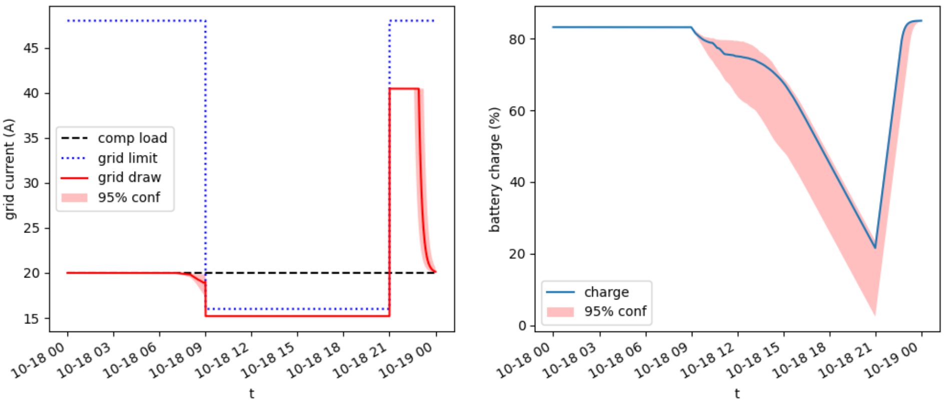
Fig. 5. Left panel: Example of an experiment with a variable computational load and grid current limited to 16 A during part of the day. Right panel: The actual battery charge stays within the forecast confidence bands over the studied period. The pink shaded area are confidence bands from the simulation, while solid lines are observations



Trajectories sampled from the model also allow Monte Carlo estimation of various path dependent variables, for example, how much current needs to be drawn from the grid and the implication on battery charge change over time, as in the examples of the right panel and left panel, respectively, of Fig. 5. The figure compares the simulated forecast with an actual experiment, where conditions were controlled such that, a variable computational load was applied while the grid current was limited to 16 Ampere (A) during part of the day. The actual battery charge stays within the forecast confidence bands over the studied period (left panel). The pink shaded area in the figures are confidence bands from the simulation, while solid lines are actual observations.

The objective of the model is to relate and build on the constraint that the input power transmission lines are limited, e.g to 16 A or lower. The experiment described in Fig. 5 permitted unrestricted grid access for two hours in the middle of the experiment, which allowed the battery to recover full charge during this period. Since there is no solar production during the second grid limited period of the experiment, there is no remaining uncertainty and consequently no confidence bands around the model estimate.

Fig. 6. Alternative simulation where grid limit stretches from 09:00 until 21:00. The system can support a load of 20 A throughout the day without exhausting the battery at the 95% forecast confidence (pink shaded area)



To allow for a somewhat more interesting example, we employ a simulated experiment for which the grid constraint is maintained at 16 A for a longer and uninterrupted time-period during the day (between 09:00 and 21:00). The results of this simulated experiment are displayed in Fig. 6, where the left panel shows the current draw from the grid as well as the computational load and grid limit; and the right panel shows the resulting simulated battery charge over the day. The confidence bands around simulated quantities are shaded pink. We note that the set-up can accommodate a 20 A computational load throughout the entire day, while limiting the grid draw to 16 A (efficiently 15 A) during a 12-hour window without exhausting the battery (at 95% confidence).

6.7 Discussion

In a possible future scenario, edge data center operators may rely on simulation models to make informed decisions. These models serve two critical purposes: first, they allow operators to confidently commit to computational capacity based on predictions, ensuring that committed resources meet service level agreement (SLA) requirements for cloud-edge network services. And second, they estimate the spare capacity available throughout the day. Armed with this information, operators can strategically offer this spare capacity in a spot market for computation, optimizing resource allocation and cost efficiency. This concept is investigated, for example by [12], who explored cost optimization for the edge-cloud continuum by energy-aware workload placement.

Related work, such as [8], also build controls targeting an uninterrupted power supply to the workloads, maximizing renewable energy utilization, maintaining healthy battery state of charge (SOC), and balancing AC source currents during unbalanced loading. In comparison, the work presented here includes uncertainty in the simulation, such that a range of scenarios with different outcomes can be considered and not only the expected outcome. This allows for risk aware planning on how to use the microgrid resources.

The simulation models allow us to determine how much computation we can commit to with a certain confidence. This is important as such resources committed will have to be delivered under certain SLA that the edge data center operator may have signed for how computing capacity must be serviced over the cloud-edge network. We can also get information about what is the likely spare capacity we will have over the day so that we can plan how to offer this computation at spot prices over the day.

Future work. A necessary next step is to validate the simulation model against historical data. This type of *backtesting* aims at quantifying the quality of the model, for example, by evaluating whether the model outperforms a baseline model (zero hypothesis) at a certain confidence level. As this type of analysis requires access to large amounts of historical forecasts and observation data for many locations, we propose to return to it for future work.

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Appendix A. Theoretical irradiation models

Top-of-atmosphere formula. Unfiltered sunlight at the top of the atmosphere perpendicular to the earth's surface is given by

$$I = S_0 E \cos\theta \tag{1}$$

where S_0≈1367 is the solar constant and

$$E = 1 + 0.0033 \cos\left(\frac{2\pi n}{365}\right) \tag{2}$$

$$\cos\theta = \cos\delta \cos\varphi_{\mathrm{lat}} \cos\omega - \sin\delta \sin\varphi_{\mathrm{lat}} \tag{3}$$

φlat is the latitude in radians and ω the hour angle determined by

$$\delta = \frac{23.45\pi}{180} \sin\left(\frac{2\pi(n+284)}{365}\right) \tag{4}$$

$$\omega = \frac{15\,(12 - t_S)\,\pi}{180} \tag{5}$$

$$t_S = t_L + \frac{t_E}{60} - \frac{4}{60}(\psi_{\mathrm{mer}} - \psi_{\mathrm{lon}}) \tag{6}$$

$$t_E = 9.87 \sin(2B) + 7.53 \sin(B) - 1.5 \sin(B) \tag{7}$$

$$B = \frac{2\pi(n-81)}{365} \tag{8}$$

ASHRAE clear-sky formula. Total irradiance at sea surface is written as a combination of beam radiation I_b and diffuse radiation I_d

$$I = I_b \cos\theta + I_d \tag{9}$$

$$I_b = A \exp\left(-\frac{B}{\cos\theta}\right) \tag{10}$$

$$I_d = C I_b \tag{11}$$

and constants A, B and C tabulated. The irradiation at the top of the atmosphere enters as

$$\cos\theta = \cos\delta \cos\varphi_{\mathrm{lat}} \cos\omega - \sin\delta \sin\varphi_{\mathrm{lat}} \tag{12}$$

Python implementation. For our numerical investigations described in Section III on Results we use pvlib [11], an open-source Python library for simulation of photovoltaic systems, which in addition to a clear-sky model, also includes support the microgrid components that include a wide variety of PV arrays and their physical installation parameters (array size, surface tilt and azimuth, etc.).

Appendix B. Deriving the Markov chain

The probabilistic weather forecast (tsim) provides three alternative scenarios $S_{t,1}$, $S_{t,2}$, $S_{t,3}$ for each future projection time t and their associated marginal probabilities through time $\pi_{t,1}, \pi_{t,2}, \pi_{t,3}$, that is, the forecast has data for j = 1, 2, 3 scenarios at each future time t

$$p_{t,j} = P(S_{t,j}|S_0) \tag{13}$$

Note the conditioning on S_0 which is the weather symbol for the current scenario (i.e now) which is known at the start of the simulation. For the simulation, however, we need the transition probabilities $T_{t,ij} = P(S_{t+1,i} | S_{t,i})$, which describe the likelihood of transitioning from a state j at time t to a state i at time t + 1 - formally a 3 × 3 matrix (whose columns much sum to one). We obtain these by marginalizing over scenario $S_{t,j}$

$$P(S_{t+1,i}|S_0) = \sum_{j=1}^{3} P(S_{t+1,i}|S_{t,j})P(S_{t,j}|S_0) \tag{14}$$

or in matrix notation

$$\pi_{t+1} = T_t\pi_t \tag{15}$$

$$e = T_t e \tag{16}$$

with $\pi_0 = p_0$ and e^T = (1,1,1) such that probabilities sum to one. Formally this system of equations can be solved by (right) multiplying π_{t+1} by the pseudoinverse of π_t. Note however that there are too many degrees of freedom and therefore not a unique solution (unless we impose additional constraints). A trivial solution exists and is equal to the matrix where we set each column equal to p_{t+1}.

Solve regularized problem under convex programming. We observe some time-consistency in the scenarios, such that a scenario with clear skies is often followed by clear skies, rain followed by rain and so on. This is contrary to the trivial solution derived above. To reflect time-consistency in the transitions we shrink the solution towards the unit matrix by minimizing

$$J_t = \frac{1}{2}\|I - T_t\|_F^2 \tag{17}$$

Under the same constraints given by equations (15) and (16), where $\|A\|_F^2$ is the Frobenius norm (i.e. sum of squared matrix elements). This is now a problem in convex programming

$$\begin{aligned}
\textbf{obtain}\, T_t &= \underset{T}{\operatorname{argmin}} \|I - T\|_F^2 && (18)\\
\textbf{subject to}\;\; T_t\pi_t &= \pi_{t+1} && (19)\\
e^T T_t &= e && (20)\\
T_t &\geq 0 && (21)
\end{aligned}$$

for e defined as above and I the 3 × 3 identity matrix.

This problem can be solved by many standard numerical packages (e.g. cvxopt or cvxpy for Python), however, those may require that we first vectorise matrices, so that, $x_t = \mathrm{vec}(T_t)$,

$$\text{obtain } x_t = \underset{x}{\operatorname{argmin}}\, x^T x - 2c^T x \tag{22}$$
$$\text{subject to } A_t x_t = \pi_{t+1} \tag{23}$$
$$B x_t = e \tag{24}$$
$$x_t \geq 0 \tag{25}$$

for $A_t = \pi_t^T \otimes I$, $B = I \otimes e^T$ and $c = \mathrm{vec}(I)$, with the symbol $\otimes$ representing the Kronecker product. We can then obtain T_t from x_t by reversing the vectorization.

Modification for non-square transition matrix. The above problem only handles square transition matrices. In real tsim forecast we may have that at some future time we only have two states with non-zero probability, or even a case with only a single state. To allow for this we need to modify the quadratic programming problem somewhat. For $\dim \pi_t = (k_t, 1)$ and $\dim \pi_{t+1} = (k_{t+1}, 1)$, we have $\dim T_t = (k_{t+1}, k_t)$ and write

$$\text{obtain } T_t = \underset{T}{\operatorname{argmin}} \|I_t - T\|_F^2 \tag{26}$$
$$\text{subject to } T_t \pi_t = \pi_{t+1} \tag{27}$$
$$e_{t+1}^T T_t = e_t \tag{28}$$
$$T_t \geq 0 \tag{29}$$

for $e_t = e_{[1:t]}$ and $I_t = I_{[1:t+1,1:t]}$ submatrices of e and I, respectively, sliced in analogy with the "MATLAB colon notation". Finally, we vectorize the quadratic optimization problem as

$$\text{obtain } x_t = \underset{x}{\operatorname{argmin}}\, x^T x - 2c_t^T x \tag{30}$$
$$\text{subject to } A_t x_t = \pi_{t+1} \tag{31}$$
$$B_t x_t = e_t \tag{32}$$
$$x_t \geq 0 \tag{33}$$

for $A_t = \pi_t^T \otimes I_{[1:t+1,1:t+1]}$, $B = I_{[1:t,1:t]} \otimes e_{t+1}^T$ and $c_t = \mathrm{vec}(I_t)$.

Appendix C. Alternative Planning Method

The optimization objective function is based on the expected total cost accumulated for a fixed action sequence X over the simulated scenarios. We distinguish alternative action sequences by index k

$$J(X) = \frac{1}{M} \sum_{m=0}^{M-1} \left(B_{m,N}(X)\, P_{\text{nom}} - \sum_{n=0}^{N-1} C_{m,n}(X) \right) \tag{34}$$

that is, we let the objective function be the average value of the battery charge *B* at end of the simulation (calculated at nominal price P_{nom}) minus the average accumulated cost *C* for electricity purchased from the grid. This is calculated for each alternative fixed action sequence X_k. To solve the optimization problem, we use the cross-entropy method [13], which is briefly described below.

Cross-Entropy Method for Optimization: First let p be the parameter vector of length N that controls the probabilities of taking action 1 at each step in the action sequence. The cross-entropy method solves the optimization problem starting from a collection of random action sequences by an evolutionary procedure that repeats the following steps, in each iteration updating the parameter vector pi according to the following steps:

1) Choose an initial parameter vector $p^{(0)}$. Let $K^e < K$ be the size of the elite sample. Set $i = 0$.
2) Generate samples $X_1, X_2, \ldots, X_K \sim_{\text{iid}} \text{Bernoulli}(\text{p}^{(\text{i})})$
3) Evaluate battery charge and cost over each simulated path and for each alternative action sequence.
4) Calculate the value of the objective function for each action sequence $J_k = J(X_k)$ and re-order the samples from largest to smallest value of the objective function: $J_{(1)} \geq J_{(2)} \geq \ldots \geq J_{(K)}$. Let $\gamma^{(i)}$ be the k-largest value of all J_k; that is $\gamma^{(i)} = J_{(K^e)}$ bounds the elite sample.
5) Use the elite sample $X_{(1)}, X_{(2)}, \ldots, X_{(K^e)}$, respecting the re-ordering in step, to solve the stochastic program; for the Bernoulli distribution we can take the maximum likelihood estimate over the elite sample to update the parameter vector $p_n^{(i+1)} = \frac{1}{K} \sum_{k=1}^{K^e} X_{(k),n}$
6) If some stopping criteria is met, for example $J_{(1)} - J_{(K)} < \epsilon$, we stop, otherwise set $i := i + 1$ and return to step 2.

We take $p(0) = 0.5$, that is, set equal probabilities for all actions through the initial action sequences. Also note that we indicate the re-ordering of the sample in step 3 by putting parenthesis around the index, such that $X_1, X_2, \ldots, X_K$ becomes $X_{(1)}, X_{(2)}, \ldots, X_{(K)}$.

Degeneracy and smoothing. As the algorithm starts to converge some sequences in the sample may give identical value of the objective function - this degeneracy is not really a problem by itself and can be dealt with by random tie breaking for the ordering. It is however worth monitoring the speed of convergence - if it happens too fast, the algorithm cannot explore the parameter space efficiently and may get stuck in a suboptimal local maximum when some $p_n^{(i)}$ reaches 0 or 1. It is common to use parameter smoothing to mitigate this effect - for this we change the update rule in step 4 according to

$$p_n^{(i+1)} = \alpha p_n^{(i)} + (1 - \alpha) \frac{1}{K} \sum_{k=1}^{K^e} X_{(k),n} \tag{35}$$

for some $0 \leq \alpha \leq 1$, such that a proportion α of the last parameter estimate is always preserved.

7 Smart Lighting systems: Dream or reality?

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Abstract

Today, lighting is responsible for 5% of worldwide CO2 emissions. Electricity demand for lighting attained 2900 TWh for a global light production of 215 Plmh. It is foreseen that in 2040 the needs for artificial lighting will increase by 25% to reach 285 Plmh. The challenge for the next decade will be to harness the increase of electricity demand. The only light source technology evolutions are not sufficient to stem uncontrollable growth. Even the best commercialized LED lamps which are almost 2 times more efficient than fluorescent tubes, are not sufficient to inhibit the well-known rebound effect. Only a transition from the conventional analogue lighting technologies to digital lighting can help. Smart lighting will become the heart of the Internet of Things in smart cities and buildings. Smart Lighting is on the way to become the 4th revolution in the domain. It can achieve more than 40% additional energy savings and encompass rebound effect. Smart Lighting market size can exceed €90 billion by 2030 which is comparable to €130 billion revenues from global lighting industry. This paper highlights the evolutions in the domain of smart lighting technologies and its impacts.

7.1 The context

Humanity's artificial light needs are foreseen to attain, by 2040, at least 285 Plmh. This corresponds to a light demand increase of 25% compared to 2020. In fact, taking 2009 as starting point, electrical lighting consumed 2 650 TWh of electricity, at that moment, this represented 19% of world electrical production [1], since then thanks to various actions from governments and industry a deflation has been confirmed. For instance, in 2019, we estimated the electricity used for lighting with around 2 900 TWh stabilized (less than 1% annual growth rate), or 13,5% of the world's annual usable electricity[1] .[2] Even if the absolute value slightly increased in the last years, the relative part of lighting reduced drastically (~4% annual decrease rate). The observed decrease is the effect of combined effort of technological developments and worldwide energy policies. For instance:

- LED technology has evolved so quickly that in 2022 best LEDs lumens per watt (lm/W) offer efficacies over 200 lm/W – double the efficacy of the fluorescent technology – with high colour rendering and stability. Following K. Lane, since 2010, the average efficacy of LEDs has improved by around 4 lm/W each year. [3]. Today, the best commercialized non-directional LED lamps are 210 lm/W over 15 times more efficient than incandescent and four times more efficient than compact fluorescent lamps (CFLs). [4]

[1] "Usable electricity": Global electricity generation minus an average 7% losses related to the electricity transport and distribution [5]

- Minimum energy performance standards are widely employed as the key driver for efficiency improvements, incandescent lamps are almost banned worldwide, and many countries are now beginning to eliminate fluorescent lighting.

However, despite these efforts, following K. Lane, electricity consumption for lighting increased in 2022, with greater efficiency not offsetting increased use of lighting. Despite the falling carbon intensity of electricity, CO2 emissions from lighting rose slightly in 2022. The emissions intensity of electricity, an important factor for CO2 emissions, fell too little to offset increased lighting demand [3]. This can be a concrete expression of the well-known "Jevons paradox" (or rebound effect"). This tendency, if confirmed, shall be considered with the highest attention because may be the sign of reaching some limits of "SSL beneficial effect" and that even if we expect some further technology efficacy increase during the next 5 years. Beyond the implication of lighting in energy, greenhouse gas emissions and abiotic resources of our planet, to evaluate the full impact of artificial lighting, we shall take into account some additional side-effects like the light pollution of the skies and the associated erosion of the biotopes. Sánchez de Miguel et al., shown that the power of global satellite observable light emissions increased from 1992 to 2017 by at least 49%. [6] The same authors conclude that, even if "these dynamics vary by region, but there is limited evidence that advances in lighting technology have led to decreased emissions." [6] This shows the absolute need to intensify and coordinate world policy efforts to harness this problem.

Consequently, we knowingly are still not serving society as effectively as we could. To encompass this lack efforts shall, not only intensify, but they shall explore new technological horizons, include new concepts like circular economic, sustainability and affordability; more important, to be more efficient, efforts shall be coordinated at supra-national level. This shall lead to the "Sustainable Smart Lighting" that is lighting-up smart, to a sustainable and affordable way, where it is needed, when it is necessary and as best as possible!

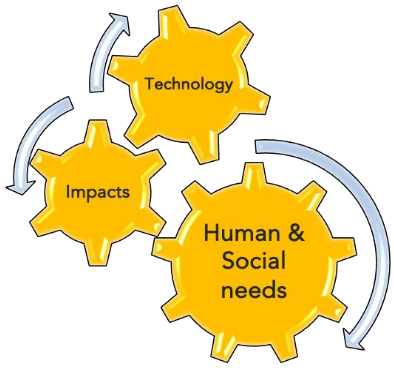
The challenge for the next decade will be to harness the increase of electricity demand, limit the associated greenhouse gas emissions and avoid undesirable effects on the biotope. The only light source technology evolutions, even supported by ambitious policies, are not sufficient to stem uncontrollable growth. In fact, as Solid-State Lighting (SSL) technology offer new control opportunities, encompassing rebound effect and maximizing the energy savings using connected/smart SSL systems, will become a challenge to address all these unforeseen, or just neglected till recently, issues.

Today, lighting is witnessing its 4th revolution: the transition to Smart Lighting systems. Smart Lighting can achieve more than 40% additional energy savings and its market size can exceed €90 billion by 2030.

Generally speaking, a smart technological object, including smart lighting, is characterized by an intelligent sensing technology that is increasingly being integrated with internet technologies, thereby allowing the react to react to and communicate with the changing environment around it. In principle, this is leading to optimal operation and global improvement in efficiency. Based on the fact that such "smart" lighting system shall serve at best the human needs and reduce as much as possible the impacts on environment and biotope, Zissis et al., proposed in 2023 the following definition [2]:

"*A smart lighting system has a principal function which is to produce, at any moment, the right light: where it is needed and when it is necessary. It should adapt the quantity and quality of light to enhance visual performance in agreement with the type of executed tasks. It must guarantee well-being, health and safety of the end-users. It should not squander passively the resources of our planet and limit actively the effects of light pollution on the biotope, or, any other impacts on the* *environment. Further, the system could offer additional optional services (geo-localization, data connectivity...) to the end-users preferably through Visible Light Communication protocols, but not only".*

Figure 1: Illustrating the SSL2 concept for lighting



To achieve such ambitious objectives to a sustainable manner, Zissis, introduced in 2023, the SSL2 concept, that defines a "Sustainable Smart Lighting (the 1st SSL in SSL2) system uses and optimizes to an intelligent way the best existing technology (Solid State Lighting, the 2nd SSL in SSL2) to best fulfil present needs for artificial light of humans and reduce undesirable side-effects, without compromising the ability of future generations to innovate." [2]. Figure 1, illustrates the SSL2 concept.

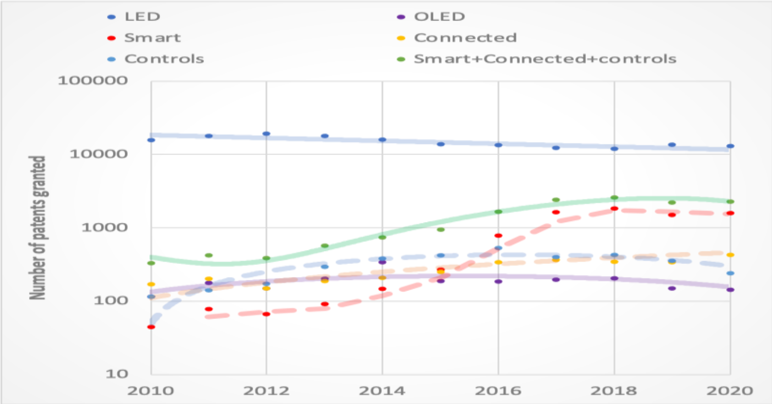
In this paper, to assess the penetration and effects of smart lighting systems, we are based on analysis of more than 175 recent (2018 and after) free accessible documents and data harvested by open access databases for more than 150 countries. Further we analysed published patents and scientific papers databases.

7.2 Smart Lighting Penetration Progress Assessment

Our first analysis was based on harvested data concerning the number of patents grated from 2000 to 2022 for four specific segments: (1) LED lighting, (2) OLED lighting, (3) Connected lighting, (4) Lighting Controls, and (5) Smart Lighting. Globally that period when more than 100 000 patents have been granted for LED Lighting, only 7 600 have been granted for OLED lighting technology and 33 800 for smart/connected lighting and lighting controls together. It is however very interesting to analyse the annual evolution of the number of patents by segment, as shown in Figure 2[2]. It can be seen that the number of patents concerning LED and OLED lighting is declining when the segment of smart (lighting controls and connected lighting) is increasing, even if a plateau appears from 2018. We can anticipate that in the next years and during the next decade, smart lighting systems will supersede simple SSL systems.

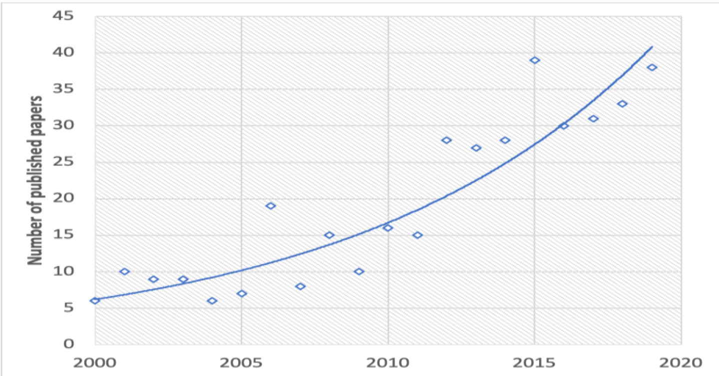
[2] Methodology: Author used the online google patent search engine (https://patents.google.com/) and formulated queries for each of the listed terms (exact form) in the full patent document, year-by-year (January 1st to December 31st). from 2010 to 2023. Only granted patents have been retained from any country. The years 2022 and 2023 are not added to the graphics because many of the submitted patents are still pending.

Figure 2: Evolution of number of patents from 2020 to 2021



Source: Data harvested by G. Zissis in from Google Patents

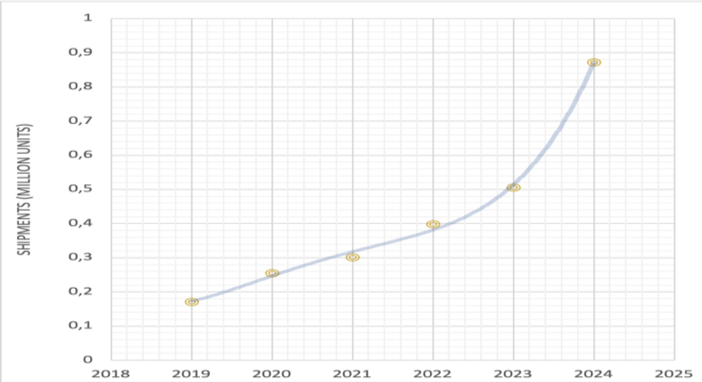
Figure 3: Evolution of number of published papers on Smart Lighting Systems



In addition, a review paper published in 2021 by Füchtenhans et al., shows the growth of scientific papers on smart lighting systems published in recognized journals. As can be seen in Figure 3 the growth is exponential. [7] The analysis of a sample of 384 papers shows that the sampled papers were published primarily in technically oriented journals that focus on facilities and buildings: Energy and Buildings (72), Lighting Research & Technology (40) and Building and Environment (27) were the three most common outlets for research in this area. In 232 papers on 384 (60,4%) energy savings induced by smart lighting are the main objective and for 128 the light quality was the central idea (33,3%). Further, 63% of the papers dealing with light source technology, 44,7% concerned light sensors and 44,3% were related on lighting controls.

A last indicator is given in Figure 4 which shows the exponentially increasing number of shipments of Smart Lighting units.

Figure 4: Shipments of Smart Lighting units.



Source: Data from [8

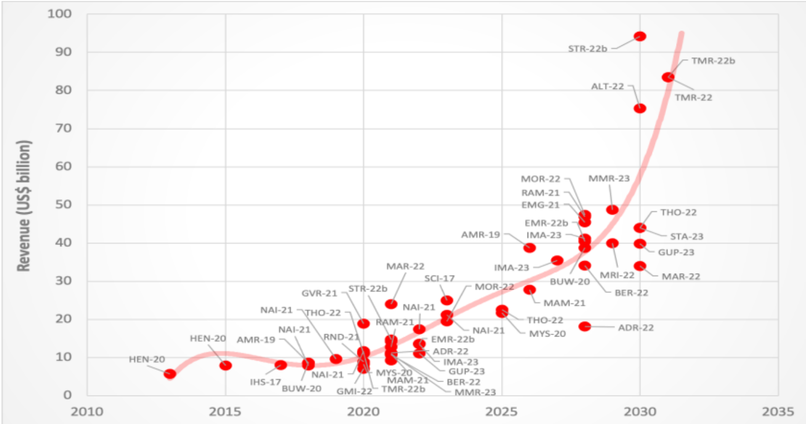
7.3 Smart Lighting Market

Historically, in 2013, the global smart lighting market industry size exceeded USD 5,7 billion. Among them, the market size of smart lamps and related accessories exceeded USD 1,2 billion. In 2015, the global smart lighting market size reached USD 7,83 billion. [9] An HIS Markit report indicates that in 2017 the smart lighting and connected lighting controls market was estimated to have been worth USD 8 billion; That year, 1,8% of luminaires shipped included connected ballasts and wireless adapters. [10]

Following a mysupplier online publication, the Smart Lighting market is forecasted to grow from USD 8,2 billion in 2020 to USD 21,7 billion by 2025 at a CAGR of 22,3% in the forecast period. [11] According to Business Wire news, the global smart lighting market is expected to generate revenue worth USD 8,68 billion in 2018, and is projected to reach USD 38,68 billion by 2028, to register a CAGR of 20,5% during the 2018-28 period. [12] Research and Markets reports that the global smart lighting market size is expected to reach USD 46,9 billion by 2028, registering a CAGR of 20,4%, from USD 12,75 billion 2021 to 2028. [13] Nair reports that the global smart lighting market will reach USD 21 billion in 2023, and is expected to grow at a CAGR of 22% from 2018 until 2023. [14] Maximize Market Research reports that smart Lighting Market was valued at USD 10,9 billion in 2021 and is expected to reach USD 48,78 billion. by 2029, at a CAGR of 20,6 % during a forecast period. [23] Following Data Bridge report, the market is expected to witness market growth at a rate of 20.45% in the forecast period of 2021 to 2028. [15] Mordor Intelligence expects the Smart Lighting Market size to be at USD 19,42 billion in 2023, and to reach USD 49,37 billion by 2028, growing at a CAGR of 20,52% during the forecast period (2023-2028). [16] Meticulous Research says that the Smart Lighting Market is expected to reach USD 39,91 billion by 2029, at a CAGR of 12,2% during the period of 2022–29. [17] Transparency Market Research forecasts that the global smart lighting market who was valued over USD 11,29 billion in 2020 will estimated to expand at a CAGR of 20,3% from 2021 to 2031 to cross the value of USD 83,52 billion by the end of 2031. Emergen Research believes that the global market size will reach USD 45,47 billion in 2028 and register a revenue CAGR of 19,7% during the forecast period. [18] Market and Markets analysts said that the global smart lighting market size is estimated to be USD 10,9 billion in 2021 and projected to reach USD 27,7 billion by 2026, at a CAGR of 20,5% during the forecast period. [19] B. Thormundsson, published in Statista that the world smart lighting market will reach USD 43,97 billion by 2030. [20]

Figure 5 combines all the above harvested date and gives a global overview concerning the Global Smart Lighting market size. Based on our data harvested from the literature our forecast shows that the segment will achieve USD 90+ billion by 2035 and this is comparable with the USD 133 billion revenue achieved in 2020 by legacy lighting industry.

Figure 5: Smart Lighting market size as given by different analysts



Source: Data harvesting from literature by G. Zissis, the labels in the graph indicate the source

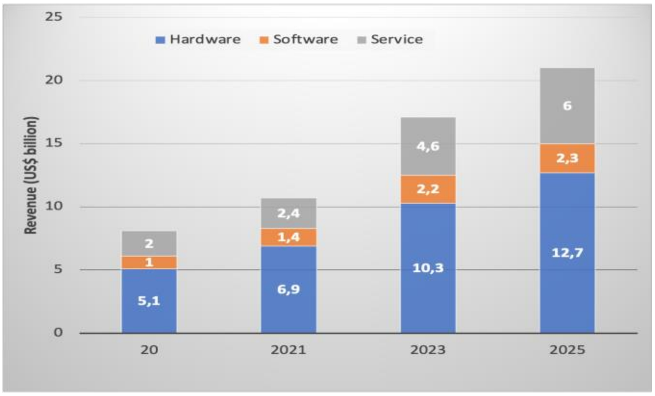
In the literature, smart lighting market is usually decomposed into: (1) Hardware segment, (2) Software segment and (3) Service segment.

The hardware segment is expected to attain the highest revenue contribution in 2020 as lamps and fixtures are an inseparable component of smart lighting. [13] The segment is forecasted to grow from USD 5,1 billion in 2020 to USD 12,7 billion in 2025 at a CAGR of 20%. [11] In 2022, the hardware segment is expected to account for the largest share of the global smart lighting market. The large market share of this segment is mainly attributed to factors such as rising penetration of smart lights, rising demand for intelligent streetlights in developing countries and rising popularity of connected lighting bulbs and fixtures that can change hues, dim lights, and switch on/off using a controlling device such as a smartphone or tablet. [17]

The Software segment is to grow from USD 1 billion to USD 2,9 billion at 22,3% CAGR. [11] The software segment is expected to register the highest CAGR during the 2022-29 period. The software application is required to facilitate the controlling of lights using smartphones or tablets. The apps also help connect smart lights with smart platforms such as Alexa, Crotona, and Siri to control using voice commands. The immense popularity of creating an ambient atmosphere and aiding in data collection in smart cities is expected to boost segment growth over the forecast period. [17]

The services segment is forecasted to grow from USD 2 billion in 2020 to USD 6 billion in 2025 at a CAGR of 24,7 [11] Emergen predicts a CAGR of 20,8%. [18] Figure 6 gives the revenue evolution of the 3 segments from 2020 to 2025.

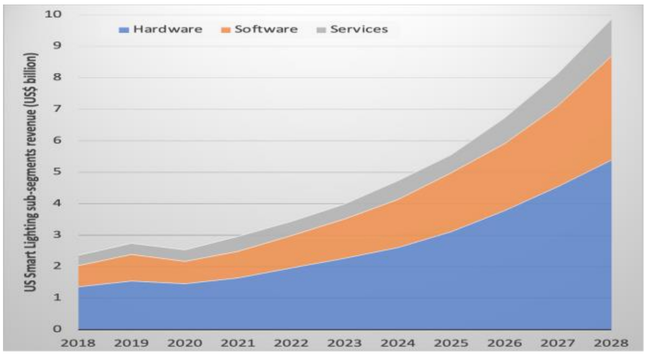
Figure 6: Revenue distribution among the 3 marker sub-segments from 2020 to 2025



Smart lighting is targeting both new Installations and retrofit. That way, mysupplier online publication, forecasted that new installations will grow from USD 5,8 billion in 2020 to USD 14,7 billion in 2025 at 20,6%, when retrofits will expend from USD 2,4 billion to USD 7 billion at 23,7% CAGR in the 5-year 2020-25 period. [11] Further, integrative Lighting systems market is expected to reach USD 3,91 billion by 2024. [21]

In 2019, North America dominated the market, contributing more than a 33% share of the overall revenue. [12] For 2020, Emergent attributed 41,1% of the market shares to this region. [18] Figure 7 gives the USA market split among the 3 usual subsegments.

Figure 7: USA smart lighting revenue by sub-segment



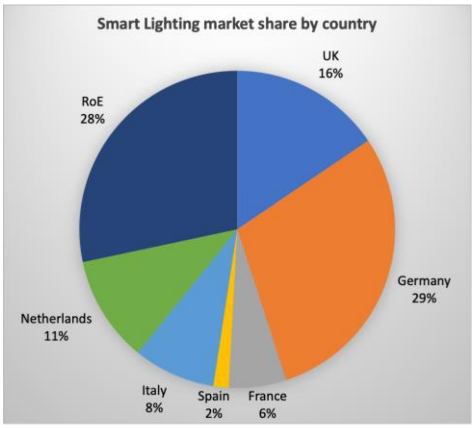
Source: Data from [22]

In 2022 Europe leads the market. [23] However, following [12] The European smart lighting segment is approximately worth USD 2 billion in 2018 and is expected to grow at CAGR of 20% from 2018 to 2024. [14]. A. Gupta, in 2023 gave the European Segment value at USD 4,04 billion. [24] The largest European market in 2021 was Germany. [25] Figure 8 gives the market shares in various European countries.

From 2023 Asia-Pacific (APAC) is expected to dominate the smart lighting market share, garnering 23,70% of the total share. [14] Following Straits Research analysts, the regional market is estimated to reach an expected value of USD 4,6 billion by 2030 at a CAGR of 19,5%. [26] APAC region is expected to witness the highest growth rate owing to the large-scale development of smart city projects in China, Japan, and South Korea. Moreover, increasing investment from India, Singapore, Thailand, and Malaysia to install energy-efficient smart lighting will boost the market growth across Asian countries. [13] APAC region market is expected to grow at a CAGR of 8,5% between 2017 and

2025. [14] China is expected to become the country with the highest market share globally and the highest revenue contribution. Due to their growing economies and significant investments in smart city initiatives, nations like Japan, India, and South Korea are expected to be at the forefront of the adoption of smart lighting. [23]

Figure 8: Smart Lighting market share by country



Source: Data from [SRT-22b]

The global smart lighting controls (hardware) market is expected to grow at a CAGR of 21% from 2018 to 2024. [14] Vantage Market Research predicts that smart lighting control systems sub-segment Size will grow from USD 56,2 billion in 2021, to reach USD 108,5 billion by 2028. This is a CAGR of 11,6%. APAC region shall drive the market growth. [27]

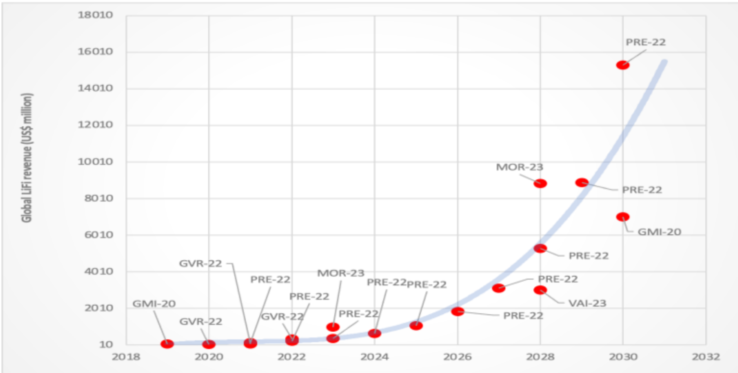
Concerning communication protocols associated to the smart systems, mysupplier predicts that the wired segment is forecasted to grow from USD 5,3 billion in 2020 to USD 13,1 billion in 2025 at 19,6%, while the wireless communication segment's forecast shows a 25% CAGR growth in 2020-25 period, from USD 2,8 billion to USD 8,6 billion. [11] Straits Research analysts forecasted that the wired segment accounted for the largest market share and is estimated to grow at a CAGR of 22,1% during the 2021-29 period. [26]

The global wireless lighting market is estimated at USD 1,32 billion in 2022. Sales of wireless lighting are expected to increase at a 3,48% CAGR over 2022-32 10-year period to reach USD 1,85 billion by 2032. [28] North America currently dominates the wireless lighting market, which is attributed to the presence of leading manufacturers in USA. In addition, there is a high demand for smart lighting across schools, colleges, universities and work spaces. Further, demand for event wireless lighting in Canada is also gaining traction amid high influx of international tourists and rising interest in media and film communities. [28] The wireless control segment shown a penetration of 33% in 2017. But, the segment in the market is anticipated to witness the fastest growth over the forecast period[3]. The growth is attributed to demand for quick connectivity using Z-wave, ZigBee, Wi-Fi, and Bluetooth. [13] It will lead the growth from 2018 onwards. [14] The emerging trend of light fidelity (Li-Fi) technology and the increasing adoption of smart lighting in commercial and residential sectors are expected to create promising opportunities for major vendors in the global smart lighting market during the

[3] The Li-Fi technology was first introduced in the year 2011

forecast period. [29] Li-Fi is a disruptive technology that will affect numerous industries is Li-Fi. The technology can unleash the IoT's potential, enabling Industry 4.0 applications and the lighting sector's impending light-as-a-service (LaaS). This VLC protocol can enable big data and other technologies, including IoT. One year after the LiFi entering the market, the revenue jus just USD 1,8 million. [30] Following Global Markets Insight analysts, Li-Fi Market size exceeded USD 70 million in 2019 and is poised to grow at USD 7 billion with a CAGR of over 50% between 2020 and 2030. [31] The LiFi market size was reached at USD 127,66 million in 2021 and it is expected to reach USD 15,31 billion by 2030 (CAGR of 51%). [32] A more recent analysis (2023) from Mordor Intelligence valuated the global 2023 LiFi market at USD 0,98 billion in 2023 and predicts, higher growth to USD 8,83 billion by 2028, at a CAGR of 55,18% during the forecast period (2023-2028). [30] This can be attributed to an increase in smart and connected devices has generated a large volume of data, straining the capabilities of current Wi-Fi, 5G, and other networking technologies. Therefore, by offering high-speed connectivity, greater capacity, and improved security, Li-Fi technology can resolve these problems. [30] Figure 9 gives a global view of various data harvested from literature.

Figure 9: Global LiFi market size as given by different analysts



7.4 Smart lighting, energy and market impacts

Smart lighting is a lighting technology designed for energy efficiency. At a first glance, to save energy controls of various technologies can be coupled with sensors. Occupancy and Motion sensors detect the presence of people in a room and automatically turn lights on or off based on occupancy. This is particularly useful in spaces like hallways, bathrooms, corridors and also in parking spaces, where lights can be automatically turned off when the space is empty. This kind of sensors are also installed some time in streetlighting configurations. Ambient Light sensors are used Daylight Harvesting in buildings. This technique involves using sensors to measure the amount of natural light entering a space and then adjusting artificial lighting levels accordingly. The objective is to maintain a consistent light level while minimizing energy usage. Arrow Intelligent Systems, based on 2016's sensors technologies estimated that use of sensors can achieve nice energy savings and Table 1 shows these estimations. In addition, legacy “dummy” (personal tuning) controls can save up to 21% of energy and any combination of those techniques can to higher savings. [33]. Today, five years later, the use of sensors allows to achieve much higher savings.

Table 1: Potential energy savings using sensors combined with controls in 2016

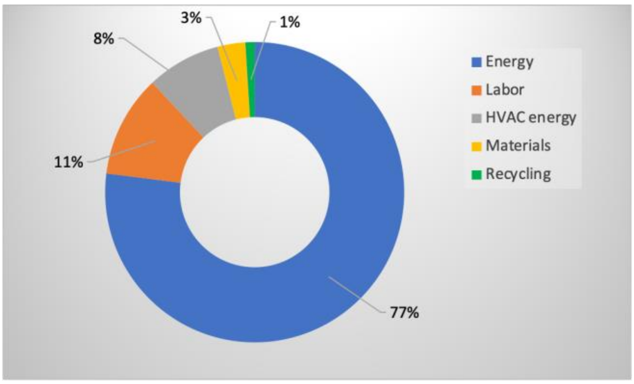
Sensor	Action	Savings
Occupancy	Adjustment of light levels according to the presence of occupants	24%
Ambient Light	Adjustment of light levels automatically in response to presence of natural light. This also called daylight harvesting.	28%
Centralized control	Adjustment of light levels, through commissioning and technology to meet location specific needs or building policies.	36%

Following Nair, the global lifecycle impact of smart LED lighting is still linked to energy use during the full life cycle. [14]

Figure 10 shows a split of the lifecycle impact for smart lighting, it shall be noted in this life cycle assessment study the HVAC power necessary to control temperature variations in light bulbs is included.

Due to the high energy savings, numerous government incentives, as well as, utility rebate programs are now supporting the smart lighting technologies. We are witnessing the transition from simple demonstrators (TRL-5-6) to large installations (TRL 8-9). The following paragraphs give some examples worldwide.

Figure 10: Smart lighting impact on energy within the full life



The governments in the US, Canada, and Mexico have always been promoting a green environment, which has resulted in a large number of smart homes in North America. Over the past few years, the governments of European countries have also been taking initiatives to adopt energy-efficient measures across the region. Regulations stated by the government are in favour of home automation systems. The governments of China, India, Japan, and South Korea are also supporting digitalization and eco-friendly measures to reduce energy consumption. [MAM-22] Additionally, governments of the United Arab Emirates, India, Austria, China, Spain, and Singapore are making huge investments in smart city projects, which is also propelling the advance of the LED lighting market.

Azad et al., estimated that, in USA, with a total labour and materials cost of USD 516 for smart wireless lighting system installation and 41% savings compared to wired solutions, the payback period for the wireless control environment is in the order of 2,3 years. [34] in January 2019, N.Y. Power Authority allocated a fund of USD 7,5 million to municipalities across the state for installing new smart LED street lights. [22] Following Nair, many global general retailers in USA, such as Wal-Mart, Target, and Costco have adopted advanced cloud-based lighting control systems to reduce energy consumption. They successfully reduced annual energy usage from 26,6 TWh to 10,7 TWh or 40,2% reduction of electricity demand. [14]

Globally smart street lighting segment size is in the order of 2-3% of the global IoT for smart city market. A Market and Markets report published in 2022 estimates that the global IoT Smart Cities market is estimated to be in 2021 in the order of USD 130,6 billion and it is forecasted to grow up to USD 312,2 billion by 2026 (19% CAGR in the 5-year period). [35] This is an excellent driver for smart street lighting development. Another analyst predicts, that outdoor lighting applications segment will grow from USD 2,8 billion to USD 8,1 billion at a CAGR of 23,4% within 2020-25 period. [36] An older analysis from SciTech shown that the CAGR was in the order of 2% in the period 2017-21. [21] MKLights relating a TrendForce forecast, estimated that the scale of the smart street lamp market will grow by 18% annually in 2021, and the CAGR will be 14,7% in 2020-25, which is higher than the overall general lighting average. [36] The reality is most probably between those two growth predictions, but we can expect a stabilization in the next decade.

The Singapore government roll out connected street lights in five districts - Tampines and Pasir Ris in the east, Jurong West in the west, and Sembawang and Yishun North near the northern tip of Singapore in 2017 at an estimated cost of USD 1 billion over 10 years. Each district will have about 4 000 to 5 000 connected street lights. In comparison, there were 500 such “smart” connected street lights in Singapore at the end of 2014. [27]

The Indian government has recently announced plans to develop 100 smart cities by 2030 and granted approval to an investment of nearly USD 15 billion for this project. [29] [37] In August 2021, Signify launched a new range of Philips Smart Wi-Fi lights in India. With this, it expanded its Phillips Smart Wi-Fi ecosystem in India under Wiz Smart Light Range. [18]

Similarly, in September 2022, the Government of United Arab Emirates launched a smart city strategy to transform Dubai into a smart city, which includes over 100 initiatives for the development of infrastructure, transport, and communications. [37]

China since 2016, had 542 cities under Smart City development and that number is expected to increase with rising government investment into this industry. It is estimated that the annual amount of investment into Smart City projects will rise from CNY 375,7 billion in 2017 to 1,23 CNY trillion CNY from 2021. [38] This a fabulous driver for smart lighting projects.

In November 2019, in Spain, Barcelona deployed more than 3 000 streetlights based on LED technology. Hence, the increasing development of infrastructure across several countries is bolstering the demand and production of smart lighting solutions, which, in turn, is helping the market advancement globally. [37] The Spanish town of Pozuelo de Alarcón, located 15 kilometres west of Madrid, now benefits from a state-of-the-art, energy-efficient and centrally controllable lighting solution. Tridonic has equipped the municipality with 2,700 smart, dimmable LED drivers for the entire outdoor area. The town can thus save more than 50% in energy costs and take a crucial step closer to its ambitious climate targets. [38]

In Non-residential lighting sector, an early study related by Craig Di Louie, concerned 1 200 control zones in 114 commercial buildings found that networked lighting control systems saved 47% on average in lighting energy, thanks to their intelligence and responsiveness. [40]

In street lighting sector, converting to smart LED lights can save an additional 10-20% over and above the cost savings achieved with switching to LEDs because smart lights turn on and off more intelligently, adjusting brightness by taking ambient light into account. But there are many more benefits to switching to smart street lights. [41] The dynamics such as rise in demand for intelligent street lighting systems in developing and developed nations, growth in need for energy-efficient lighting systems for sustainable development drive the street-smart lighting market. Reports and Data analysts estimated, in 2022, that the number of smart street lights that would be installed in cities across various countries would reach around 73 million by 2026. [42]

Smart street lights can deliver a wide range of capabilities. Thanks to the Internet of Things (IoT) and connectivity services, safe city solutions enable governments and police departments to better protect their citizens from many threats; from terrorist attacks to natural disasters. Lighting systems equipped with city video cameras can play a decisive role in this evolution because there are almost everywhere in the cities and beyond. Following a Solution Brief from INTEL, video monitoring can help cities better understand traffic and pedestrian patterns, make adjustments, as well as route emergency-response vehicles around congested areas. Street light sensors can provide information about available parking in densely populated areas, as well as monitor vehicles for parking violations without sending personnel out on the street. Street lights with video cameras can aid police in solving crimes after they happen, as well as deter new crimes from occurring. With sound sensors, police can pinpoint specific information, such as gunshots, and then rapidly secure an area. Atlanta, Georgia, has reduced crime by 28% through its use of smart street lights. [41] Street lights can be equipped with sensors that identify toxic chemicals, pollen counts, or air pollution levels. Speaker-equipped lights can be used to warn people in the vicinity of storms or other imminent dangers. Street lights can serve as public aids that provide directions to area shopping or public transit schedules. [41] However, for citizens, the smart lighting with cameras raises primary privacy and surveillance concerns, given the data that could be collected. [43] Further, city budgets are often limited, prohibiting the investment in the transition to smart connected lighting or integrated smart lampposts. Further, the deployment of additional networks (internet, additional power supply) can lead to high costs. [43]

Conclusions

Today, lighting is responsible for an annual worldwide greenhouse gas emission of 1,38 billion metric tons. Electricity demand for lighting is estimated to be in the order of 2 900 TWh (which 13,5% of world's net electricity production) for a global light production of 216 Plmh. It is foreseen that in 2040 the needs for artificial light shall attain almost 285 Plmh corresponding to an increase of 25% in lighting service demand. Further, beyond the implication of lighting in energy, greenhouse gas emissions and depletion of abiotic resources of our planet, artificial lighting, has some additional important side-effects like the light pollution of the skies and the associated erosion of the biotopes.

The challenge for the next decade will be to harness the increase of electricity demand, limit the associated greenhouse gas emissions and avoid undesirable effects on the biotope. The only light source technology evolutions, even supported by ambitious policies, are not sufficient to stem uncontrollable growth. This report illustrates the effect of some regulations and policies to harness uncontrollable increase of lighting demand and to the promotion of innovative technologies.

In fact, since 2000's, the rise of Solid-State Lighting (SSL) has been considered as the 3rd revolution in the domain of lighting. The best commercialized non-directional LED lamps are 210 lm/W, over 15 times more efficient than incandescent, 4 times more efficient than compact fluorescent lamps and 2 more efficient than fluorescent tubes. However, this is not sufficient to inhibit the well-known rebound effect. Only the transition from the conventional "analogue" lighting technologies to "digital" lighting can do it!

Smart lighting is becoming the 4th revolution and it will be the heart of the "Internet of Things" in smart cities and smart buildings.

As has been shown by patent and lighting technology shipments evolution, Smart Lighting is on the way to take more and more shares. Smart Lighting can achieve more than 40% additional energy savings in the next decade and the market size can exceed EUR 90 billion by 2030. In Smart Lighting, the residential segment seeks customizable lighting options to create ambiance and cater to individual preferences. As architectural designs become more innovative and intricate, the demand for lighting solutions that complement and accentuate these designs continues to rise. Thus, a significant trend in the architectural lighting market is the increasing adoption of human-centric lighting solutions. In fact, the global user penetration in the comfort and lighting segment of the smart home market continuously increased between 2023 and 2027 by in total 13,2%. The dynamics such as rise in demand for intelligent street lighting systems in developing and developed nations, growth in need for energy-efficient lighting systems for sustainable development drive the street-smart lighting market. Reports and Data analysts estimated, in 2022, that the number of smart street lights that would be installed in cities across various countries would reach around 73 million by 2026. The emerging trend of light fidelity (Li-Fi) technology and the increasing adoption of smart lighting in commercial and residential sectors are expected to create promising opportunities for major vendors in the global smart lighting market. Li-Fi is a disruptive technology that will affect numerous industries is Li-Fi. The technology can unleash the IoT's potential, enabling Industry 4.0 applications and the lighting sector's impending light-as-a-service (LaaS). This VLC protocol can enable big data and other technologies, including IoTs.

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8 Energy efficiency in lighting based on the implementation of MEPS

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Abstract

Minimum energy performance standards for lighting are legislative instruments designed to improve the energy efficiency of lamps on the market. They help eliminate inefficient lamps by setting minimum performance requirements, particularly the luminous efficacy level (lm/W) of lamps that can be placed on the market. The main objective of this paper is to propose minimum energy performance standards for lighting in Morocco and to analyse their energy, economic, and environmental impact. A progressive application of MEPS for lighting is proposed for residential lighting (90 lm/W from 2027, 110 lm/W from 2029, 120 lm/W from 2031) and public lighting (120 lm/W from 2027, 140 lm/W from 2029, 160 lm/W from 2031). The results obtained revealed an energy savings of 8,409 GWh (resp. 4,276 GWh) for residential lighting (resp. public lighting), a reduction in carbon emissions of 6.18 million teqCO2/year (resp. 3.14 million teqCO2/year), a reduction of 19 451 839 (resp. 699 471) in light point changes, and a reduction in peak power demand of over 6 583 MW (resp. 988 MW) over a 10-year evaluation period. This represents a 29% (resp. 28%) reduction in both energy consumption and carbon emissions, an 18% (resp. 8%) reduction in re-lamping, and a 29% (resp. 29%) reduction in peak power. The total economic gain over the project evaluation period amounts to 10 365 million MAD and 6 449 million MAD (The current exchange rate for the Euro is 10.96 MAD), respectively, for residential and public lighting. Authors strongly recommend the MEPS for lighting application across the total national lighting park.

Introduction

Aware of the energy challenges, Morocco has adopted a national energy strategy that aims, among other things, to achieve energy savings of 20% in the key economic sectors [1]. In this context, the building sector is a priority since it accounts for 33% of total final energy consumption, therefore, it represents a potential source of energy efficiency [2], [3].

Lighting will account for around 15% of national electricity consumption in 2021 [3], [4]. This consumption covers residential buildings, the tertiary sector, and public lighting, with 48%, 27% and 25%, respectively. The demand for lighting is constantly increasing as the population grows and lifestyles improve. For example, a survey by the Ministry of Housing and Urban Policy shows an annual increase in housing units of around 130,000 per year [5,6]. This implies an annual increase in energy demand for residential buildings, particularly for lighting, of over 37 GWh, given that electricity consumption for lighting will reach almost 288 kWh per house per year in 2021. Similarly for public lighting, demographic projections drawn up by the High Commission for Planning show a growth rate of 350,000 more inhabitants per year [5]. This increase translates into a growing demand for public roads, with a ratio of 14 inhabitants per light point, which generates an annual electricity consumption of over 20 GWh for lighting, considering a ratio of 818 kWh per light point [7].

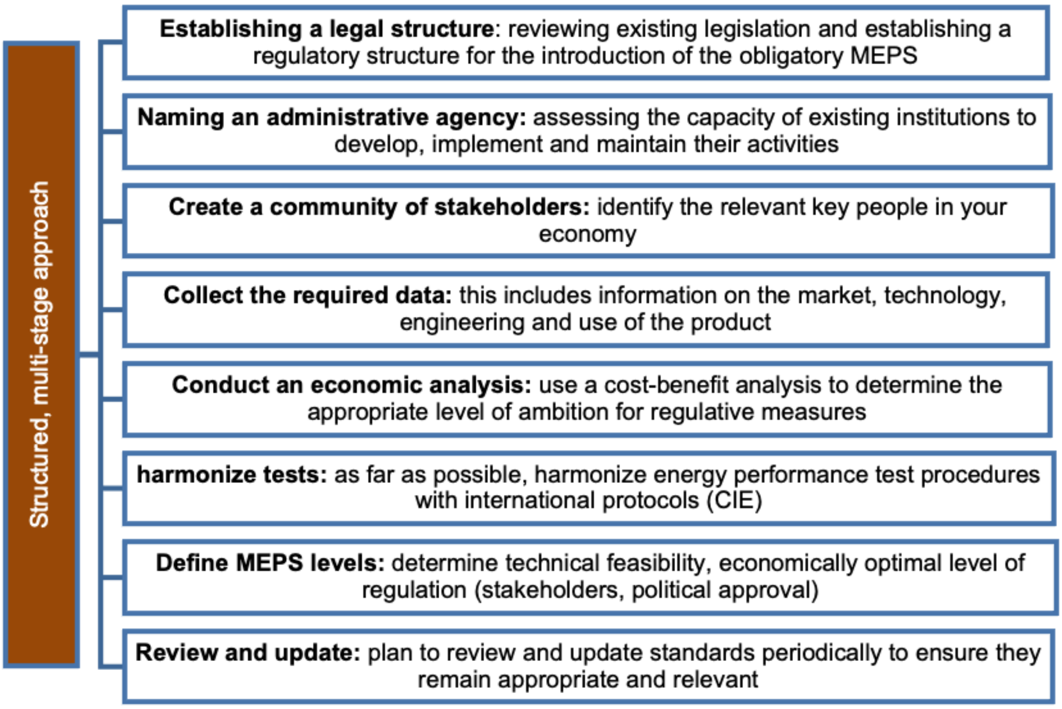
Aware of the importance of rationalizing energy consumption in the lighting sector, Morocco has adopted energy labelling standards, notably NM 14-2-303 [8], aligned with French standards. Class classification, as shown on the energy label, enables consumers to choose products according to their energy efficiency, from the most efficient (class A++ above 120 lm/W) to the least efficient (class E below 9 lm/W). However, since September 1, 2021 France has adopted a new label reverting to a simpler A to G scale, accompanied by stricter luminous efficacy levels above 210 lm/W for class A and above 85 lm/W for class G. Therefore, it is highly advisable to update the legislation periodically so that it is above the technological level, to boost the lighting market towards energy savings and contribute to changing the purchasing practices of suppliers, distributors and in-fine end-users in favour of more energy-efficient lamps.

In fact, one of the most relevant energy efficiency measures for rationalizing lighting power consumption is the adoption of minimum energy performance standards (MEPS). They are legislative instruments designed to improve the energy efficiency of lamps placed on the market, and to eliminate inefficient ones by setting minimum performance requirements, in particular, the luminous efficacy level (lm/W) of lamps that can be placed on the market. These regulations not only help to ensure energy savings in the lighting sector but also contribute to establishing fair competition between economic operators (importers/manufacturers). In this context, Morocco has already introduced MEPS for refrigerators, air conditioners, and, in particular, electric motors with a power rating of over 75 kW in the industrial sector [9].

The international benchmark conducted as part of this study reveals that over 90 countries worldwide, particularly in the MENA region, have adopted MEPS lighting regulations and governance for the deployment of energy-efficient lighting [10]. These countries have announced strategic energy targets and national energy efficiency action plans based on the application of MEPS standards [11], [13]. The benchmark reports that successful implementation of the MEPS regulations is strongly linked to a set of steps to be followed as part of a well-structured, multi-stage approach (figure 1). The impact of MEPS lighting implementation is highly appealing, particularly from an energy and economic point of view. In the case of Tunisia, the application of MEPS lighting regulations is expected to reduce energy consumption related to internal lighting by over 50%, public lighting by between 50% and 60%, and commercial lighting by over 46% [14].

The main objective of this research paper is to propose minimum energy performance standards for lighting in Morocco for residential, tertiary, and public buildings. In addition, a comparative analysis of the energy, economic, and environmental impact of integrating the MEPS scenario versus a baseline scenario without MEPS will be done as part of this research work. The impact analysis will focus mainly on the lighting Park for residential buildings and public lighting.

Figure 1. Process of Implementing MEPS – Lighting [12]



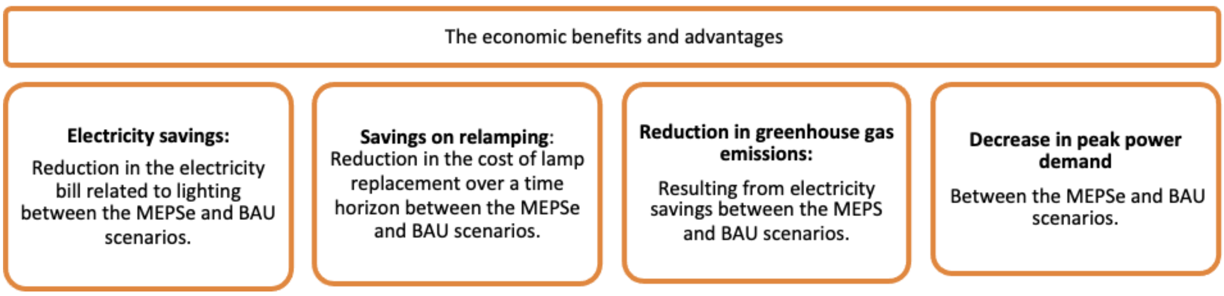
8.1 Materials and Methods

8.1.1 Cost-benefit analysis

This analysis based on a rigorous cost-benefit analysis approach [15] allows us to quantify the costs and benefits resulting from the implementation of MEPS. A comparative approach between the proposed MEPS scenario and the "Business as Usual" (BAU) baseline scenario is adopted for a better understanding of the impacts.

The section below highlights the benefits arising from the implementation of MEPS in the lighting sector:

Figure 2. The Economic Benefits Arising from the Implementation of Lighting MEPS



To illustrate more precisely the previously mentioned benefits, the specific calculation formulas for each benefit are presented below:

<u>Electricity savings</u>: To assess the electricity savings of the MEPS scenario compared to the BAU scenario, the electricity consumption of the former is calculated as follows for each sector:

Residential buildings:

$$EC_{year} = \frac{S_{year} \times Lux}{LE_{lamp}} \times D_{year}$$

Public lighting:

$$EC_{year} = N_{lamps-year} \times P_{avg-lamp} \times D_{year}$$

With:

- EC_{year}: The annual electricity consumption.
- S_{year} : The estimated floor area occupied in the current state.
- Lux: The illuminance requirement of the baseline scenario. It is around 220 lm/m^2.
- LE_{lamp}: The average luminous efficacy of the lighting stock, assumed to be equal to the average luminous efficacy upon importation before the implementation of MEPS. It is equal to the value of MEPS after the progressive application of the project.
- $N_{lamps-year}$: The estimated number of lamps in the public lighting stock.
- $P_{avg-lamp}$: The average power installed per lamp.
- D_{year}: The annual illumination duration considered for each sector.

Reduction in CO_2 emissions gain: obtained by multiplying the energy savings gain in kWh by the factor of 0.735 gCO_2/kWh [15]

Relamping gain: The key element is to estimate the annual number of lamps to be replaced using the following formula for both sectors:

$$N = \frac{N_{lamps-year} \times D_{year}}{L_{lamp-avg}}$$

With:

N: The number of lamps to be replaced.

$N_{lamps-year}$: The total estimated number of lamps in each sector.

$L_{lamp-avg}$: is a weighted average lifespan of the lamps comprising the lighting park by multiplying the lifespan of each lamp by its percentage at importation.

The annual relamping cost for the MEPS scenario and the BAU scenario is found by multiplying the number of lamps to be replaced each year by the average cost of lamps in the lighting park.

Peak power reduction gain: The peak power for both scenarios is obtained using the following formula:

Residential buildings:

$$PP_{\ year} = \frac{S_{\ year} \ \times \ Lux}{LE_{lamp}}$$

Public lighting:

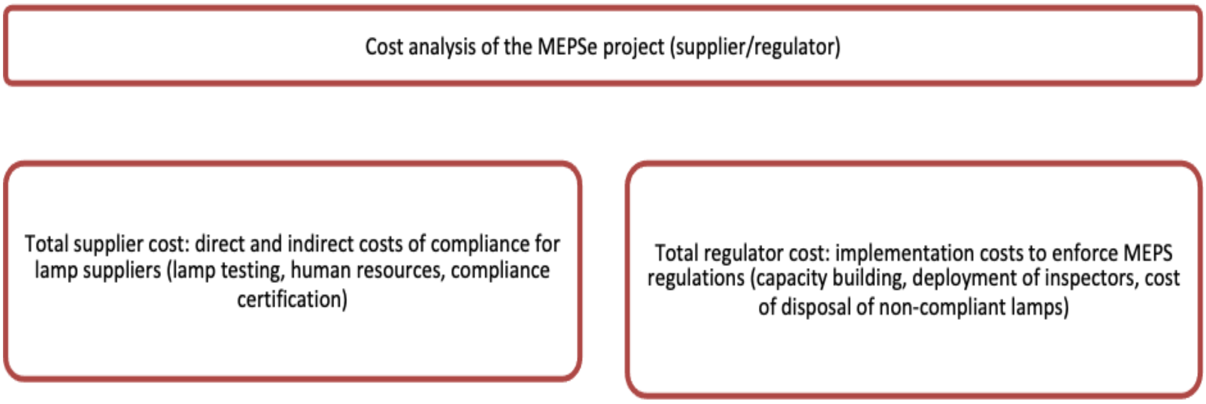
$$PP_{year} = \ N_{lamps-year} \times P_{avg-lamp}$$

With:

- $PP_{\ year}$: The peak power for each scenario.

Regarding the costs resulting from the implementation of the MEPS, we mainly identify costs related to lamp suppliers and others related to the national regulator.

Figure 3: Costs related to the implementation of MEPS for lighting



In this analysis, we will examine the costs and benefits of implementing MEPS for the entire market in both the residential and public lighting sectors. To do this, we primarily consider the following assumptions:

- A 10-year cost-benefit analysis evaluation period for the MEPS project, from 2025 to 2035.
- Progressive application of energy efficiency for each sector as indicated in Table 3.
- An annual lighting duration of 1278 hours for the residential sector and 4326 hours for public lighting.

The lamp characteristics included in the study for each sector are detailed in the following tables.

Table 1. Lamp characteristics utilized in the Analysis - Residential buildings

Lamps		Luminous efficacy (lm/W)	Lamp lifespan (h)	Unit cost upon importation (MAD)[16]
BAU Scenario	Inc.	60	8 500	5,7
	Fluo.	15	1 000	3,3
	LED	75	20 000	6,4
MEPS Scenario	LED	90	25 000	8
	LED	110	25 000	8
	LED	130	25 000	8

Table 2. Lamp Characteristics utilized in the Analysis - Public lighting

Lamps	%	Number [7]	Power (W) [7]	Luminous flux (Lm/PL)	Lamp lifespan (h)	Unit cost (Dh)
SHP 150W	80%	1 269 949	150	16 500	32 000	100
SHP 250W	11%	174 618	250	32 000	25 000	200
LED 135W	9%	142 869	135	16 200	50 000	100
Total/Average	100%	**1 587 437**	-	-	27 250	111

8.2 Results and Discussion

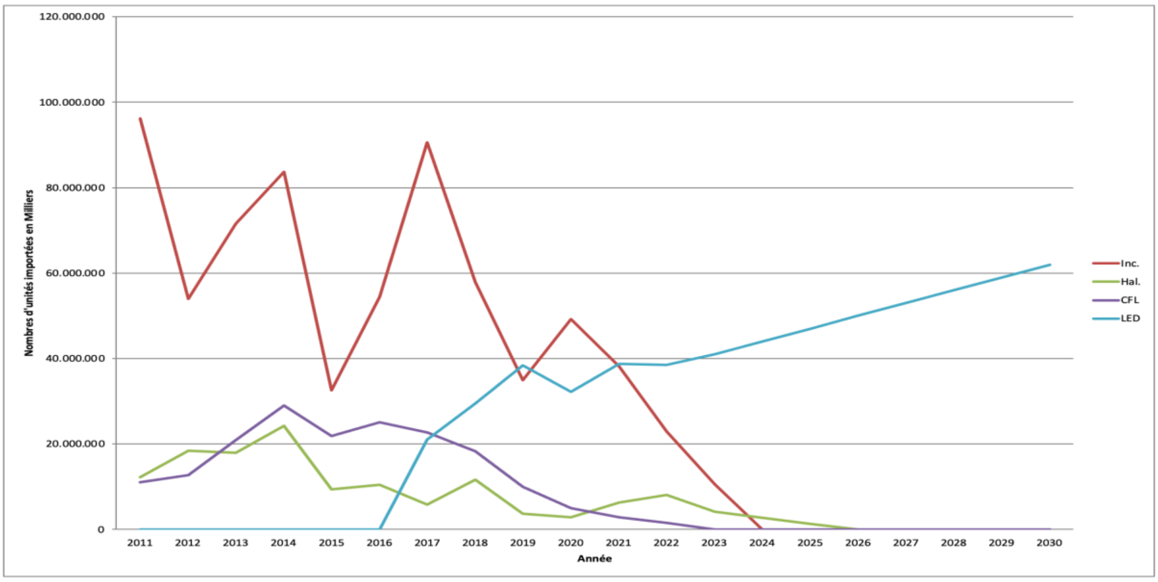
8.2.1 Proposal of minimum energy performance standards for lighting

An appropriate choice of technical specifications to be included in the MEPS lighting regulations remains a decisive step in the success of this MEPS project. Indeed, this parameter will be a decisive lever in eradicating incandescent, halogen, fluorescent lamps, and LED lamps of lower quality.

International benchmark also reflects that while the EU and the UK are already adopting a minimum standard of 90 lm/W for luminous efficacy, the UK has proposed an ambitious plan to increase minimum energy performance for lighting to never before achieved levels, with a target of 120 lm/W from 2023 and a further increase to 140 lm/W by 2027. MENA countries (e.g. Tunisia) are also aligned with European directives on the subject, which require a minimum luminous efficacy threshold of 90 lm/W [18]. India and Indonesia have MEPS for lighting close to the 90 lm/W level, with an actual luminous efficacy of 80 lm/W [19]. On May 24, 2023, South Africa published new efficacy requirements for all General Service Lamps (GSLs), which must achieve at least 90 lm/W. Indeed, the principal energy performance requirement of the proposed technology-neutral MEPS is a minimum efficacy of 90 lm/W under the first level of regulation and 105 lm/W under a more ambitious second level.

At the national level, surveys of the lighting market show that the energy classes of lamps/luminaires most commonly deployed for domestic lighting are at least A+ (70 lm/W and 120 lm/W). For public lighting, on the other hand, the most common energy classes on the market are above A++ (> 120 lm/W). In the tertiary sector, they are well-informed customers already engaged in energy efficiency, most of whom have switched to LED. These results are very well validated by an analysis of import trends. Indeed, time-series-based projections show that incandescent, halogen, and fluorescent lamps are showing a strong downward trend and that within 2 to 3 years, there will be no more imports of this type of technology. In this case, market regulation would be mainly linked to LED technology [17].

Figure 3. Forecasting of lamp technology imports



In addition, a review of experience shows that countries have adopted lighting MEPS on an evolutionary basis. This evolution generally sets an increase in the EL level of 20 lm/W at 2-year intervals. This evolution is crucial to keep a balance between the evolution of technology and the leverage effect of regulations on the lighting market. Moreover, experience shows that the time between the adoption of MPES and their implementation is two years. This period is used to clear stocks of products that do not comply with the specifications set out in the MEPS.

Finally, Table 3 shows the minimum luminous efficacy levels that could be fixed for each type of use:

Table 3. Proposal of minimum energy performance standards MEPS lighting

Year	Residential Lighting	Public lighting	Tertiary Lighting
2025	Developing the legislative text for MEPS lighting		
2026			
The obligation of MEPS lighting			
2027	90 lm/W	120 lm/W	100 lm/W
2029	110 lm/W	140 lm/W	120 lm/W

2031	130 lm/W	160 lm/W	140 lm/W

8.2.2 Analysis of energy, economic, and environmental impact of MEPS lighting

The results of the project cost analysis, namely the costs associated with suppliers and regulators, indicate that they are negligible compared to the benefits. Therefore, only the benefit outcomes will be considered.

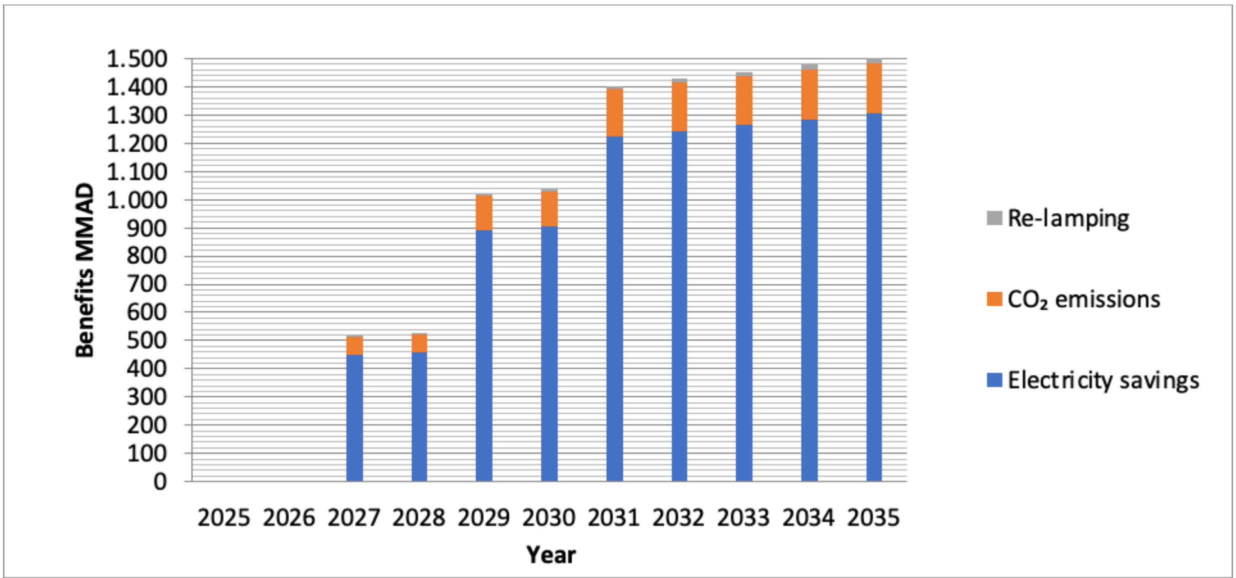
Residential sector

The analysis conducted demonstrates that the total benefits of the MEPS for lighting project for the residential sector during the evaluation period are significant, reaching 10.365 MMAD, mainly derived from energy savings, representing over 87%.

Table 4. Total benefits of the implementation of MEPS – Residential buildings

Benefits	Quantification and Key Figures	Percentage Gain
Electricity savings	Reduction in electricity consumption of 8409 GWh.	29 %
CO_2 Emissions	Reduction in CO_2 emissions of 6.18 million teqCO_2.	29 %
Re-lamping	Reduction in light points changes of 19 451 839.	18 %
Peak power	Reduction in peak power demand of 6583 MW.	29 %

Figure 4. Evolution of Economic Benefits of the MEPS Scenario - Residential buildings



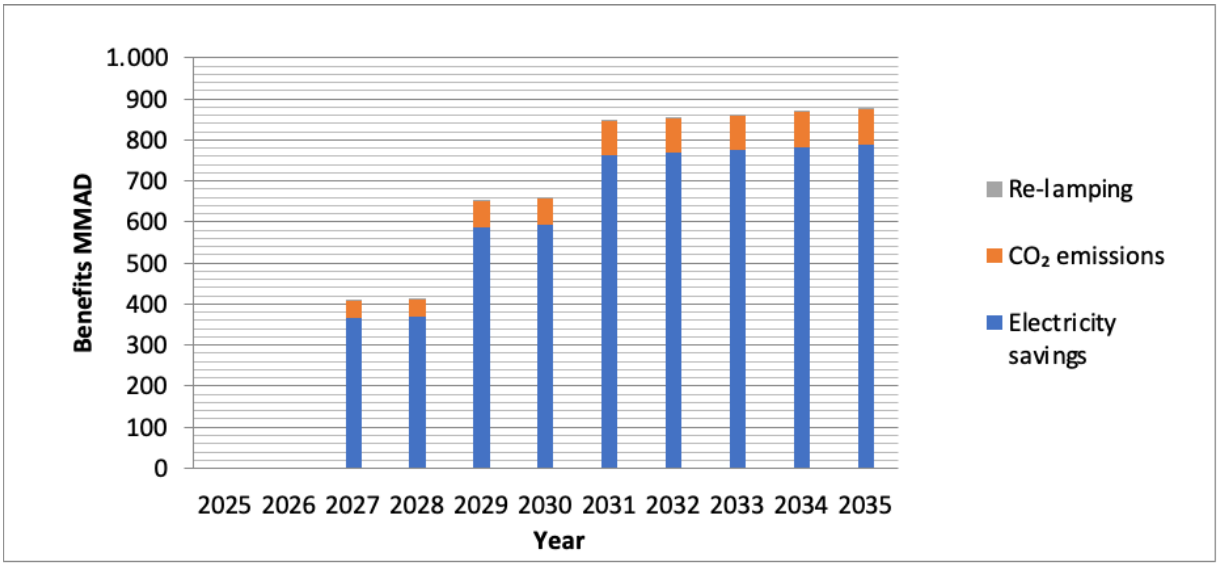
Public lighting

For public lighting, the total benefits brought by the MEPS for lighting project during the entire evaluation period amount to approximately 6.449 MMAD, with a significant contribution from energy savings, representing nearly 90% of the total benefits.

Table 5. Total benefits of the implementation of MEPS – Public lighting

Benefits	Quantification and Key Figures	Percentage Gain
Electricity savings	Reduction in electricity consumption of 4278 GWh.	28 %
CO_2 Emissions	Reduction in CO_2 emissions of 3.14 million teqCO_2.	28 %
Re-lamping	Reduction in light points changes of 699 471.	8 %
Peak power	Reduction in peak power demand of 988 MW.	29 %

Figure 5. Evolution of Economic Benefits of the MEPS Scenario – Public lighting



The two figures illustrate three levels of evolution, corresponding to the gradual implementation of the MEPS for lighting project, with thresholds of 90 lm/W, 110 lm/W, and 130 lm/W for residential lighting, and 120 lm/W, 140 lm/W, and 160 lm/W for public lighting.

The results of the economic evaluation of the MEPS for lighting project compared to the BAU scenario demonstrate its profitability, thereby encouraging the adoption of more energy-efficient LEDs.

In comparison, a recent study conducted in South Africa indicates similarly promising outcomes. Their results suggest that the introduction of MEPS for general lighting is expected to yield significant, positive net economic benefits for the South African economy. Specifically, the total present value of the economic benefits was calculated to be just over R12.1 billion over fifteen years [15].

Additionally, findings from Tunisia suggest a different but significant impact of MEPS lighting regulations. The application of these regulations is anticipated to reduce energy consumption related to internal lighting by over 50%, public lighting by between 50% and 60%, and commercial lighting by over 46% [14].

These variations in results underscore the diverse economic and energy-saving benefits potentially achievable through the implementation of MEPS for lighting across different regions, highlighting the positive impact of MEPS in fostering sustainable energy practices worldwide.

Conclusion

This ambitious project aimed at introducing MEPS for lighting in Morocco and improving lighting efficiency represents a crucial step in the national strategy to achieve significant energy savings. Through a methodical approach, efforts have been made to assess the impact of this initiative on various energy challenges, while promoting the adoption of more efficient lighting technologies.

The main objective of this research paper is to propose minimum energy performance standards for lighting in Morocco for residential, tertiary, and public buildings. In addition, a comparative analysis of the energy, economic, and environmental impact of integrating the MEPS scenario versus a baseline scenario without MEPS was done as part of this research work. The impact analysis focuses mainly on the lighting for residential buildings and public lighting. The main achievements of this research work are given below:

- A progressive application of MEPS for lighting is proposed for residential lighting (90 lm/W from 2027, 110 lm/W from 2029, 120 lm/W from 2031) and public lighting (120 lm/W from 2027, 140 lm/W from 2029, 160 lm/W from 2031)
- The energy saving achieved through the application of MEPS for lighting is about 8,409 GWh (resp. 4,276 GWh) for residential lighting (resp. public lighting). This leads to a reduction in carbon emissions of 6.18 million teqCO2/year and 3.14 million teqCO2/year for, respectively, residential lighting and public lighting.
- The MEPS lighting application will also allow a reduction of 19 451 839 (resp. 699 471) in light point changes and a reduction in peak power demand of over 6 583 MW (resp. 988 MW) over a 10-year evaluation period.
- Expressed in percentages, the application of MEPS for lighting allows a 29% (resp. 28%) reduction in both energy consumption and carbon emissions, an 18% (resp. 8%) reduction in re-lamping, and a 29% (resp. 29%) reduction in peak power.
- Through rigorous cost-benefit analysis, we have found that the introduction of MEPS or lighting has resulted in significant benefits in terms of energy savings for residential lighting (respectively public lighting) of 9,025 MMAD (5,797 MMAD), as well as in terms of CO2 emission reduction of 1,236 MMAD (629 MMAD) and savings on re-lamping of 104 MMAD (23 MMAD).
- The total economic gain over the project evaluation period amounts to 10 365 MMAD and 6 449 million MMAD, respectively, for residential and public lighting.

The results obtained demonstrate not only the financial viability of this analysis but also its crucial importance in transitioning towards more sustainable lighting solutions. Therefore, the authors strongly recommend the MEPS for lighting application across the total national lighting park.

In this perspective, it is essential to pay particular attention to consumer awareness and the implementation of incentive measures. Incentives such as subsidy programs or tax reductions for the purchase of eco-energy products can further encourage the adoption of these technologies.

In summary, this project is significant in pursuing national goals for energy savings and sustainability. By introducing MEPS for lighting, we are contributing to building a more efficient and environmentally friendly energy future for Morocco.

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9 Lessons learned from analysing PED case studies

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Abstract

The development of Positive Energy Districts (PEDs) is a complex process that involves the integration of various technologies, stakeholders, and policies. To facilitate this process, a database for PEDs has been developed as a joint effort of COST Action 'PED-EU-NET', IEA EBC Annex 83, and JPI Urban Europe. This paper reports analyses international strategies for PED planning and its implementation. To learn from best practice examples, there is an increasing demand for PED cases descriptions that offer a variety of implementation strategies and conceptualizations for the PED concept. The collection of case studies from various settings so far has shown that there is no one-fits-all solution for PED implementation, and the overall PED framework definitions require further detailing in the local context. In this paper the challenges and key success factors for planning and implementation of PEDs is described with a focused analysis of three PED cases. One PED case each from Europe, from Canada and from Japan highlights the challenges of PEDs. Similarities and differences of the PED cases are compared and key success factors distilled. Thus, the DNA of PEDs can be further revealed. These are technological solutions, depending on the local circumstances (natural and imposed constraints), planning and implementation processes, and overall local settings (municipality or private sector as a driver) that define the successful implementation of a PED. Overall, the PED-Database provides a valuable tool for the development of sustainable and energy-efficient urban areas.

Introduction

The systematic use of data, the collection of information about enabling factors, barriers and frameworks (regulatory and governmental) are fundamental to support the planning of urban interventions towards climate-neutral transition of our cities. Tackling the challenges of climate neutrality at urban level, the European Commission set out the SET Plan 3.2. which contained several ambitions - i.e. 100 pioneer zero-emissions cities by 2030 [1] and 100 pilot PEDs by 2025 [2] by focusing on implementation and testing of solutions on district-scale and in an efficient, resilient and climate-neutral manner.

In this perspective, there are several international research activities ongoing that try to collect these ambitions, e.g. COST Action (CA) 'PED-EU-NET' [3] in connection with further international initiatives working on PEDs concept; PED initiative, coordinated by JPI UE [4], aims to develop 'Positive Energy Districts and Neighborhoods for Sustainable Urban Development'; 'IEA EBC Annex 83 - Positive Energy Districts' coordinated by IEA EBC [5] - with the aim of mapping PED relevant experiences and collecting key parameters to characterize these districts and support their uptake around Europe and beyond; the European Energy Research Alliance Joint Program on Smart Cities (EERA JPSC) [https://www.eera-sc.eu/], whose mission is to contribute to research and innovation in smart cities by promoting actions, at building, district and city level, that facilitate the transformation of the European built environment towards climate neutrality. In this process, a PED Database (PED DB) (https://pedeu.net/map/) is the outcome of this collaborative research.

9.1 State of the art in PED databases

Studies and researches focusing on PEDs [6-10] underline the emerging need to pass from isolated best practices - i.e., pilot districts - to innovative, systematic, holistic and integrated approaches supporting the planning of green, healthy, efficient, liveable and resilient districts, working in strict connection with the local planning instruments - such as SECAPs, SUMPs, City or District Plans, etc. - and relying on stakeholders expectations and citizens' needs.

Not many tools exist that allow to deepen the knowledge and characterization of PED models. JPI Urban Europe published the PED Booklet with a collection of PEDs case studies [11], structured in two main sections: 'PED Projects' - i.e., cases that have the proper ambition to achieve a positive energy balance and 'Towards PED Projects' - i.e., cases that, even without aiming at an energy surplus, adopt innovative approaches and solutions for efficient and high quality districts. Zhang et al., 2021 [12], analysed the cases mapped in the PED Booklet, based on a matrix for an interoperable and updatable platform able to compare the characteristics and peculiarities of the PED models according to some relevant and specific parameters and to ensure a transversal overview of the analysed cases towards the definition of a series of PED archetypes or models.

The study conducted by Soutullo et al., 2020 [13] focused on mapping of PED Labs - intended as pilot experiences acting as context-specific laboratories to catalyse the grounding of PEDs at local level. Through a SWOT analysis, the research identifies the main strengths, weaknesses, opportunities and threats linked to the 16 investigated laboratories and highlights the need to test solutions in the real environment, in order to evaluate the replicability potential for these experiences in different geographical, social and economic contexts.

As part of the European Cities4PEDs project (https://energy-cities.eu/project/cities4peds/), a catalogue, called 'PED Atlas' [14], was defined. Starting from the identification of 25 PEDs cases. 7 pilots were selected - 3 new construction and 4 regeneration interventions - and for each of them an interviews-based storytelling was drawn highlighting the perspectives of key involved actors, underlying the main lessons learned, barriers and success factors, and extrapolating some recurring PEDs approaches and dynamics.

Still investigating the PED topic, some studies and publications work on the systematic collection and cataloguing of the following key aspects:

1. technologies and solutions for PED effective implementation [15], [17],
2. financing tools and business models to support PED technical feasibility and economic affordability [18], [19]
3. social tools to facilitate stakeholders mapping, to foster citizens' awareness on environmental issues and to support community engagement [20], [21]
4. criteria and performance indicators (KPIs) to monitor and evaluate PEDs impacts on the built environment [22],[25].

9.2 Case studies of energy communities

By shifting the focus of cataloguing tools on Energy Communities (EC) - a transition model in many respects considered similar to PED concept [26], [27], the Joint Research Center (JRC) of the European Commission, following the two Directives that define the EC model at international level [28], [29], has published a preliminary report tracing an overview of 24 Communities distributed in 9 EU countries [30]. The Commission is currently developing an interactive platform, called 'Energy Communities Repository' [31], with the aim of incrementally mapping community ongoing experiences in the European context [32]. Currently the first available online version of the platform consists of a map connected to a detailed sheet for each case study that allows to display the information collected divided in thematic sections - i.e., overall information, activities, governance, energy, economy, social impact and useful links. The above-mentioned studies represent key resources and inspirations to support the PED DB conceptualization, the definition of its relevant contents (e.g., sections, parameters, answer options, etc.) and the selection of the most relevant cases and projects to be mapped and analysed.

This paper focuses on the urgently needed internationalization of the PED model by comparing it with other community or district scale transformation projects. In fact, in continuity with the above mentioned researches, the PED DB has the objective to work towards the dissemination of PEDs practices and it is structured as a comprehensive tool that brings together case studies, projects, solutions, KPIs, policies and strategies to support the large-scale development of innovative pilot districts, working both on the implementation of new interventions and on the large-scale renovation of existing urban areas. It is this international focus (or opposite of focus: widening view) which is urgently needed in order to be able identify the challenges and key success factors for planning and implementation of PEDs. For this purpose, it was chosen to focus on three PED cases from Europe, Canada and Japan to highlight the similarities and differences of PED models and to distill key success factors. Technological solutions, depending on the local circumstances (natural and imposed constraints), planning and implementation processes, and overall local settings (municipality as a driver) that define the successful implementation of a PED are collected and compared. This information will enrich the PED-Database and helps to develop this valuable tool for the development of sustainable and energy-efficient urban areas.

9.3 Methodology

Case studies from different parts of the world. Three specific examples of PEDs from around the world were collected:

1 example from Europe:

A total of six declared PED programmes (Sparcs, RESPONSE, Atelier, MAKING-CITYMAKING-CITY, +CityxChange and POCITYF) were identified within which each contains two case studies selected to be lighthouse cities [33, 34]. The distribution of lighthouse cities per country is as follows: three lighthouse cities are located in Finland, one in Norway, one in Ireland, three in The Netherlands, one in Germany, one in France, one in Spain and one in Portugal. General data on climatic, spatial, urban, infrastructural and renewable energy characteristics were collected and compared with the information obtained from the individual districts through bibliographic sources and by submitting specially created questionnaires to representatives of the individual projects, and the results were grouped under the Lighthouse Cities to which they belonged. The information obtained was then organized according to the climate category of the Köppen Climate Classification to which they pertained. Each city has made different technological, social and spatial planning choices according to its characteristics, needs and implemented policies. As an example, the Finnish case study in Espoo city is selected from the SPARCS project. Espoo (the only case study without a defined historical centre) chose one in an existing area, and one in a new built-up area, such as lighthouse districts, with the aim of turning them into mobility, social and economic nerve centres of the city in SPARCS project) [35]. SPARCS is working to create a network of Sustainable energy Positive & zero cARbon CommunitieS in two lighthouse and five fellow cities. The project supports these cities as they deal with the multifaceted challenges they face on their path to sustainability. By setting up inclusive management and planning models and processes, SPARCS aims to demonstrate and validate innovative solutions for smart and integrated energy systems that will transform these cities into sustainable, zero carbon ecosystems with improved quality of life for their citizens. It will do this by engaging with all the relevant stakeholders from industry and innovative SMEs and research organizations, to urban planning and technical departments. A key criterion for success is citizen involvement, and SPARCS has a clear focus on engaging with citizens and putting urban dwellers at the heart of its efforts.

1 example from America:

The City of London is the fifth largest municipality in Ontario with an estimated population of 422,000. The municipality's 2016 Official Plan established a strategic direction for London to become one of the greenest cities in Canada. Specific policies within the new official plan supported the creation of a Green Strategy as well as a Community Energy Action Plan to support more environmentally friendly and affordable energy usage. West Five is a 28-hectare greenfield property located in the northwest of the City of London. Community planning commenced in the late 1990s with a conventional suburban development form reflecting the market realities of the day. With time, demand for mid-rise and high-rise developments increased. Land use plans for the area began to intensify but around a traditional arterial road pattern. In the mid-2000s, the company Sifton Properties began development of a new vision for the West Five lands as a walkable, mixed-use community. These plans were put on hold after the market crash of 2008 but were renewed again a few years later. In 2015, an application for approval of a draft plan of subdivision and official plan and zoning by-law amendments was submitted by Sifton Properties to the City of London. All planning approvals for West Five, including site plan, were received in 2016. The special policy for the area supported and promoted sustainable and renewable energy initiatives, including solar electricity generation, district heating, ecologically efficient transportation systems, and green infrastructure technology. Consideration of the need for alternative development standards for streets, utilities and infrastructure was also included. Today, West Five has been planned as a complete community including a mixture of office, retail, residential and public open spaces. The community is to be a model of "smart" community design incorporating significant energy saving and renewable energy initiatives to achieve net zero energy. The design is pedestrian-oriented and has numerous green spaces, including a central park. The first net zero energy office building and ~90 townhouses were completed in 2017. The net zero energy vision for the West Five project has been led by Sifton Properties and S2E Technologies; it proceeded any energy policies in the official plan. The financing model was based on the development of a micro-utility through a partnership between Sifton, S2E and London Hydro. The micro-utility provides efficient energy services to the community while externalizing the incremental capital cost of achieving net zero energy from the developer's perspective. The EVE (Electric Vehicle Enclave) PARK project, situated within the West5 sustainable community in London, Ontario, represents a pioneering endeavour to establish a pilot-scale of an all-electric community fueled by solar photovoltaic energy. The private sector project developer S2E has constructed 84 residential units in four separate buildings with eco-friendly materials and surrounding green spaces with a total of 18,823 sqm. As the regulatory framework for electricity distribution and generation differs from that of Europe, establishing such projects is crucial to demonstrate the potential of renewable energy resources such as Solar PV (with a capacity of 499kW in Eve Park and 2.7 MW in West5). The original concept for the microgrid design was a behind-the-meter (BTM) battery, tied to multiple buildings with a DC bus and multiple inverters (one for each building). However, several barriers were identified as the design developed, for example the buildings are separated by a public road and only local distribution companies are allowed to cross public roads with conductors and these companies do not do DC distribution. Regulatory issues with the Ontario Energy Board would have required obtaining an exemption for allowing energy to be moved from BTM of one property to BTM of another property. The idea of using the battery to distribute energy from one building with excess PV generation to one with inadequate PV generation was eclipsed by the community net metering pilot that West Five has entered into with the IESO. These, and other issues led to the redesign of the microgrid as an asset for the 27.6kV medium voltage feeder that supports West Five. This allows a large battery to be located within the microgrid boundary and support buildings on both sides of the public road. The battery is a 2MWh lithium iron phosphate modular system from CATL, tied to a 1.3MW EPC Power Conditioning System (PCS) inverter. A 1.5MVA transformer ties the battery PCS to the feeder. Beyond the imperative of sustainability, EVE PARK's encompasses enhancing resident well-being and quality of life through initiatives such as expansive green spaces and optimal air quality standards. Embracing emissions-free transportation through electric vehicle-sharing programs further underscores the commitment to GHG reduction goals. Crucially, the initiative seeks to foster community engagement and elevate public awareness regarding the numerous benefits of sustainable energy communities. As a pioneer of its kind in Canada, EVE PARK can provide decision-makers with economic and environmental results to pave the way for future development and more flexible regulations in favour of net-zero energy communities.

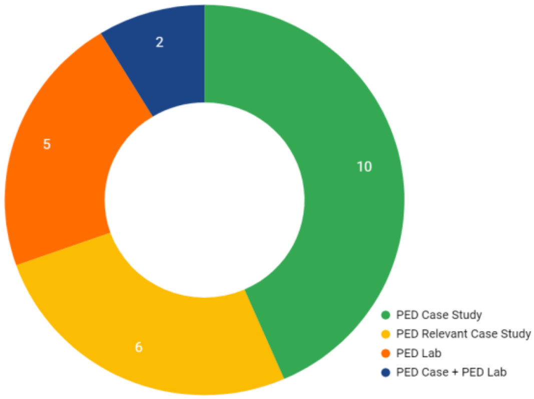
1 example from Asia:

There are many district-scale energy community practices in Japan. However, these are not called PED yet. Compared with the European super grid, the electricity network in Japan is not large. Therefore, the interaction between the districts and the grid are not active enough. Toward achieving the carbon neutral goal in 2050, the Japanese government launched political action to support local municipalities promoting district scale energy management. The government called the proposals from the municipalities and 74 sites are selected as a pilot model until 2023 [36]. These case studies were analysed with regard to PED criteria and compared. This allows users to understand and compare different PED scenarios by customizing their solution, accessing the information provided by real PED cases that best meets their expectations and goals. In this paper the challenges and key success factors for planning and implementation of PEDs is described with a focused analysis of three PED cases. One PED case each from Europe, from Canada and from Japan highlights the challenges of PEDs. Similarities and differences of the PED cases are compared and key success factors distilled. Thus, the DNA of PEDs can be further revealed. These are technological solutions, depending on the local circumstances (natural and imposed constraints), planning and implementation processes, and overall local settings (municipality as a driver) that define the successful implementation of a PED. Overall, the PED-Database provides a valuable tool for the development of sustainable and energy-efficient urban areas.

9.4 Results

The PED platform is set up and running, a first round of data collection is being performed both at case study and project level. Figure 1 gives an overview As first result from the collection of the PED cases in the PED DB, located in 13 different European countries. 10 of them are PED Cases studies, 6 of them were classified as PED relevant, while 6 are PED Labs and 2 of them can be classified as both PED relevant and PED lab. Finland and Spain are currently presented with 4 PED case studies each, while Sweden, Austria, Portugal, and the Netherlands each have 2 case studies. Norway, the Czech Republic, Turkey, Estonia, Italy, Germany, and Greece each have a single PED case study.

Figure 1: Case studies currently included in the database 23 from 13 countries (only including Europe)



The selection of the entries that should be collected by the database was made. This selection was expanded and agreed upon by the different working groups of the initiatives involved, resulting in a list of variables required in different sections of a survey to characterize each case study. These are organized in different sections.

It is structured in the following six sections: 'Section A' which consists of A1. Global Characteristics, A2. Technological Aspects and A3. Non-technological Aspects), 'Section B' which consists of B1. PED Case studies in detail and B2. PED Labs in detail and 'Section C' with C1. Drivers and barriers, 'Section D' on General Projects/Initiatives, 'Section E' on National Policies and Strategies and 'Section F' on Technological and Non-technological related Solutions/Innovations. 'Section D' has been fully developed and integrated into the online platform. Currently, a total of 125 parameters and 462 options are collected in this block and implemented in the online platform.

The designed PED-Database introduces definitions and insights that will guide cities' stakeholders in the creation of capacity at different levels as well as by defining core capabilities. The developed framework provides an understanding of PED concepts, planning values, and functionality criteria to create a learning environment for capacity building and, at the same time, to establish a vision for future districts. The structure developed by this database has generated an interface that shows the results stored in a differentiated way in map or table view. Each of the stored PED developments can be assessed in detail or even compared with other cases, facilitating the identification of common or differentiating elements. Another aspect to highlight is that this web platform facilitates quick access to general project information, as well as identifying the PED cases associated with each project.

9.4.1 Example from Finland

Project choices were influenced by geographical, political and economic reasons. An example of this is the city of Espoo, which (in addition to the Smart Otaniemi programme) joined the Sparcs programme following the city's adhesion to the Covenant of Mayors and chose to buy renewable certified electricity [37]. It means that the city buys electricity from renewable sources (in this case mainly wind), as they are not implemented or implementable in inhabited areas. This is why Espoo is referred to as a virtual PED [37]. From a geographical analysis of the lighthouse cities, these are mainly located in northern and central Europe. This distribution may be due to the fact that northern cities are better prepared (in optimization, optimized planning process, design process, digitization of city infrastructure and co-creation project) for the realization of such projects. In addition, many municipalities in these areas already have sustainable energy planning offices, which are able to implement this type of project by connecting the various actors (technology producers, energy utilities and building developers) in the area. Another factor that would influence this distribution could be the greater number of start-ups and companies that already exist in the area and can guarantee a rapid design and realization of the installations and companies that are able to guarantee the maintenance of the infrastructure over time.

9.4.2 Example from Canada

Using renewable energy sources in the format of an energy community (REC) is not widespread throughout Canada compared to European countries. Reasons are the cheap energy prices, but also legal barriers. But the imperative of developing these resources is undeniable, which arises from the increasing need for electricity because of cases such as, increasing electrification of the building sector, the growing prevalence of Electric Vehicles, and the burgeoning population. Addressing this heightened demand presents a formidable challenge for the centralized utilities in many provinces. The governmental policies and incentives are influential in the development of REC and the associated business model for them. In Canada, the regulations are different in each province, particularly in the energy market structure, incentives, and electricity tariffs. For example, there is a monopoly in Quebec from Hydro Quebec, while Ontario offers a free electricity market and pricing based on auction. The following table compares the differences between the four main provinces' jurisdictions regulating in Canada.

Incentives and regulations in Canada for renewable energy generation

Title	Item	Scale	Building Type	Alberta	British Columbia	Ontario	Quebec
Tariff structure	Fixed	Provincial	Both	*	-	-	-
	Time of Use (ToU)	Provincial	Both	*	-	*	-
	Segmented	Provincial	Both	-	*	*	*
Allowed market models	Auction-based open energy market	Provincial	Both	*	-	*	-
	Government electricity provider	Provincial	Both	-	*	-	*
	Third-party retailer	Provincial	Both	*	-	*	-
Incentives	Net metering	Provincial	Both	*	*	*	*
	Virtual net-metering	Regional	Both	-	-	*	-
	FIT	-	-	-	-	-	-
	Accelerated Capital Cost Allowance (ACCA) tax incentives	Federal	Businesses	*	*	*	*
	Clean Investment Tax Credit	Federal	Businesses	*	*	*	*

	(Clean Technology Investment Tax Credit)						
	Canadian Renewable and Conservation Expense (CRCE) tax incentive	Federal	Businesses	*	*	*	*
	Provincial Tax Exemption	Provincial	Both	-	*	-	-
	Property Assessed Clean Energy (PACE) loan	Regional	Both	*	-	*	-
	Carbon Offset	Provincial	Both	*	-	-	-
	Canada Greener Home Grant (rebate)	Federal	Residential	*	*	*	-
	Canada's greener home loan	Federal	Residential	*	*	*	-
	loan/rebates (per W of solar energy installation)	Regional	Both	*	*	*	-

As shown, Quebec has the least number of incentives for renewable energy development among other Canadian provinces. However, the similarity among them is the existence of net metering as an incentive plan for households to use renewable energy resources. In Ontario, there is no limitation for the capacity of renewable energy sources installed by a single user, and the credits can be transferred up to 12 months to the following bills. It can include a storage system. However, the users are not allowed to use the utility-owned distribution system and wiring. Recently, Ontario started allowing community net metering (virtual net metering) for the case study described (West5) with up to 10 MW capacity limitation for ten years. The maximum renewable energy system capacity is 100 kW in British Columbia and 50 kW in Quebec. In Alberta, the unused credits at the end of the year are paid to the users by the retailer, and the credit price is equal to the electricity provided by the retailer for the system under 150 kW and the hourly wholesale market price for the system from 150 kW up to 5 MW. British Columbia also pays for the annual surplus at CAD 0.106 for 2023. The excess credit will expire in Ontario and Quebec after one and two years, respectively. The West5 and EVE PARK community is considered to be a micro-grid which the electricity is generating within its geographical boundaries. The possibility of trading electricity with the main grid is also met in the design. Considering the Canadian climate which extreme weather in winter, supplying the heating electricity with heat pumps and geothermal energy and battery storage adds resilience to the system.

9.4.3 Example from Japan

The key aims of the sites are not only challenges for carbon neutral, but also creating new jobs in local, raise resiliency for emergent situations such as natural disasters. Ishikari City in Hokkaido is planning to allocate a data centre which is a huge electricity user at the port area and to supply that electricity with renewable energy. The cluster of industries in the planning zone. For Ishikari citizens, the goal is to revitalize the region through sector coupling between the region and public transportation. Another case, Higashi Matsushima City in Fukushima, which is in the moment of declining population reconstruction from the earthquake in 2011, aims to creating new jobs in the city by promoting greening of the natural environment, inviting companies to the fields of new energy industry through the Higashi Matsushima Mirai Tosh Organization (HOPE), a general incorporated association established by the city, the Chamber of Commerce and Industry, and the Social Welfare Council, and by improving transportation systems utilizing next-generation vehicles. The promoting decentralized local energy production and management is an opportunity for regenerating local society. By modifying PED concept to fit for Japanese context, PED can be acceptable. And Kitakyushu city is one of the large industrial cities located in the southern part of Japan. Through collaborating with local small and medium industries and local towns, the city plans to reboot the local industries and regrowth of local economy. The existing office buildings are redeveloped with renewable energy production. Table 1 shows the key technologies of each city. All cities have solar PV generation and CV cars as key technology. Because of the requirements in emergency situations under natural disasters, energy storage is an essential factor rather than grid interaction. From the point of configuration of stakeholders, the city coordinates the consortium including local industries and companies.

Table 1: The main technical data from the three different city districts in Japan

	Ishikari City	**Higashi Matsubara City**	**Kitakyushu City**
Solar PV	Yes	Yes	Yes
Biomass	Yes		Yes
Wind		Yes	Yes
EV	Yes	Yes	Yes
Battery	Yes	Yes	Yes
Hydrogen	Yes		Yes
Microgrid	Yes	Yes	

9.5 Comparison

A comparison of the three different case studies Espoo, Finland; Eve Park, Ontario, Kitakyushu City, Japan was made and is summarized in Tables 1 and 2. Table 2 shows the main technical data of the three case studies while Table 3 summarizes the objectives of the three different sites/districts.

Table 2: The main technical data from the three different case studies (Espoo, Finland; Eve Park, Ontario, Kitakyushu City, Japan) (compare also [38]).

Technical data	**Espoo, SPARCS**	**EVE PARK**	**Kitakyushu City**
Wind	Yes (virtual)	No	Yes
Solar PV	Yes	Yes	Yes
Geothermal	Yes	No	No
Hydrogen	No	No	Yes
Bioenergy	Yes	No	Yes

Waste energy	Yes	No	No
Electrical storage	Yes	Yes	Yes
Heat storage	No	No	???
Heat pumps	Yes	Yes	???
E-mobility	Yes	Yes	Yes
District heating network	Yes	No	???
Combined heat and power	Yes	No	No
Microgrid	???	Yes	???

Table 3. Comparison of the objectives of the three different sites/districts

Objectives	**Espoo, SPARCS**	**EVE PARK**	**Kitakyushu City**
Positive energy	Yes	Yes	
Zero emissions	Yes	Yes	
Energy efficient	Yes	Yes	
Carbon free	Yes	Yes	
Energy flexibility			

9.6 Discussion

The design of the PED database highlights the use of data as enabler for cities to uphold global Agenda 2030 commitments, thus to deploy technology and innovation in a way that ensure sustainability, inclusivity, prosperity and human rights in cities. The collection and use of data can be considered as a support tool for cities enhancing alignment and direction of their plans, increase awareness of their Citizens, Public and Practitioners about future scenarios and address vexing and seemingly intractable problems of urban governance.

The database for PEDs is a joint effort of COST Action 'PED-EU-NET', IEA EBC Annex 83 and JPI Urban Europe to provide a wealth of information about new and refurbished urban environments aiming to produce more energy than they consume. The realization of the PED-Database framework and its online implementation in the form of a web interoperable platform has been designed in a modular way which allows the division of the general survey into smaller and independent sections that facilitate data entry and subsequent processing.

The development process moved through a database development life cycle (DDLC) starting with the scoping phase of establishing requirements expressed as a statement of requirements with the aim to create a framework for data collection from demo cases.

- There is no one-fits-all solution for PED implementation. Overall PED framework definitions require further detailing in the local context. The PED Database provides an overview of not only different implementation strategies, but also existing different conceptualizations and approaches for the PED concept.

- Thanks to contributions, all inputs are collected in the Database, the users of the platform can visualize and compare different scenarios of PEDs by customizing their selection. Before exporting, it can be displayed in the user-friendly frontend of the PED-EU NET Database that covers each KPI resulting from the gathered information by DB editors. Then, the selected comparison can be saved as an output file and successively can be exported as a .csv format file. In this way, users of the tool can select and work on the information that best meets their expectations, goals, and then build their own further storytelling.
- On an international level, more work needs to be done. The concept of PED is not well known outside of Europe. Other concepts like microgrids, or carbon neutral communities need best practice examples to show case costs and benefits.
- The analysis of the collected international cases from Europe, America and Asia, shows on the other hand, there are common features that can be noted. All developments apply solar PV on site and generate electricity. Thus, the district becomes a “prosumer”, producing and consuming electricity. Special rules and regulations occur in microgrids, where electricity trading between the buildings (and their users) is allowed.

Conclusions

Future developments and conclusions

The platform is set up and running, a first round of data collection is being performed both at case study and project level. The designed PED-Database introduces definitions and insights that will guide cities’ stakeholders in the creation of capacity at different levels as well as by defining core capabilities. The developed framework provides an understanding of PED concepts, planning values, and functionality criteria to create a learning environment for capacity building and, at the same time, to establish a vision for future districts. The structure developed by this database has generated an interface that shows the results stored in a differentiated way in map or table view. Each of the stored PED developments can be assessed in detail or even compared with other cases, facilitating the identification of common or differentiating elements. Another aspect to highlight is that this web platform facilitates quick access to general project information, as well as identifying the PED cases associated with each project. PED DB is something updatable/interoperable and can be connected to other tools e.g., interoperable dashboard from (Zhang et al., 2021) [22]. In comparison with EU Energy Communities the PED database is not only trying to map experience, but to comprehend with a deep analysis of each case study. This underlines the different approach that was chosen for the PED database development.

Widening the perspective to global scale

Positive Energy Districts (PEDs) are still a relatively new concept, but they are gaining traction around the world. There are now 23 PED Labs and cases underway in over 13 countries. These are just a few examples of PEDs from around the world. As PEDs become more popular, they are likely to play an increasingly important role in the global transition to a clean and sustainable energy future. Overall, PEDs offer a number of advantages over building-level and city-level approaches to sustainable development. PEDs take a holistic approach that considers the needs of the entire community. This allows for a more coordinated and comprehensive approach to sustainable development, which can help to reach the SDGs more effectively. PEDs can be a more effective way to reach the Sustainable Development Goals (SDGs) than on a building or city level because they take a holistic approach to energy and sustainability. PEDs consider the needs of the entire community, including residents, businesses, and government agencies. This allows for a more coordinated and comprehensive approach to sustainable development. These are global challenges and PEDs offer a good approach to tackle these in a holistic manner. The database will help to spread the examples and identify the key success factors of planning, implementation and monitoring of PEDs.

Replication potential of cases in database

The Database supports a paradigm shift towards an integrated and comprehensive approach to innovation. Even if technology will be an important factor, a transition can only happen if there is also innovation on organisational and societal level. It is therefore important to consider aspects beyond technology. At least three levels need to be integrated that facilitate a structured approach to fostering innovation in PED projects. On the other hand, it might contribute to compatibility, intermobility, scalability, and replicability.

1. Technology – The database can help to define which technology or system solution is needed (components, hard & software, prototypes, incremental improvement or breakthrough, interoperability, etc.).
2. Market - The database can help to show how to organise it it the most effective way (living labs, sandboxes, business models, regulatory frame, market design, socio-economic research, etc.).
3. Transition – The database helps to find answers to the motivation for PEDs (design, retail, community & society, social sciences, education, policy, governance etc.).

These three levels can be further used related to system integration where more than one of the three levels must be covered. The methodologies and approaches, which are used in the different case studies to work on aspects on the different levels should be clearly defined. The work plan and deliverables should reflect all included levels and the potential interconnections between them.

This would give the potential to define replication schemes and highlights the need for setting up interdisciplinary teams including partners and/or experts with different backgrounds (e.g. economy, market design, management, social sciences, and technology) to bring greater value for the project. It is also important that the risk assessments for the projects fully consider all levels involved in the project, not only potential technological aspects.

The different levels can be used to clearly describe research and innovation activities that integrate technology with cross-cutting dimensions. In general, the level represents three domains where barriers to transition may be present.

It would be good to include a PED Readiness assessment in the next step that allows to assess the dynamics of PED developments by measuring the status and the potential for future development towards an “ideal” PED or a sustainable built environment.

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