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Review

A Practical Review to Support the Implementation of Smart Solutions within Neighbourhood Building Stock

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Abstract: The construction industry has witnessed an increase in the use of digital tools and smart solutions, particularly in the realm of building energy automation. While realising the potential benefits of smart cities, a broader scope of smart initiatives is required to support the transition from smart buildings towards smart neighbourhoods, which are considered critical urban development units. To support the interplay of smart solutions between buildings and neighbourhoods, this study aimed to collect and review all the smart solutions presented in existing scientific articles, the technical literature, and realised European projects. These solutions were classified into two main sections, buildings and neighbourhoods, which were investigated through five domains: building-energy-related uses, renewable energy sources, water, waste, and open space management. The quantitative outcomes demonstrated the potential benefits of implementing smart solutions in areas ranging from buildings to neighbourhoods. Moreover, this research concluded that the true enhancement of energy conservation goes beyond the building's energy components and can be genuinely achieved by integrating intelligent neighbourhood elements owing to their strong interdependencies. Future research should assess the effectiveness of these solutions in resource conservation.

Keywords: smart building; smart energy grid; smart energy management; neighbourhood building stock; sustainable development goals

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1. Introduction

The provision of sustainable energy has become the main priority of developing and developed countries, particularly European Union members, which are among the top fossil-fuel-importing countries in the world. According to a Statista report, Europe imported approximately 13.5 million barrels of oil per day in 2021 [1]. Owing to the large amount of carbon dioxide and other harmful environmental emissions it releases, the construction industry has earned a reputation as a serious contributor to global climate change. Furthermore, vintage buildings and inefficient construction materials in the historic neighbourhoods of European countries have spurred a greater need for energy, making them major energy-intensive sectors [2]. These concerns have imposed pressure on European governments and energy markets to seek cost-effective solutions that strike a balance between reducing energy consumption and decarbonising construction activities. Subsequently, in recent years, the construction industry has discovered that the application of digital technologies and smart solutions is a promising approach to reduce the environmental repercussions of buildings and improve the quality of life of residents [3].

The implementation of smart systems utilising information and communication technologies (ICT) can create excellent opportunities to deliver different building- and urban-scale services through an integrated set of smart grids and address the existing challenges hindering the achievement of the sustainable development goals (SDGs) [4]. Technically, when smart and intelligent tools aim to meet sustainability objectives, they can be interpreted within the domain of smart sustainability (also known as digital sustainability).

Therefore, an inclusive program intended to introduce the application of these tools must cover all the committed goals, such as economic, environmental, social, and cultural norms and spiritual values [5,6].

Generally, with the advancement of technology towards digitalisation and smarter devices, more daily activities are being affected by computer tools and intelligent devices. This evolution has caused a significant shift towards more automated and connected ways of living, and increased dependency between humans and technologies [7]. Meanwhile, technologies such as smart grids, machine-learning approaches, the Internet of Things (IoT), and artificial intelligence are clear examples that have transformed daily routines and construction activities in different socioeconomic and environmental contexts [8]. These emerging technologies have added value to urban management by introducing novel methods of responding to urban needs (e.g., distributed energy generation from renewable sources and storage facilities that simplify the response to demand) [9]. With these technological advancements, every point and subject can be read and analysed using sensors, cameras, and software, which is a significant component of an IoT network. It has been alleged [10] that by the year 2030, more than 50 billion devices will be connected to the IoT network, and approximately 52% of users will use smart and digital systems to improve their activities. Therefore, connecting different nodes and elements of smart cities to the Internet is an essential requirement that should be considered in every smart city [11]. Although the myriad benefits of creating these data flows have not yet been fully realised, they are widely regarded as the cornerstone of the transition towards the true development of a smart and efficient city [4]. In other words, digitalisation and smart systems can provide many beneficial tools, and their utilisation should be examined to ensure their alignment with sustainable objectives and to avoid their designation for frivolous purposes [12].

Integrating ICT technologies with building and urban elements has introduced new interactive features to European energy markets, such as dynamic responses to residents' needs and the flexible adjustment of system operations with respect to their internal and external conditions [13]. Similarly, enabling buildings to intelligently optimise their energy usage based on time-of-use electricity tariffs and residents' energy demands has become one of the leading perspectives in this sector [14,15]. For instance, Ref. [16] highlighted the significance of transitioning from conventional building energy design to the deployment of smart heating, ventilation, and air conditioning (HVAC) systems that manage energy demand and generation according to weather conditions, energy grid balance, and residents' needs. This paradigm shift in the building automation process requires a detailed technical guide to define and clarify the required smart readiness levels, thereby enabling data transfer and management in an integrated building energy system. To this end, the European Commission (EC) developed the Smart Readiness Indicator (SRI), a comprehensive descriptor in the Clean Energy for All Europeans package, to define and support smart elements that can be deployed in smart buildings. The SRI report presents a classification of building components that can be automated at different levels to provide more efficient energy operations [17].

However, various research gaps in this context must be investigated. One of the main limitations of using the SRI is that there is no practical or enlightening example to demonstrate the potential percentage of energy reductions that might be obtained by applying the automation list. This lack of a numerical evaluation of the energy performance of smartened buildings may cause discouraging confusion among stakeholders who have no perspective on the final performance of the project. Moreover, alongside the building-scale initiatives outlined in the SRI, there is a broad spectrum of smart solutions at higher scales that can support energy conservation, the integration of renewable energy, and other live elements of the community, which must be considered. However, there is no technical benchmark similar to the SRI that supports these smart initiatives at the community level in a practical manner.

To bridge these research gaps, with a specific reference to projects at the neighbourhood scale, which is considered the most important and practical scale of urban development [18], this research investigates diverse smart solutions and innovative technologies that can support the attainment of global sustainable programmes (i.e., the SDGs) and energy optimisation, both at the building and neighbourhood scales. One of the novelties and contributions of this study is the definition of a clear boundary to confine the domains and elements that can be smartened across the neighbourhood building stock. Moreover, presenting the potential achievements obtained through these smart solutions stimulates the integration of all the elements through the use of ICT. Clarifying the actual definition of smart solutions allows us to distinguish them from common sustainability measurements that have been widely carried out in this context. To this end, a literature review was conducted to collect, from scientific papers, the technical literature, and European projects, all the smart solutions that could be applied at the neighbourhood scale. The structure of this paper is as follows: The methodology of this research is explained in Section 2. Section 3 explores the multifaceted aspects of utilising the collected smart solutions in six community-scale domains, further classified into different smart solutions. Finally, Section 4 concludes and summarises the overview and perspectives obtained from this research.

2. Methodology

There are numerous types of literature reviews, including systematic, cumulative, developmental, and narrative [19]. The first type is used when theoretical objectives and boundaries can be established in advance to eliminate bias and obtain a more reliable set of findings. Cumulative reviews aim to summarise the findings of papers that focus on specific topics, and they often help identify research gaps in the literature. Developmental reviews track the evolutionary trend of a particular issue. Finally, a narrative literature review provides an overview of studies conducted on a particular topic without strict restrictions on the inclusion or exclusion of articles [20].

The methodology used in this study was based on a combination of narrative and systematic literature reviews. As the main objective of this research is to present an elaboration of the use of smart solutions that can be applied across the neighbourhood building stock, it begins by searching scientific articles, the technical literature, and EU projects to find existing smart solutions, which are almost always accompanied by the deployment of novel technologies. In this study, the definition of a smart solution is based on the concept of a smart system. To perform smart actions, a smart system incorporates sensing, actuation, and control functions based on data collected from internal and external sources. As there is no scientific benchmark to confidently determine smart solutions that can be implemented in a neighbourhood, a narrative literature review was conducted to initially encompass all disciplines, the management of which can be bounded in this context.

In the following step, all the smart solutions that can be implemented at the building and neighbourhood scales are separated and thematically classified into five domains, namely, building-energy-related uses, renewable energy sources (RESs), water, waste, and open space management, which are widely discussed in many sustainability protocols. The collection of smart solutions in the search process is based on the answer to the following three research questions (RQs) respecting the sustainability performance of each domain: (i) Which smart solutions can improve each domain? (ii) How can smart solutions improve each domain? (iii) To what extent can these smart solutions improve each domain?

In the following steps, certain filtrations are adapted to exclude smart solutions that are beyond the scope of this study. For instance, although many sustainability protocols deal with improving the economic or mobility elements of a neighbourhood, these issues cannot be incorporated in this context. In addition, there are many neighbourhood planning and regeneration initiatives that may enhance the quality of the neighbourhood’s elements (e.g., proximity of facilities and bus stations). However, based on the above-mentioned definition of smartness, they cannot be considered smart and should be excluded. Figure 1 schematically illustrates the methodology used in this study.

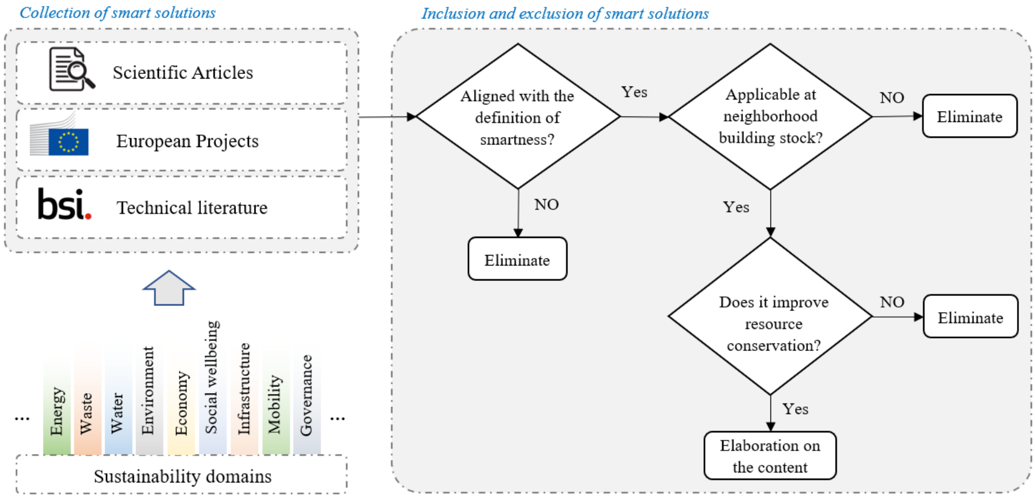

Figure 1. Schematic steps for the inclusion and exclusion of smart solutions.

It should be clarified that the smart solutions collected in this research aimed to delivering a series of smart services that not only enhance human intervention to make smarter decisions but also improve energy conservation (e.g., smart parking systems that steer drivers towards empty slots and reduce the time of use of cars, a smart irrigation system that controls sprinkler operation based on plant needs and reduces energy consumption related to water use).

Finally, smart solutions are organised in thematic order to highlight the constituent elements of each domain, which are also emphasised in different references. Although the availability and advancement of existing smart solutions have not been consistently addressed within different domains, a comprehensive review of the collected documents demonstrates a relative consensus among researchers and urban developers regarding the importance of certain classifications. Moreover, the description given for each smart solution may cover either digital ICT technologies (e.g., optimisation algorithms in design, communication protocols, and mobile applications), physical devices (e.g., sensors and digital screens), or the integration thereof (e.g., smart thermostats). The description also includes some examples of the implementation of smart solutions, presented in tables, to compare their potential benefits with their corresponding base-run scenarios, which are almost all non-smart approaches.

3. Results and Discussion

This section presents smart solutions that have been applied in building and neighbourhood contexts to boost energy conservation in a smart manner. The findings collected from the literature review are organised into two main sections, building-energy-related uses and neighbourhood scales, which are further classified into different domains and smart solutions. As shown in Figure 2, each domain is investigated using one or more smart solutions.

The content of each domain is presented in narrative form such that each domain starts by raising the needs that have prompted the development of smart solutions. As outlined in the methodology, to better structure the content of the collected information describing the smartness of a domain, it is thematically broken down into one or more sets of smart solutions that can be applied. Owing to the interrelationships among different domains, the outcomes of smart solutions may cover direct or indirect impacts on energy conservation (e.g., reducing water consumption and simultaneously reducing the energy required to deliver water), and smart solutions are strictly divided based on the primary subject that they address. In the following sections, a description of the smart solutions collected to answer the RQs is first presented for the buildings and then investigated for the shared area of the neighbourhood, which has five domains in total.

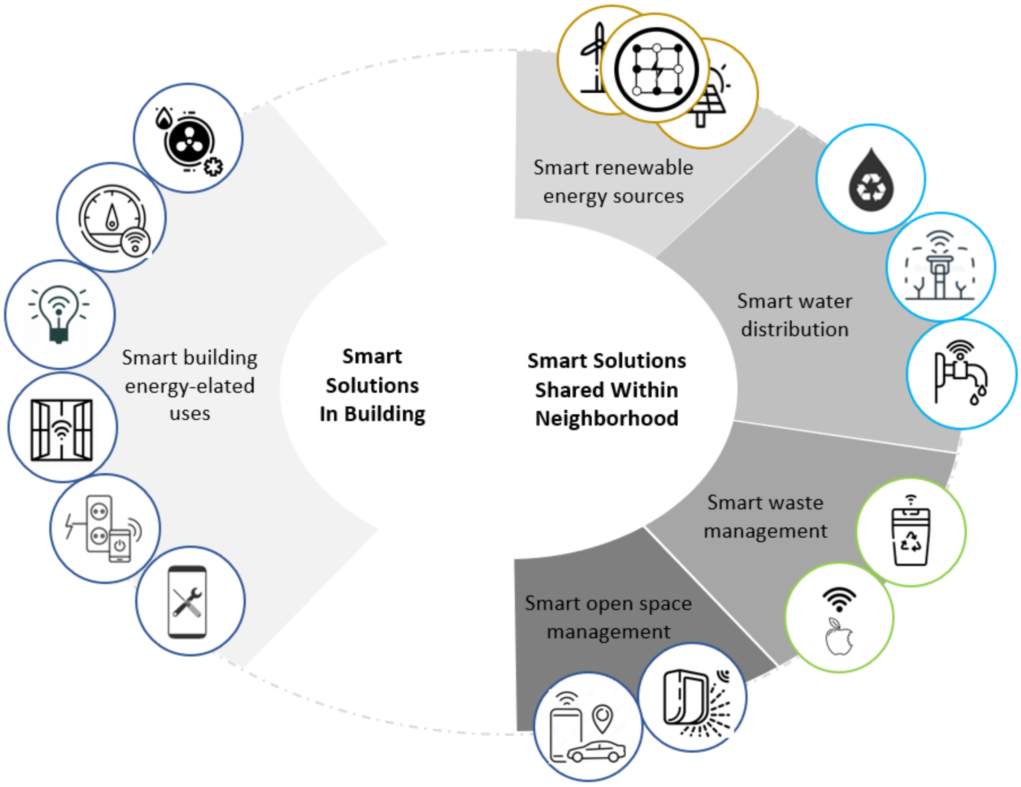

Figure 2. Classification of applicable smart solutions in the neighbourhood building stock.

3.1. *Smart Solutions for Buildings Energy-Related Uses*

With the rapid growth in the urban population, it is estimated that energy consumption in the building sector will increase by approximately 65% by 2050. A study [21] demonstrated that approximately 50% of the total energy consumption in public buildings is related to HVAC systems. The authors of [22] also claimed that the average energy consumption of residential buildings for heating, domestic hot water (DHW), cooling, and lighting was 27.3%, 13.1%, 11.8%, and 7.2%, respectively. The lack of reliability in conventional energy management plans and the manual collection of data related to energy consumption are among the critical obstacles to upgrading building energy systems. In addition to the residents' misbehaviour in the use of energy systems, the low thermal performance and poor quality of building envelopes have often brought about overheating risks or caused high energy consumption due to overcooling. From another perspective, other possible factors, such as the installation of faulty elements, inappropriate adjustment of energy systems, and poor maintenance of equipment, may also lead to a large amount of energy wastage from buildings [23]. In this regard, different control systems and strategies have been proposed to mitigate the operating time, energy consumption, and costs across all elements.

3.1.1. Smart HVAC System

The ultimate goal of smart HVAC systems is to maintain a comfortable indoor environment in terms of temperature and air quality with minimal energy consumption [24]. Previously, the utilities used to create comfortable indoor environments were limited to heating and cooling functions. Indeed, the incorporation of the thermostat and control system allowed for HVAC systems to operate more efficiently. Since then, the introduction of communication technologies to the heating and cooling equipment circuit boards has enabled them to operate more intelligently. In this case, instead of relying on manual control or rigid settings for heating and cooling operations, which often lead to overheating or overcooling in indoor spaces, smart HVAC systems can intelligently adjust their operation based on data collected from the surrounding environment, such as indoor temperature, outdoor temperature, and number of occupants [25].

In particular, for smart ventilation systems, the concept of demand-controlled ventilation (DCV) was introduced to specify the response to the temporal or spatial ventilation needs [26]. DCV strategies can be classified based on the types of sensors, control algorithms, and building regulations [27]. Similarly, Ref. [28] proposed a classification of different ventilation control strategies, including variables such as outdoor temperature, zone occupancy, predicted or measured exposure to contaminants, zonal control (single or multiple zones), dynamic or fixed direction, and rate of airflow (exhaust, supply, balance). For instance, Ref. [29] developed a control system to monitor local occupancy, grid signals, and outdoor temperature. This smart ventilation system, designed for residential buildings in California, achieved a 20% energy reduction and delivered demand response benefits. A comparison of different types of DCV strategies, which include occupancy and contaminant trackers [30], shows that smart ventilation scenarios developed based on zonal control and unzoned control (i.e., supplying the entire dwelling) can reduce energy consumption by approximately 20% and 7%, respectively. The authors of [31] developed an outdoor-temperature-based smart ventilation control strategy to maintain the equivalent indoor air quality, aligned with ASHRAE 62.2-2013; the implementation of this DCV on a two-story residential building delivered an up to 6% reduction in annual energy use. The authors of [32] developed smart ventilation strategies for humidity control, and applied them to near-zero-energy buildings. This study, which evaluated ten smart control strategies across six types of climatic conditions, revealed that smart control systems could reduce the fraction of annual hours of relative humidity (RH) from above to below 60% (in the worst climatic conditions, it was approximately 16%). The authors of [33] developed different smart ventilation strategies based on occupancy detection and auxiliary fans, demonstrating that the energy savings obtained from occupancy control were not significant owing to the intensified recovery period required when residents returned home (i.e., up to double the rate of airflow). Concerning the intensified operation of the ventilation system after re-occupancy, Ref. [34] stated that the energy performance of the occupancy-based ventilation control could be improved if the control strategy automatically turned on the ventilation system at a normal level before the residents' arrival time.

Although the results obtained from these strategies can vary between different climatic conditions [35], smart ventilation systems often provide significant energy savings in all situations, except for climates with fewer seasonal temperature variations.

In light of this trend, based on the specific goal of the control system, the following parameters can be obtained from sensors installed indoors and outdoors and signals in energy grids: (i) occupancy, (ii) air quality conditions (e.g., parameters such as humidity and temperature), (iii) electricity grid status, (iv) contaminants, and (v) the operation of HVAC systems (e.g., fans, flow rates, and velocity) [35]. Figure 3 shows an example of the general components of the smart HVAC system. To model smart ventilation systems, the recommended values and ranges of the following contextual parameters were obtained based on the daily events and activities of households and extracted from the cited standards and guidelines: occupancy, CO_2 [36], moisture [37], particles [38], generic contaminants [39], and weather conditions [40]. Table 1 illustrates some examples of smart components of HVAC systems.

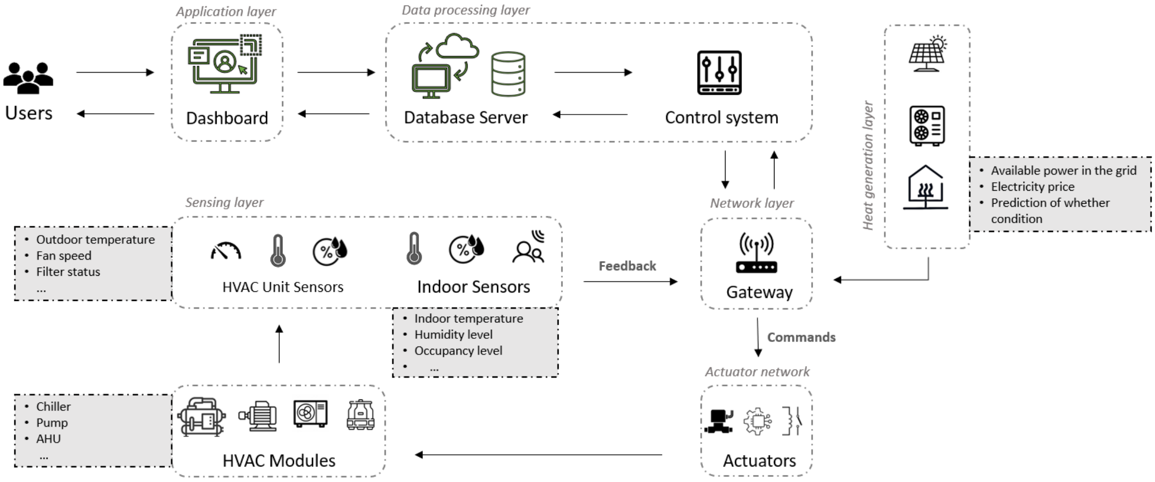

Figure 3. Schematic architecture of data flow in smart HVAC systems.

Table 1. Examples of smart solutions for smart HVAC systems.

Reference	Smart Solutions	Results
[30]	Zone-based in occupancy detection (dwelling).	○ Savings for smart HVAC systems of 0–19%. ○ Savings for ventilation energy of 0–41%. ○ CO_2 reductions between 9 and 19%.
[34]	Occupancy-based control (1–2 story buildings).	○ Up to 15% energy reduction.
[41]	Changing temperature set points and defining two types of real-time tariff (two medium/large households).	○ Energy cost saving of 10.8% ○ 12.8–24.7% saving for peak load ○ 4.3% saving for HVAC systems
[42]	Changing temperature set point by predicting demand response potential (single residential unit).	One-degree setpoint adjustment, which resulted in 2.5% energy savings.
[43]	Changing temperature set points, using humidity-controlled ventilation system (16 apartments).	○ Up to 35% reduction in airflow. ○ No condensation, no RH higher than 43%.
[44]	Relative humidity control, occupancy sensors (31 new apartments).	Approximately 37% of the time: ○ 35% reduction in electricity consumption. ○ 23% reduction in heating needs.
[45]	Control strategies for air handling (multifamily dwellings).	20–30% electricity reduction.
[46]	Using the smart cooling system to customise thermal comfort temperature based on body mass index (BMI) of the residents.	35% energy reduction on average.
[47]	Forecasting indoor temperature, and scheduling different set points using IoT-based solutions to improve the contribution of users (a lab building).	○ 8.1–10.9% energy reduction. ○ 11.3% cost reduction.

3.1.2. Smart Water Management in Buildings

The ultimate goal of smartening water systems in buildings is to measure water flow characteristics and optimise them based on user needs and behaviour. Generally, water consumption can be curbed at a large scale (i.e., infrastructural actions and regulations) and individual conservation scale (i.e., building and community efforts). At the building scale, this can be achieved through the use of advanced meters based on ultrasonic or electromagnetic readings that provide more accurate data (e.g., potential leakages and amount of water consumption) than conventional meters [48,49]. The authors of [50,51] underlined three initiatives that can be achieved by deploying smart water meters: (i) increasing the community awareness of water value, (ii) billing and alternative pricing schemes, and (iii) forecasting water consumption, which results in water and energy preservation. The authors of [52] suggested the use of an in-home display (IHD) to provide real-time feedback to users, resulting in a 16% reduction in water consumption. The authors of [53] also used IHDs to notify users when consumption exceeded predefined limitations and consequently led to a 23% reduction in water use.

In addition to precise measurements, smart water systems designed for buildings incorporate intelligent control systems that automatically adjust the desired temperature and volume of water based on consumption patterns, ensuring that water is used appropriately while minimising energy consumption. By dynamically adapting these to user requirements, these systems can optimise water usage without compromising comfort or convenience [54]. Indeed, in addition to the adaptation of well-established measures, such as the insulation of pipelines, careful planning of draw-off points, and use of renewable energies, there are smart solutions to improve the energy efficiency of DHW systems [55–57]. The authors of [58] reported that, among the types of energy consumed in the European building stock, the energy required for heating and DHW accounted for 64% and 15% of the total energy, respectively. According to this study, resident behaviour and lifestyle have a more significant impact on energy consumption than the type of heat source. To address this issue, Ref. [55] proposed the application of submeters, also known as the individual metering and charging (IMC) of hot water, as a potential solution in a multifamily case study in Poland, and achieved a 20% reduction in the use of DHW. To measure the amount of water accurately, it is necessary to install different sensors and auxiliary devices to collect and transfer data with high accuracy in a short time, particularly when RESs are used to supply the heating required for DHW [55]. An example of a smart solution in this field is presented in [59], which measured the impact of the data collection interval on energy consumption and found that by reducing the interval from 1 min to 6 s, the energy required for peak demand could be reduced by 40%. DHW meters typically quantify and demonstrate the total household consumption that is suitable for calculating bills. Using individual smart sub-meters provides the possibility of transmitting interpretable real-time information to residents, which can significantly reduce their consumption [60,61]. According to [55], the most critical value that can be obtained by a DHW smart meter is the calorific value required for supplying hot water, which requires typical equipment such as temperature sensors, flow meters, computing cores, and communication sectors. This study also introduced other important data that can be collected from servers, such as water temperature and time synchronisation, which can be analysed to deliver valuable information such as endpoints, discarded energy, flow, accumulated, and instantaneous energy. Moreover, Refs. [50,51] underlined three initiatives that can be achieved by deploying smart water meters: (i) increasing community awareness of water value, (ii) billing and alternative pricing schemes, and (iii) forecasting water consumption. Smart water metering can pave the way towards more flexible water pricing methods and resource management.

The authors of [62] claimed that the remote control of boilers equipped with smart sensors helps determine consumption patterns in advance (i.e., the desired temperature, required volume of water, and time of use), which results in water and energy savings. According to [63], which highlighted the 50% heat loss in conventional DHW systems with storage tanks, an efficient effort has been the 4th-generation district heating, which circulates hot water at lower temperatures and subsequently lowers energy use. However, one of the main challenges of low-temperature district heating (LTDH) is the increased risk of Legionella growth [64]. To solve this problem, Ref. [65] suggested using dual-functional residential thermal stations (RTS), in which standby loss is eliminated and the energy provided for the heating system is also used for DHW. In these systems, the control methods of electric tracing can significantly affect the final performance of the system.

Table 2 presents several examples of the application of novel ideas and smart solutions to smarten and enhance the water management system, along with the corresponding benefits that are claimed to be achievable through this approach.

Table 2. Examples of smart solutions in water management systems.

References	Smart Solutions	Results
[52]	Provide IHDs devices to offer real-time consumption data, shifting consumption to the time with the low-price tariff (10,000 households).	○ 16% increase in water consumption. Significant reduce in water bills
[53]	Provide IHDs device, alarm to announce more consumption than predefined limitations (44 households).	27% reduction in water consumption.
[54]	Providing feedback on water consumption and subordinate promoting strategies for water-saving.	Average of 19.6% reduction in water consumption in all related studies.
[55]	Use of sub-meters for accurate reading of energy and flow in discarded hot water (i.e., interval of 1 min). (918 household projects).	○ Increase of 38% in the accuracy of DHW demand measurement. ○ Saving of 3.3% in energy demand. Saving of 5.2% in flow demand.
[64]	Improvement in the conventional DHW system supplied by medium-temperature district heating (i.e., base run scenario: S1) within two scenarios: - Decentralised substation systems with LTDH (S2). - Innovative decentralised substation system with LTDH (S3).	Reduction in annual distribution loss compared to S1: ○ S2: 30%. ○ S3: 39%. OPEX cost reduction: S3: 36% operating cost reduction.
[65]	Development of a control system to manage electric tracing in a residential thermal station (RTS) (one- or two-family dwellings).	31% energy improvement compared to the DHW storage.
[66]	Development of an electric heat tracing system on DHW (a multi-residential building).	○ Reduction of 10% in power use. ○ Reduction of 18% in heat loss. ○ Loss reduction of 34–67%.
[67]	Smart heat pump for heating water.	○ Reduction of 60% in energy consumption. ○ Reduction of 30% in energy cost
[68]	Use of smart water meters with daily report.	○ 13% reduction in water consumption.
[69]	Showerhead prototypes equipped with light and IHD to show duration of shower and water consumption (residential district).	Reduction of approximately 9.6% in DHW consumption.
[70]	Comparison of different types of interventions when translating data to useful information, such as education and providing feedback (221 households).	Intervened group consumed 7.9% less water compared to the control group.
[71]	Providing feedback to consumers through online portal and a comparison with normal consumption.	6.6% drop in water consumption compared to the control group.
[72]	Detailed feedback via an online portal on both electricity and water consumption (Dormitories).	○ 3% average reduction in water use (max 11% reduction in one building). ○ 32% reduction in electricity.
[73]	Wireless data transmission of water consumption to the users.	30% reduction in water consumption and their bills.
[74]	An application of SCADA system and smart water metering.	Reduction in water loss from 40% to 15%.

3.1.3. Smart Lighting Systems

The ultimate goal of smart lighting systems is to provide comfortable and healthy lights based on the specific the environment and occupant demands. A smart lighting system (SLS) may comprise different elements, namely, efficient light sources (i.e., light emitting diodes (LEDs)), as a prerequisite, a smart control system that may include a wireless communication network, software and sensors, and a remote control system that realises specific innovative actions [75]. In light of this trend, Refs. [76,77] concluded that applying an SLS in office buildings could save up to 95% of energy, depending on the activity patterns and type of control system. For example, a control system equipped with the occupancy detection sensors adopted in [78] saved up to 60% of energy. Having highlighted the impact of building and window characteristics (e.g., direction and latitude) on the efficiency of SLSs, Ref. [79] adopted a daylight-integrated lighting control system (i.e., enabling lamps to dim or completely turn off after detecting an adequate amount of natural light) to save up to 47% of energy compared with conventional systems. They calculated energy savings of 35% and 20% through the separate use of occupancy detection and daylight-harvesting sensors, respectively. The authors of [80] analysed the application of a time-based lighting control system, which depends on the clarity of commuting patterns, to save from 10% to 40% of energy in office buildings. Although most projects on SLS have focused on issues related to energy conservation, recently, the examination of residents' well-being has become more significant, and the improvement of features such as the aesthetic aspects of the environment, visual comfort, and light effects beyond vision is actively discussed [81,82]. Table 3 presents the energy efficiency and cost reductions achieved by SLS deployment.

Table 3. Examples of smart solutions for smart lighting systems.

References	Smart Solutions	Results
[65]	Occupancy detection, daylight harvesting, and smart bulbs [1] (single-family home).	23% energy savings.
[78]	Occupancy detection based on users' behaviour and activity pattern (sixty office buildings).	Energy saving for different spaces: ○ 29% for break rooms. ○ 58% for classrooms. ○ 47% for conference rooms. ○ 38% private offices. ○ 59% for restrooms.
[79]	Control system equipped with occupancy detection, daylight-harvesting, and dimming control (deep-plan office building).	○ Occupancy sensors: 35% energy savings. ○ Daylight-harvesting: 20% energy savings. ○ Dimming: 11% energy savings. ○ All together: 42–47% energy savings.
[83]	Daylight harvesting, light quality control, remote control.	○ 54.7% energy savings. ○ Maintaining the desired lighting colour.
[84]	Combination of control (occupancy detection), fault diagnosis, and prognosis module diagnosis.	50% energy savings and increase in the reliability of the system.

[1] Light bulb connected to the Wi-Fi without any external hardware.

3.1.4. Smart Buildings Openings

The ultimate goal of smart building openings is to adjust solar radiation by transmitting, reflecting, and absorbing sunlight through windows. The building can conserve energy and maintain a comfortable environment [85] using movable shading devices or by adopting dimmable glass (also known as smart glass or switchable glass). Although many sustainable design solutions can be applied to design and form a façade that is able to improve the energy performance of buildings (e.g., double-layer air corridors, external and internal insulation layers, windows with low U-values) [86], a building envelope can only be considered intelligent and smart when it can automatically adapt itself to weather conditions, occupant behaviour and needs, and conflicts [87]. Because it is not possible to predict 100% of the environmental and climate conditions, an intelligent envelope system must be able to manage the strategy required to deal with these variables [87]. The control system used for intelligentisation of the envelope should be designed for self-powered sensing, control, and actuation. According to EU Commission projects, smart windows can also provide better natural ventilation [88]. To this end, the volume of air that leaves and enters a room must be managed to mitigate the need for mechanical ventilation. From an architectural perspective, an additional smart solution involves the application of AI technologies to strike a balance between a comfortable environment and energy efficiency by considering the building orientation and opening dimensions for optimal lighting, heating, cooling, and ventilation [89].

Along with this trend, Ref. [90] proposed two new models of smart windows, thermochromic and electrochromic windows, utilising crystal droplets and suspended particles to change glass transparency. The authors of [91] designed a solar smart window system in which flexible photovoltaic cells were installed on one side of the blind and cooling coats on the other side, which led to a 4–9% reduction in temperature during passive cooling performance. Examples of smart windows are listed in Table 4.

Table 4. Examples of the use of novel and smart implementations in the building envelope.

References	Smart Solutions	Results
[88]	Smart shadings to control sunlight.	25% energy reduction.
[89]	Using a feature selection method and game-theoretic method (office building) to find an energy-efficient configuration of envelopes.	Two types of envelopes were proposed, which saved 10.6% and 21.2% of energy.
[90]	Smart thermochromic windows to automatically switch between a heat/light transition state to a blocking state, and vice versa.	8% reduction in energy consumption compared to double-glazed windows.
[92]	Smart thermochromic windows to automatically switch between a heat/light transition state to a blocking state, and vice versa.	35% reduction in energy consumption compared to double-glazed windows.

3.1.5. Smart Electric Device Management Systems

The ultimate goal of smart electricity management in a building is to automatically manage the time and mode of operation of electric devices, aiming to shift loads and reduce electric bills. Although there are several systems that allow for residents to remotely control electric devices through installed actuators (e.g., switching washing machines or ovens on/off through mobile phones), they are merely intended to enhance residents' comfort and are different from interfaces that provide an intelligent reduction in energy consumption [93]. In November 2016, the European Commission updated the application of smart technologies in the Energy Performance of Building Directive (EPBD), which was first introduced in 2002 to optimise energy use in buildings [94,95]. A corollary of this update reveals the potential benefits of smart buildings in creating an intelligent environment integrated with home automation to enhance comfort, safety, and energy efficiency [96]. A significant capability in this area is the collection of data from devices and their processing using heterogeneous and dynamic sources. An advanced IoT-based system can consider variables such as building data, current and the predicted amounts of available renewable energy (in the case of a smart grid), energy prices, weather data, and end-user behaviour to optimise the time and mode of electrical device operation [47]. These optimisations can be designed using a set of rules that are incorporated into intelligent electricity management [97].

Similarly, Ref. [98] showed that demand-side load management, which refers to the shift in residents' consumption towards the period of off-peak demand, can effectively improve the overall energy efficiency. The authors of [99] developed an electricity management tool that provides a personalised plan with awareness services that lead to behavioural changes in users. Several tools are available to support end-user energy management. For instance, Siemens Synco is designed for mixed-use small to medium-sized buildings, in which the control system manages energy plants by monitoring and adjusting HVAC electrical equipment [100]. Honeywell Attune Advisory Services is another monitoring and optimisation tool supported by Software as a Service (SaaS) and cloud-based technologies, which help facilities determine the best way to save resources [101]. These tools are helpful for energy service companies, specialists, and facility managers willing to use the collected data and processed information to make decisions and set rules [102]. Some well-known tools and companies working in this field are as follows: Loop Energy Saver and Origami Energy in the United Kingdom [102,103]; NUUKA and OPTWATTI in Finland [104,105]; Bidgely, Enetics, and PlotWatt in the USA [106–108]; Plugwise in the Netherlands [109]; and SMARAKIA in Spain [110]. Indeed, these tools utilise IoT-based systems to collect and analyse input data and provide monitoring and controlling services, such as data visualisation and notification, that assist users in identifying potential ways to reduce electricity consumption [47].

Another important function that has shown great potential for being smart is the use of metering methods and reporting systems. Because smart meters, such as gas and electricity meters, are often installed in out-of-sight places, installing an IHD, a small monitor displaying valuable and understandable information from smart meters, has been recommended [111]. The authors of [112] alleged that a control system that manages smart meters can analyse and provide valuable information as a virtual assistant for residents, showing defective consumption patterns and discovering energy guzzlers in their homes. The authors of [113,114] helped improve users' insight into their lifestyle by listening to the unique energy signature of homes and subsequently proposing a different series of recommendations, enabling remote control, and automatically turning off electricity. The authors of [115] showed that offering feedback about consumption patterns to consumers can reduce their consumption by approximately 5–15% compared to the baseline. In addition, approximately 64% of the people with smart meters in their homes think twice about the energy consumption of their devices. Table 5 presents the outcomes that specific smart solutions can obtain from a system.

Table 5. Examples of smart technologies in smart electricity management.

References	Smart Solutions	Results
[72]	Detailed feedback via an online portal on both electricity and water consumption (dormitories).	Approximately 32% and 3% reductions, respectively, in electricity and water use.
[116]	Demand–response scheduling model: ○ Time of use. ○ Critical peak pricing. ○ Real-time pricing. (single-family homes).	Reduction in peak–valley difference in energy term: ○ 9.04%. ○ 9.04%. ○ 7.56%. Total energy reduction: ○ 0.29%. ○ 1.07%. ○ 1.52%.
[117]	Smart appliances and different tariffs of use of electricity to shift load (community of 1–2-story residential buildings).	Savings of 10% of energy, with individual savings of up to 20%.
[118]	Using real-time pricing by tariff based on estimated consumption pattern (a city).	Approximately 10.4–17.4% load reduction in peak demand.

Table 5. *Cont.*

References	Smart Solutions	Results
[119]	Individual metering and charging (multifamily buildings).	20% energy savings.
[120]	Individual metering (2400 Danish dwellings).	15–30% heat energy savings.
[121]	Balance between electricity tariffs and CO_2 intensity (30 smart buildings in UK (electricity/thermal storage, boiler, CHP, wind turbines, conventional grid)).	○ 7% bill reduction. ○ 13% CO_2 reduction.
[122]	Direct feedback on energy consumption (a case study region).	○ Approximately 5–15% energy reduction.
[122]	Direct feedback on energy consumption (20 households).	○ 8.1% energy reduction.

3.1.6. Smart Maintenance and Commissioning

The ultimate goal of smartened maintenance and commissioning is to enhance the efficiency of the maintenance and monitoring processes of building services by carrying them out at the right time and in the most cost-effective manner [123]. In light of the technological evolution in different sectors of the building industry, it is vital to progress through the concept of utility services and commissioning to realise the smart maintenance concept. To this end, integrating two well-known terms, lean and smart maintenance, has led to the formation of a dynamic, intelligent, and value-added management model that embraces all building components [124]. The highest step in the maintenance hierarchy is smart maintenance and commissioning, which goes beyond the fixed commissioning plan by embracing the measurements conducted using diagnostic tools integrated into the control system [124]. Indeed, apart from the specialist contractors, an integrated network of IoT devices that are actively patched to the firmware is needed to provide and transfer updates on the operation status of systems within a reasonable timescale to keep the network secure [125]. Therefore, smart maintenance can provide services based on intelligent systems operated by technologies embedded in various urban or buildings elements [126]. To develop a smart management plan, it is necessary to consider the following aspects:

- Data management: Using data generated by cyber-physical systems for predictive maintenance.
- Knowledge management: Externalisation of existing technical knowledge to new labourers.
- Learning orientation: integration of fundamental steps into the maintenance cycle.
- Weak-point elimination: Big data analytics and IT systems are used to eliminate weak points.
- Employee qualifications: Precise qualification of specialists working in maintenance sections.
- Optimisation of maintenance strategy: Optimal decisions between reactive, preventive, predictive, and proactive measurements.

As it is still difficult to explore the benefits of recent smart maintenance and commissioning programs, no quantitative elaborations have been found.

3.2. Smart Solutions Shared within a Neighbourhood

3.2.1. Smart Solutions to Improve Energy Provision

The high energy demand and environmental repercussions of fossil fuel depletion have stimulated the development of renewable energy technologies for many years. Depending on environmental and contextual features, available technologies, and urban management systems, the community may decide to deploy a specific type of RES (i.e., solar, geothermal, wind, biomass, and even hydraulic energy) to generate energy [127,128]. However, uncertainty in the efficiency of the energy generation process makes it difficult to calculate the return on investment (RoI), which discourages investment in this area. Another challenge in this field is the low capacity (i.e., the realised output to the maximum possible output) of renewable power plants. Because of the intermittent nature of renewable sources (e.g., lack of strong winds and cloudy weather), which means that these energy resources are not always available, the capacity factor is often lower than that of fossil-fuel-based plants [129]. This periodic availability of all RESs exacerbates the mismatch between supplied energy and demand, which can make blackouts and low voltages regular occurrences [130,131]. However, enlarging plants and designing them based on peak demand can impose additional financial pressure. In this regard, deciding between underproduction and overproduction in plants has remained a major issue for several years [127]. Nevertheless, smart solutions exist, and innovative ideas can resolve these obstacles.

Smart Renewable Energy Grid

The ultimate goal of smartening a renewable energy grid is to secure the energy supply and improve widespread access to energy without a dependency on fossil fuels. The smart management of renewable power plants relies on the integration of all components in energy generation systems with smart infrastructure, considering different objectives (e.g., energy efficiency improvements and emission control) in real time. As energy management in a smart energy network can be automated by a technical control centre that allows for immediate real-time data transmission and analysis, Refs. [132,133] highlighted the significance of identifying and executing corrective actions to diagnose and prevent errors in time. Although existing renewable energy grid systems may already cover some smart functionalities, such as balancing supply and demand, Ref. [134] demonstrated that achieving a real smart grid system requires the incorporation of ICT into all aspects of electricity supply, delivery, and consumption. In this regard, Ref. [135] classified the application of ICT in the development of renewable energy plants into two imperative disciplines: optimal power flow (OPF) and configuration strategies (CSs); CSs deal with the placement of RESs or generators in the power distribution system, whereas OPF refers to load flow problems and operating conditions. Owing to the uncertain availability of RESs, different ICT technologies and forecasting algorithms have been employed to boost CSs and OPF [136]. The authors of [137] claimed that incorporating a multitude of RESs into a microgrid has potential benefits, such as a greater effectiveness of the local implementation of computational intelligent models, facilitating configuration and fault control, eliminating deep charge problems, and increasing the quality and reliability of power. The authors of [134] demonstrated that, depending on the types of renewable energy and geographical demand profiles, the highest ratio of renewable energy supply to the peak load (defined as the renewable penetration level) in an electricity system can be classified into three levels. The lowest level can be implemented without smart technology, with a capacity penetration of less than 15%. The medium penetration level of renewables is between 15% and 30%, which necessitates the consideration of smart components throughout the grid. The authors of [138] also alleged that incorporating digital tools and innovative designs within a renewable smart grid could secure a capacity penetration higher than 30%.

Moreover, given the high potential for intelligentisation in energy storage, this has become a theme that has stimulated active discussions. The authors of [127] stated that energy storage is a logical solution for saving energy in a system, making variable renewable energy systems more desirable and feasible in existing electrical grid systems among communities. Although electricity can be stored in different storage media, such as batteries, fuel cells [139], flywheels [140,141], and compressed air energy storage (CAES) [140,142], only batteries and fuel cells are appropriate for neighbourhood-scale projects owing to characteristics such as their charge/discharge time and energy density. Although all these systems are equipped with sophisticated pieces of technology, without smart self-control over their performance, they are dumb machines that can only store and discharge energy. A smart energy storage system can be defined based on the following features:

- Self-optimisation and justification of charging and discharging processes based on electricity prices.
- Control of the time and energy source to achieve a longer cycle life.
- Coordination of operations with other storage systems, power plant capacity, and load demands.
- Prediction and prevention of failures and unusual catastrophes that may degrade the battery performance (e.g., thermal runaway and energy imbalance among cells in a battery pack).

Energy storage can benefit from smart solutions that use precise and well-structured data to empower AI systems. Similarly, Ref. [143] clarified that the automation and optimisation of energy storage systems require sufficient knowledge and real-time communication regarding power plant production and consumer load demands. This crucial information enables decentralised decision-making for regulating the microgrid components. These microgrid operations can be executed by a central control, whose main task is to maintain power quality and reliability by regulating the frequency and voltage in the grid [144]. Figure 4 shows an example of the general components of a community-scale microgrid.

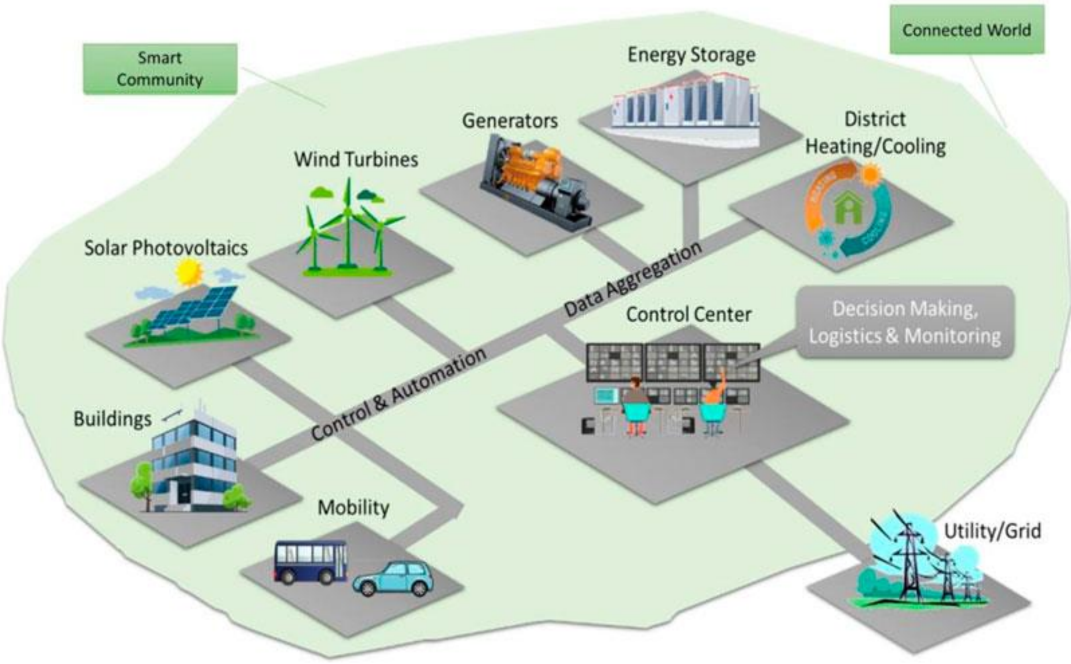

Figure 4. General architecture of a smart energy grid [145].

In addition to the above-mentioned smart solutions, the International Renewable Energy Agency (IRENA) also released guidance for the effective deployment of smart grids and renewable energies, in which the technologies that can be utilised were investigated [134]. Accordingly, IRENA classified the smart technologies related to smart grids into nine groups: advanced metering infrastructure (AMI), advanced electricity pricing, demand response (DR), distribution automation (DA), renewable source forecasting, smart inverters, virtual power plants (VPPs), and microgrids. This report elaborates on these technologies throughout different disciplines, such as maturity levels, market availability, capital and operational costs, and timescales. Table 6 presents the quantitative impacts of the different smart methods introduced in the existing literature on electricity generation from renewable sources.

Table 6. Examples of smart solutions in smart energy grids.

Reference	Smart Solutions	Results
[143]	Application of the adaptive intelligence technique (AIT) in systems with variable energy regulations; use of multiple renewable power plants including wind turbines and PV panels (community micro-grid).	40% overall improvement in energy usage.
[146]	Small-scale microgrid including responsive load demand, energy storage, and two energy sources such as PV panels and wind turbines (home scale).	21% cost reduction in bills.
[147]	Use of game theory and genetic algorithm to optimise the switching sequence and reinforcement among multiple microgrids (supplied by distributed RESs).	○ 60% total cost reduction. ○ 90% reduction in losses.
[148]	Combination of a genetic algorithm and a mixed-integer linear programming to optimise renewable power plants; formulation of grid's constraints to host more renewable sources with lower CO_2 emissions and cost (some buildings considered as energy hubs).	○ 45% CO_2 reduction. ○ Potential for adding an extra 45% of renewable energy. ○ 18% cost reduction.
[149]	Integration of windmill and PV panels; launch of different tariffs on electricity consumption; shift in the peak demands (smart building connected to the smart grid.	○ 48% cost reduction.
[150]	Introduction of the concept of energy hub to integrate distributed renewable energy plants at district level using linear programming.	○ 81–95% CO_2 reduction.
[151]	Shifting daytime cooling load to nighttime cooling storage (meteroplex).	○ 12.2% reduction in fuel consumption.
[152]	Optimisation of discharge power and period of the storage system (office building).	○ 28–48% cost reduction.
[153]	Effect of charging/discharging schedules of battery installation on changing people's behaviour (mid-sized UK family home).	○ 10% reduction in energy bill using PV panels. ○ 38% reduction in energy bill using energy storage system.
[154]	Use of the genetic algorithm approach to optimise the size of the energy storage system and daily operation to increase RoI and minimise the energy consumption; optimisation of charging/discharging profile; different tariffs of use on electricity consumption (a single-family home).	No quantitative results.
[155]	Cost-optimal control and rule-based control for PV self-consumption maximisation (residential low-energy detached house including PV panels, Li-ion battery, thermal and DHW storage).	13–25% reduction in electricity bills.

3.2.2. Smart Solutions to Improve Water Distribution Networks

According to World Bank data, the amount of non-recovery water loss due to leakage and breakage in developing countries is approximately 35–50% of water consumption [156] and related auxiliary energy (water treatment, distribution, etc.) [157]. The intricate system of pipes with different profiles buried in the ground is a major obstacle to better water management. The long-term exposure of cast iron pipes to moist soil may accelerate the corrosion process and reduce their expected useful life. However, a complete replacement of all systems' cast iron pipes, which are, in some cases, more than 120 years old, would impose a huge financial pressure on municipalities; therefore, the inability to diagnose the problem or predict system deterioration requires expensive crisis intervention. In addition to the financial and physical barriers, the global water crisis requires a practically efficient method to address these challenges [158].

Several smart solutions have been proposed. Different advanced technologies can be employed to collect the required data and simulate the performance of water systems. Although retrofitting activities are often managed at the district or city scale, some smart measurements and technologies must be considered and applied at the neighbourhood scale. In the following sections, smart solutions related to water delivery in neighbourhoods are summarised.

Smart Water Distribution Systems

The ultimate goal of smartening a water distribution system is the continuous monitoring and control of the water-supply network and its performance in carrying potable water under effective pressure. According to [128,159], a smart water distribution system addresses two aspects: (i) smart leakage detection and (ii) smart water quality preservation. Smart water distribution systems deploy high-tech equipment and systems to monitor the different characteristics of water flow and abnormalities in distribution network pipelines. Technologies, such as sensors, integrated communication modules, software, and open-source platforms for cloud access, are required [159]. From the perspective of pressure management, which affects the related energy consumption, sensors can also be utilised in different methods to detect abnormal water flow, such as bursts and leakages. To this end, hydraulic-based solutions and acoustic sensing have often been used to analyse variations in the flow and pressure of water at different nodes of the network. For instance, Ref. [160] used wavelet analysis and cumulative sum (CUSUM) (a widely used statistical control method) to identify potential burst events across pipelines by revealing the accurate time of abnormalities in pressure and flows. Because of the high cost of installing sensors, the number of sensors in these models must be optimised and allocated to strategic nodes in the network [161]. Therefore, the smart water grid refers to the smart design and placement of all physical components of the system to realise the operational efficiency of smart water management, as expected and foreseen with smart devices. Figure 5 presents a general perspective of a smart water distribution system in a neighbourhood. Different critical components of the water distribution system (e.g., pumps, valves, tanks, and end-use water taps) can be monitored through a network of sensors, each of which is connected to a microcontroller that can store and interpret the data and send the information wirelessly to desired points (e.g., users or technician teams) [159,162].

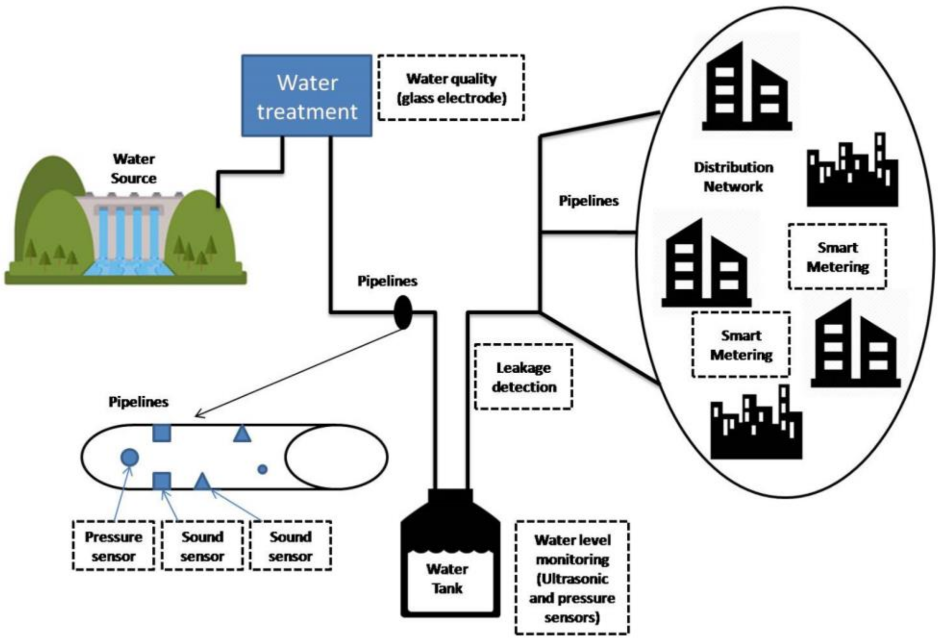

Figure 5. Example of smart solutions in a water distribution system [163].

A practical application of the abovementioned smart solutions is the optimisation of maintenance plans. The authors of [69] identified high-risk pipes based on the likelihood of failure (calculated based on age, material, pressure of the pipes, and type of soil around them) and the consequences of failure (calculated based on the sensitivity of customers to water loss) to optimise the maintenance models. In summary, Ref. [69] listed the following benefits of a smart water grid:

- Real-time monitoring of conditions across pipelines, which enables technicians to apply preventive maintenance at the right time.
- Real-time measurement of water quality and pressure for the early identification of potential contaminants and leakage.
- Automatic control of valves to prevent flooding, damage, water loss, and spread of pollution.
- Real-time feedback on technical measurement to calibrate pumps, and subordinate utilities.

According to [164], deploying a smart supply system in Lisbon reduced nonrecovered water losses by approximately 40%. In a comprehensive review article, Ref. [165] investigated the application of supervisory control and data acquisition (SCADA) in water distribution systems and revealed that deploying real-time alarms and automatic operation plants could result in 30% energy savings and a 20% decrease in water loss. In addition, Ref. [69] leveraged joint time-frequency analysis (JTFA) to analyse the pressure signals collected throughout the sensors for burst event identification within the range of from 3 to 71/s (the burst event is often treated as a discrete occurrence; therefore, the higher the rate, the more accurate the system). The authors of [166,167] highlighted the financial benefits of using smart water technology, which can decrease the initial investment required for water utilities by 12.5%. Table 7 presents examples of the use of smart technologies in neighbourhood-scale water distribution systems.

Table 7. Examples of performance improvements in smart water distribution systems.

References	Smart Solutions	Results
[69]	Use of joint time-frequency (JTFA) approach for burst detection analysed by pressure sensors.	○ Efficient identification of bursts varying from 3 to 71/s.
[159]	Monitoring model to collect data by sensors in a network managed by a powerful microcontroller.	○ More accurate data. ○ Prototype system capable of measuring water flow. ○ Minimal errors.
[168]	- Use of Kalman filtering to detect abnormalities. - Multi-parameter water quality monitoring system. - Accurate flow metering.	○ Online detection of abnormalities in water consumption. ○ Enhanced efficiency of water pipe operation.
[169]	Use of inverse transient to control bursts detected by analysing pressure sensors.	Identification of pipeline burst event of 7.71/s.
[170]	Use of CUSUM and Haar wavelet analysis to measure pressure signals.	Identification of burst event causing leakage from 3 to 8.331/s.
[171]	Commercial leak-detection devices.	○ 30% reduction in water consumption. ○ 25–35% savings in energy used to push water.
[172]	Design of a smart water network.	○ 20% reduction in the average cost. ○ 7.4% reduction in leakages.
[173]	SCADA method: Real-time alarm, automatic control of network operations.	○ 30% saving in energy use. ○ 20% reduction in water loss. ○ 20% reduction in disruption.
[174]	IoT-based water monitoring.	6.66% less water consumption.

Smart Irrigation Controllers

The ultimate goal of smartened water irrigation systems is to automatically adjust the watering volume and time based on environmental conditions (e.g., soil moisture and humidity) and plant needs. Two decades ago, the so-called smart irrigation controllers were developed to implement advanced methods of irrigation for residential and commercial landscapes [175]. Smart irrigation systems comprise different sensor feedbacks and devices to monitor the real site conditions and subsequently collect the required data such as wind, soil moisture, slope, and plant type. Communication protocols transmit these data as inputs to the control system to determine a precise irrigation schedule based on the real needs of the plants and current and future site conditions [166]. This system also includes mobile applications for remote interventions in irrigation management [176]. Machine learning techniques have also been used to manage and operate decision support systems for smart irrigation at a higher level of advancement and require expert knowledge to train algorithms [177,178]. Figure 6 illustrates the general components of a smart irrigation system.

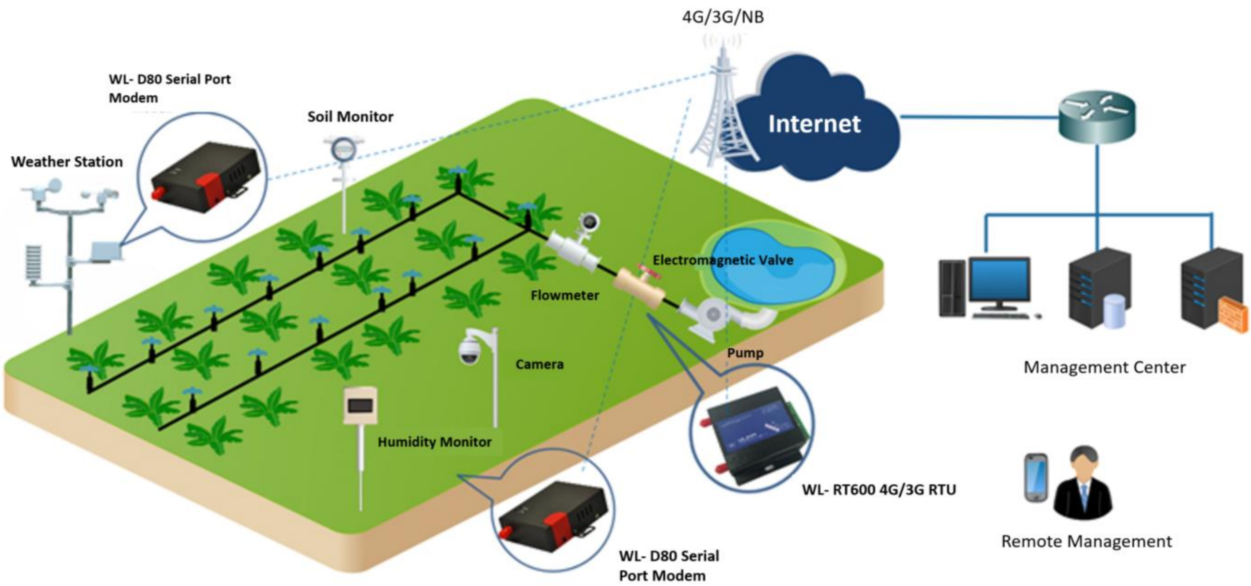

Figure 6. General components of smart irrigation systems [179].

In general, the systems often proposed to monitor and control irrigation systems are based on a dynamic multi-agent system architecture. A multi-agent architecture is capable of merging information from multiple data sources and enables stakeholders to include or exclude new sensors based on landscape requirements [180]. Many research projects have been conducted in this area, some of which were financed by the European Community [181,182]. Table 8 presents examples of the use of smart irrigation controls and their subsequent impact on water conservation.

Table 8. Examples of smart solutions for irrigation control systems.

References	Smart Solutions	Results
[181]	Autonomous sprinklers operating based on field data (sprinkler positions, water pressure, land characteristics, etc.).	Approximately 20–30% reduction in water use.
[182]	Wireless communication and environmental sensors to actuate irrigation at an accurate time and place (farmlands).	21% reduction in water use.
[183]	Smart farming covering weather forecasting, moisture, nutrient content of the soil, watering, and fertilisation scheduling.	20% reduction in water use.

Smart Grey Water Reclamation Systems

The ultimate goal of green water reclamation is to establish and secure reliable treatment systems that can detect abnormal materials in sewage flows, potential risks, and errors. In light of digitalisation and smartness in grey water reclamation, Ref. [184] mentioned the types of components and volumes of sewage flow in the short and long term, which can change because of the diverse steps required for the treatment process. Accordingly, Refs. [185,186] highlighted the use of real-time control in the treatment process, in which anomalies in the components of grey water can be immediately detected and transferred to expert technicians or control systems to take further urgent measures. To this end, different intelligent technologies, such as big data, sensors, IoT, and artificial intelligence methods, may be used, focusing on monitoring and controlling patterns, identifying and diagnosing anomalous plant behaviour and errors, and predicting wastewater inlet flow and required workloads. For example, sensors allow for the acquisition of physical and chemical parameters, such as pH, nitrates, temperature, and ammonium. These parameters can be collected within specific short intervals (e.g., 1 min) in a cloud environment and processed in a higher layer of modules [184].

In addition to using sensors and smart control systems, some novel ICT-based methods are available. For instance, artificial intelligence (AI) technologies have been widely used to reduce the energy and costs of these processes. The authors of [187] employed the data mining (DM) method to optimise the aeration process and reduce the required energy by 31.4%. The authors of [188] also used the DM method to optimise the activated sludge process (ASP), an aerobic biological process, by controlling the dissolved oxygen in the wastewater, which resulted in a 15% reduction in the required airflow. Using an expert system (ES) method in an oxic reactor (i.e., a treatment process with high biogas production and low energy consumption) [189] can reduce total treatment costs and energy consumption by 40%. The authors of [190] also used advanced control in Flemish plants, which resulted in a from 10% to 20% reduction in the energy needed for the aeration process and a 30% reduction in chemical doses. Data collected from the wastewater flow can also be used to calculate the optimal tank water level, which reduces the high pressure behind the pipes in the network and subsequently reduces leakage risks [191].

3.2.3. Smart Solutions for Waste Management

Recycling and reusing materials has been one of the main priorities of municipalities in recent decades, aiming to achieve a circular economy [192,193]. However, limited knowledge of the formal or informal sectors responsible for such activities and a lack of advanced facilities and infrastructure to efficiently collect and sort waste are the two main challenges that have caused inefficiencies in solid waste management, particularly in developing countries [194]. Another critical issue is the open dumping and burning of organic waste in low-income districts and cities, which can be used as a source of waste-to-energy or composting plants [4,195]. Using current methodologies to control composting or sorting and recycling processes is a time-consuming and high-energy task, which requires highly skilled workers [196].

To achieve such sustainability objectives, it is crucial to adopt intelligent measures that can effectively control waste management processes at either the building or neighbourhood scale. Although the application of smart waste management is a city-scale vision that requires sufficiently advanced infrastructure and components (e.g., smart waste collectors equipped with GPS and connected to the sensors of smart bins), some elements should be handled at the neighbourhood scale. The following section presents two smart solutions that can be used in this field.

Smart Waste Bins

The ultimate goal of smartening waste bins is to automate some of the initial steps in the waste management chain, such as minimisation, collection, and separation, in an intelligent manner, which culminates in energy and cost reductions. According to [197], the potential for reducing the amount of unrecycled material is between 30 and 130 kg/y per person. Hence, numerous digital tools have been developed to support the gradual transformation of the "design, use, disposal" model to a circular model in which discarded waste can be recycled and reused [197]. For instance, smart bin deployment can make a direct contribution to waste minimisation by the digital tracking of waste, where residents would be charged based on the content and weight of their trash through the new system of "pay-as-you-throw" (PAYT) [198,199]. This system sends feedback based on the historical data of individuals and introduces different procedures to decrease costs. Berlin introduced the application of radio frequency identification (RFID) to PAYT systems in communities [199]. The authors of [200,201] also highlighted smart bins equipped with other types of technologies, such as sorting features based on image recognition technology (e.g., using sensors to identify waste content or the colour of plastics) and a conveyor belt that separates waste. The authors of [202] introduced a smart bin model in which a solar-powered compacting lever was added to compress the volume of waste by approximately 700% and reduce the collection frequency by 85%. To realise these solutions, the required sensors and devices must be mounted in smart bins. Figure 7 shows a sample of a smart bin equipped with fill-level sensors and solar-powered compactors. In another step in smart waste management that should be supported by a higher administrative level of urban management, data related to the districts' waste containers can be collected through cloud computing and, once processed, the control system can navigate waste trucks towards full containers in an efficient route via a mobile application [203].

Figure 7. Typical components of smart waste bins for transmitting data [204,205].

The authors of [206] presented an application of autonomous sweeping vehicles designed to clean streets and public spaces. These compact-size smart sweepers are often equipped with an odometer and high-precision positioning system (e.g., Global Navigation Satellite System (GNSS)) that enable the control system to adjust the time, position, speed, and attitude of the machine. These smart machines are currently employed on advanced campuses and parks in Beijing, China [207]. Table 9 lists the potential performance of related technologies in different research projects.

Table 9. Examples of smart waste collection systems (e.g., smart bins).

References	Smart Solutions	Results
[197]	Use of neural networks and robotic arms to separate waste, using driverless trucks.	○ Reduction of approximately 20% in unrecycled waste. ○ 30% reduction in demand for landfill capacity. ○ 75% reduction in costs due to transition of materials.
[202]	Smart bins equipped with solar power compactors.	85% reduction in waste collection.
[208]	Development of "pay-as-you-throw" system and radio frequency identification (RFID) for waste collection.	Reduction of approximately 35% in the time required for waste collection.
[209]	Smart bins with fill-level sensors for optimised routes of trucks.	80% less manpower, emission, and fuel used for waste collection.
[210]	Installation of smart bins (urban scale).	50% improvement in waste collection efficiency.
[211]	Analysis of 17 interventions to increase the level of awareness (awareness campaign).	28% reduction in food waste.

Smart Organic Waste Composters

The ultimate goal of a smart organic waste composter is to monitor and control the composting operations by automatically adding the precise amounts of water and air required and reducing human intervention. Generally, the provision of small-scale composting plants in the neighbourhood effectively eliminates the gap between the places where organic waste is generated and where it is processed to produce fertilisers [212]. This system reduces the CO_2 emissions, costs, and energy consumed when collecting and transmitting organic waste. Intelligent composting has been used to monitor and control the moisture and temperature of the process, which are indispensable for obtaining high-quality products [196]. The authors of [196,213] introduced different types of sensors in intelligent composting machines to control air circulation and measure the moisture and temperature of the composting material in different nodes of piles, and subsequently transfer data to the control system through wireless sensor networks (WSNs) in real time. The same procedure was used to build composting plants at different scales, and small machines are now available for households, buildings, and neighbourhoods [212,214]. Although these smart systems can significantly contribute to waste reduction and energy conservation, no quantitative results have been reported regarding the benefits obtained from these smart solutions.

3.2.4. Smart Solutions for Outdoor Spaces

The smart solutions categorised in this domain are those that cannot be included in any specific subjective domain (e.g., buildings and waste) or in building-energy-related uses.

Smart Outdoor Lights

The ultimate goal of smartening outdoor lights is to provide residents with a safe and comfortable environment in shared public areas while reducing energy consumption and light pollution. Smart outdoor lighting fixtures employ special technologies such as cameras, optical sensor photocells, and other sensors to perform real-time monitoring functions and the intended tasks [215]. By providing adequate brightness at the appropriate time, smart outdoor lighting systems not only foster a sense of satisfaction and safety among residents but also reduce energy consumption. The technology used in smart outdoor lighting systems can be similar to general smart lighting technologies, such as motion detection, lighting, and dimming control, and the infrastructure of this system can also be used as the backbone of other activities, such as monitoring weather, air pollution, and traffic [216–218]. Table 10 presents the results obtained from previous related research projects concerning the effect of using smart outdoor lights on energy consumption and cost reductions.

Table 10. Examples of smart technologies in outdoor lighting systems.

References	Smart Solutions	Results
[216]	Not simultaneously turning on all lampposts.	6.7% cost reduction.
[217]	Using LED, adaptive control of illumination level, occupancy detection, and rain sensors.	○ 48% reduction in energy consumption.
[218]	Using LED and different lighting sensors based on occupancy detection and adaptive illumination levels.	○ 84.7% reduction in energy consumption.
[219]	Switching to LED streetlights. Adding smart remote management. Connected street lighting system.	○ 50% reduction in energy consumption. ○ 21% reduction in street crime. ○ 30% reduction in personal injuries.
[220]	Using LED, control of illumination level, occupancy detection.	43% reduction in energy consumption.
[221]	Using LED, control of illumination level, occupancy detection.	From 35% to 55% reduction in energy consumption.
[222]	Examples of street light refurbishment (non-smart).	From 30% to 50% energy reduction.

Smart Parking Systems

The ultimate goal of a smart parking system (SPS) is to provide real-time data on the availability of parking lots for different types of vehicles, such as cars, EVs, and bicycles, in the neighbourhood and surrounding areas to save time and energy and stimulate the use of more efficient vehicles. The authors of [223] alleged that an SPS is one of the fundamental elements of smart mobility, particularly in densely populated neighbourhoods and districts that suffer from a scarcity of parking spaces. An SPS is a good solution for remediating traffic congestion, thus reducing air pollution and the concomitant health risk [224]. In this regard, Ref. [225] used a multi-agent system (MAS) to empower drivers to negotiate parking fees with an SPS based on predefined criteria. The atuhors of [226] employed IoT and RFID tags to develop a car parking framework that provides payment facilities, parking lot retrieval, and security. The authors of [227] used the Global System for Mobile (GSM) to develop a system in which the driver can securely reserve a parking spot using a simple short message (SMS) through a layout animation of parking space occupancy status. The authors of [228] presented a visual vehicle parking space for real-time occupancy detection using a deep convolutional neural network (CNN). These services may be provided on different user interfaces, such as smartphone applications, web applications, and vehicle information and communication systems (VICS). Figure 8 schematically depicts the architecture of an SPS in which all parking spaces are monitored through sensors connected to a control system.

Although these platforms are usually developed for large-scale areas, the facilities and technologies equipped in parking lots can be implemented individually in a single parking area in a neighbourhood. Hence, Ref. [224] reviewed the different types of services that the SPS proposed.

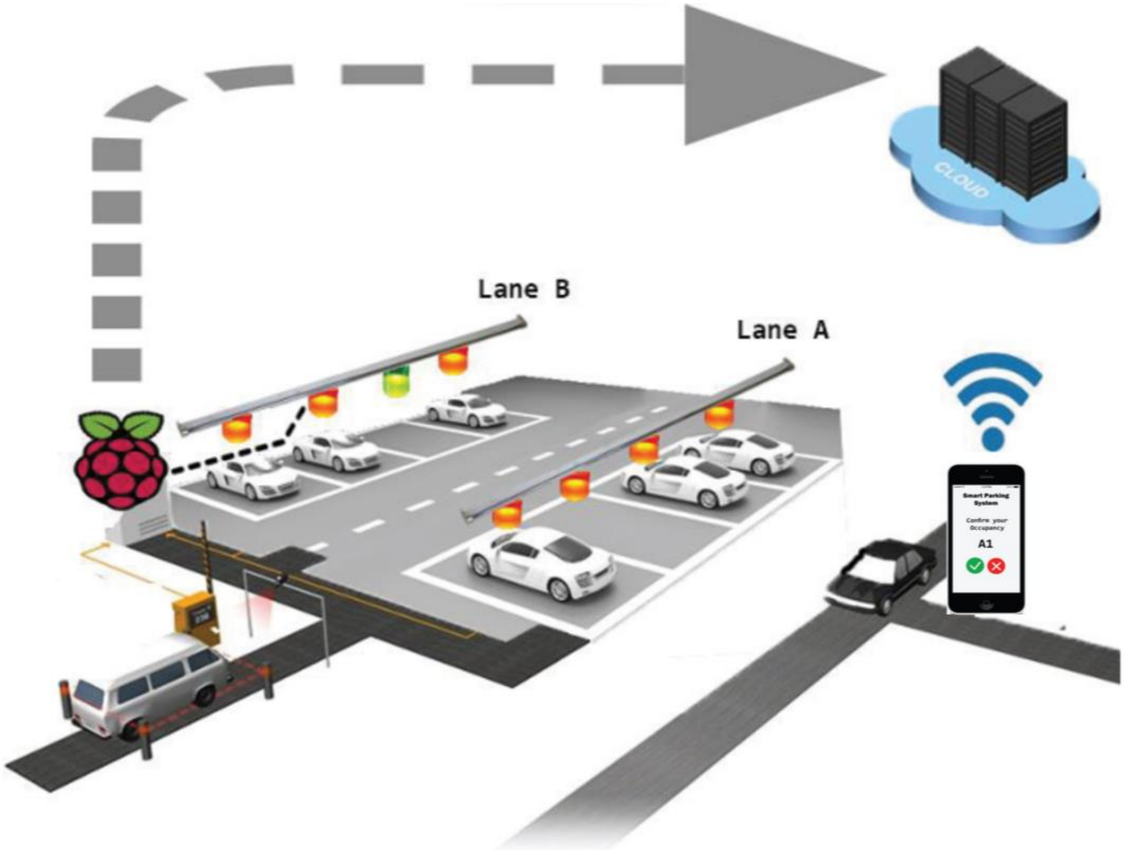

Figure 8. Smart parking system [229].

- Parking guidance and information system (PGIS): This provides a real-time number of available parking spaces using sensors at the parking entrance and exit. In some cases, it can guide drivers to designated parking spaces [230].
- Transit-based smart: In addition to public transportation schedules, this presents the real-time occupancy of parking lots and arrival routes [231].
- E-parking system: A single platform that integrates different features of smart parking facilities such as vehicle guidance to the nearest parking area, occupancy status of parking lots, different payment methods, lot retrieval announcements, and reservation facilities [229].
- Automated parking system (APS): A mechanical system that automatically moves a vehicle to an available space without human intervention [232].
- EV charging station: allocation of lots in parking areas to EV charging stations. There are different applications through which EV owners can check the status of their car charge and be notified when it is completed [233].

Another sustainability concern in this field that can be addressed through digital solutions is bike parking stations. The authors of [234] also mentioned that the availability of safe bike parking stations in a neighbourhood could encourage more people to choose bicycle commuting as a viable transportation option. A bike storage rack can be equipped with a smart entrance to enable access to users through different digital gadgets (e.g., mobile applications, cards, RFID tags). The authors of [235] highlighted the need for more advanced bike stations, which provide the possibility of charging e-bikes similar to those in EV parking lots. Table 11 presents the results obtained from previous related research projects concerning the use of smart parking systems.

Table 11. Examples of smart technologies in smart parking systems.

References	Smart Solutions	Results
[236,237]	Smart parking system	Reduction of approximately 90% in the need for parking slots, reduction of approximately 50% in CO_2 emissions, reduction in mortality.
[238]	Smart parking system	Reduction of up to 43% in the time required to find parking space, reduction of 30% in miles travelled.
[239]	Smart parking system	From 4.5% to 18% increase in economic profits.
[240]	Real-time parking information (university campus)	15% reduction in parking time.
[241]	Addition of pop-up bike lanes (a city in Germany)	48% increase in cycling.

4. Conclusions

The aim of this research was to propose a collection of smart solutions and novel ideas that can be applied to the neighbourhood building stock for energy conservation purposes. To this end, numerous scientific articles, the technical literature, and European projects pertaining to the application of smart approaches and ICT in different domains were collected and scrutinised. As most of the guidelines presented in this context focused on smart homes or smart cities, the boundaries of which are more clearly determined, the first contribution of this research lies in the presentation of a complete set of smart solutions that are particularly applicable to the neighbourhood building stock. The key difference between the neighbourhood building stock and urban planning strategies or single-home renovation is the set of activities that are socioeconomically feasible at this scale. In this regard, clarifying a clear boundary among all the smart solutions and selecting those that can be deployed in the neighbourhood-building stock could play a crucial role in assessing opportunities for intelligentisation. This study also significantly contributes to clarifying the direct and indirect impacts of smart solutions on reducing energy consumption.

In this research, all the smart solutions were investigated in two main sections, building and neighbourhood, and further classified under five domains: building energy-related uses, RESs, water, waste, and open space management. The smart solutions collected in the building energy-related domain are almost entirely laid out in the SRI report [17]. However, a comparison of the levels of functionalities presented in the SRI report and the collected smart solutions in the first domain revealed that only the last two levels of each indicator could be considered smart. A literature review in this domain showed that one of the main obstacles that may prevent the realisation of this expected improvement is the lack of skill among building users, preventing them from adapting their energy usage profile to an appropriate behavioural pattern. In the field of energy generation, there is a naïve general overview that the supply of sustainable energy from RESs can be interpreted as a smart solution at any level. This research strove to make a clear distinction between sustainable and smart measures by summarising the elements that should be deployed in the renewable energy grid to solve their major challenges. Moreover, in the fields of waste management and water distribution networks, which are inseparable subjects of all sustainability protocols, all the smart solutions that should be applied at the neighbourhood scale and supported by higher levels of urban management were elaborated. A review of the potential impacts of smart solutions proved that energy enhancement is not only limited to the intelligentisation of building components but can also be achieved through other neighbourhood elements in direct and indirect ways. For instance, owing to the strong interrelationships among these elements, increasing community awareness in different fields through the use of smart water meters, smart energy meters, and smart parking systems can boost the effective conservation of energy and other resources.

Although potentially missed articles and projects could have contributed more to this review, the various indispensable aspects of the neighbourhood scale covered here revealed an uneven workload distribution in the development of smart tools across different disciplines. This uneven distribution has resulted in certain areas, such as smartening water reclamation and smart composting plans, which have rarely been investigated in this context. In addition, most smart-oriented studies merely focused on designing and developing new tools and methods, without examining their effectiveness. Although this trend has led to a rapid advancement in smart and digital tools, it can be an obstacle for stakeholders seeking observable investment outcomes.

Considering all these factors, having a comprehensive framework not only as a guideline but also to measure and compare the level of smartness and potential achievements in energy conservation can play a significant role in structuring the content of this field. This study introduces a novel perspective on the concept of smartness by focusing on the intermediate scale between the city and building levels, which has the potential to accelerate the development of smart solutions, particularly in neighbourhoods characterised by residents who share common values, such as housing cooperatives. Increasing policymakers' awareness of the benefits of implementing smartness at this scale makes it possible to bridge the gap between theory and practice, and contributes to the overall implementation of smart city initiatives.

Moreover, this study emphasises the importance of considering the boundaries and limitations of smart solutions, from the building to the neighbourhood scale, to ensure a holistic and sustainable approach and enhance the practical applicability of smart city development. In this regard, this research highly recommends that future studies focus on developing a comprehensive reporting framework (similar to the level(s) specified for building sustainability [242]), with specific reference to smart solutions for energy conservation in the neighbourhood building stock.

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