Digitalization in Urban Energy Systems

Outlook 2025, 2030 and 2040

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1. Introduction

According to the United Nations (UN), currently, **55% of the population lives in cities**, and this number **is expected to increase** by 15 percentage points by 2050 [1]. **Cities still account** for **70% of global CO_2 emissions, as well as 60-80% of global energy use** [2]. For this reason, cities need stronger commitments and ambitions to reach climate neutrality goals. **Digitalisation is an opportunity**, as only 10% of the data generated is being analysed and applied. Digitalisation is defined as the transformation of a business or industry by using digital technologies to improve its processes [3]. Digital tools can help to integrate and analyse data, **underpin more effective and sustainable policymaking and urban planning, provide information and insights, and create benefits for citizens**. Specially for urban dense areas, digitalisation can assist to **reduce resource demand and improve flexibility to respond to changes** [4].

As stated in '*Digital Europe - How to spend it: a digital investment plan for Europe report'*, **digital technologies have the potential to reduce by 20% the global CO_2 emissions by 2030**, especially in sectors such as energy, transport, construction, agriculture and manufacturing [5].

Digitalisation **can improve cities' liveability in multiple domains,** such as security in streets (e.g. cameras or smart surveillance systems), healthcare and wellbeing (with telemedicine, real-time air quality monitoring, etc.), economic development and housing (e.g. peer-to-peer accommodation platforms), engagement and community (e.g. local connection platforms), and the management and operation of mobility (e.g. smart traffic signals), water (e.g. leakage detection), waste (e.g. optimization of waste collection routes), and energy (e.g. smart buildings, smart street lighting, etc.) [6]. McKinsey's consultant thinks there are **three layers of smartness in a city.** The first one is **technologies**; the second one **change of behaviour** (physical and social); the last one is **intelligence** that should be embedded in smart applications and data analysis capabilities (translating data into alerts, services, and tools) [7].

Thus, the research question of this report is formed as **how we can leverage this digital transformation into cities towards effective climate action** to contribute to the implementation of the Paris Agreement and also achieve the target of achieving 100 climate neutral cities by 2030.

In this report, **section 2** presents the **methodology** developed for the literature review of the urban energy systems framework. **Section 3** deals with the **state of the art** in digitalisation of urban energy systems detailing the role of citizens towards digitalisation of urban energy systems and the limits of digitalisation of the urban energy sector. In **section 4**, **replicable digital technologies and tools are reviewed** with the related business models that drive the urban energy transition, citizen engagement and impact on energy sectors. **Section 5** is a horizontal cross cutting aspect through all sections, **conducting learning processes and knowledge sharing between experts** of digitalisation in urban energy systems. Finally, **section 6 provides an outlook for the years 2025, 2030 and 2040,** defining the barriers and gaps and setting plausible scenarios **for digitalisation of urban energy systems**.

2. Methodology

A comprehensive critical review is presented mostly in section 3 and section 4, based on academic literature, research reports, legislation, and key databases for digital urban energy system. The review of replicable technologies, tools, and processes is performed using **sources particularly from Horizon Europe Smart City Lighthouse (SCC) projects, renewable energy communities (REC) projects, IEA Annexes, and case studies from global networks and catalogues**. The essential body of literature is broken down into thematic categories. The related information is extracted from the literature and summarised in tables and figures.

The review in section 3 presents the state of the art of digitalisation in cities and urban energy systems. The review firstly **explores the concept of the 'urban energy system'(UES)** to achieve a common understanding of the concept and the boundaries for the study. The state of the art of digitalisation around the defined UES concept is compiled for the different sectors identified within those boundaries, by considering the supply chain from energy production to final use. Next, the limitations of digitalisation on UES is examined, including technical and non-technical limits. The review looks into the respective limitations of each step from supply to end-users at both global and EU level through reviews of reports and publications.

Section 3 answers part of the questions of the 'state of the art of the digitalisation of UES' and 'to what extend the urban energy sector has been digitalized'. Besides, this section also explores the role of citizens and further local innovation ecosystems towards digitalisation of urban energy systems (DUES): Citizens that are at the centre of the digital transition and form communities to have a stronger voice; and all of the other stakeholders are also building local innovation ecosystems to create innovative business models to sustain the transition. Aligned with this, this section looks for answers the question *"What is the state of the art of using (digital) tools and technologies that allow citizens / end-user to engage themselves in the energy transition process?"*

Section 4 of this document considers the digital technologies and tools that are available on the global market, to answer the question *"What kind of digital technologies and tools are available on the global market and for which geographical areas are they suitable?".* To analyse that, **technical** (sensors, automation, 3D printing, robotics, etc.) **and non-technical** (business models, co-creation, and citizen engagement through digital tools) **processes and tools** are reviewed. Furthermore, **case studies are analysed by sector where they are applied** (assessing the benefits to urban energy systems) **and by location** (geographical areas). A benchmarking of digital tools, technologies, and processes is created.

In section 4.1, the report firstly focuses on the technical digital technologies, tools, and processes, such as artificial intelligence (AI), blockchain, machine learning, advanced data analytics, internet-of-things (IoT), big data, cloud computing, sensors, automation, 3D printing, robotics, data platforms, etc. These technologies can be applied **in different sectors and allow to improve processes** (in terms of energy efficiency, logistics, etc.), **which ultimately can reduce energy needs and decarbonize** urban energy systems.

Section 4.2 **continues on business models** that drive the urban energy transition, which can be facilitated through digitalisation. Citizens can be connected with market platforms, as well as contribute to streamlining administrative processes or enable peer-to-peer energy trading (for example, through blockchain). Case studies that digitalize business models are reviewed, by identifying barriers, enablers, and gaps.

Section 4.3 reviews **practical examples of citizen engagement** that have been facilitated through digitalisation, to get feedback from users, understand their behaviours, and include them in the decision-making processes. Data platforms, digital engagement platforms, and, mobile phone applications used, among others, used in case studies are reviewed, to identify the best practices, barriers, enablers, and gaps.

Moreover, other approaches, such as **online digital fora (via ResearchGate), workshops and interviews,** were also used to identify the solutions to different questions under the umbrella of digitalisation of UES, and to gather the lessons learned from various implemented projects.

Finally, an analysis of the impacts of digitalisation of the different sectors of urban energy systems is carried out in Section 4.4., using information available from key references and selected projects, on energy efficiency, environmental, economic, and social aspects.

2.1. Urban energy system framework

The review is organised in terms of what we understand as an Urban Energy System (UES). First, the energy system concept is reviewed. For instance, according to the Cambridge dictionary, *an* ***energy system*** *is a group of things that are used together to produce energy.* The definition includes mainly the **supply side of the energy chain**. Instead, an **urban energy system can be understood as** *those designed to cater the energy demand in cities and urban areas* [8]. This definition is a bit broader which **includes the supply and distribution network, as well as the integrated infrastructures** (e.g. storage). Rutter sees **urban energy systems** as a representation of the *''the combined processes of acquiring and using energy'' to meet the energy service demands of an urban population* [9]. Lastly, Grubler et al think that the urban energy system "comprises *all components related to the use and provision of energy services associated with a functional urban system, irrespective of where the associated energy use and conversion are located in space. The full urban energy system entails both energy flows proper (fuels, 'direct' energy flows) and 'embodied' energy (energy used in the production of goods and provision of services imported into but also exported from an urban system). Include the types of activities they pursue and the infrastructural and functional framing conditions (service functions) urban agglomerations provide*". The first two definitions are quite limited because the final energy use is not well covered, which is really needed for a new "integrated urban energy systems" [10]. **The review in this report finally defines its scope in between the third and fourth definition**.

However, due the limited time framework of the study, this research has to limit the sectors covered to buildings (stationary energy and its energy supply) and mobility, while other sectors or services (e.g., water, waste, mobility services…) are not considered. So, we understand "Urban Energy Systems" as follows:

Urban Energy systems for SCALABLE CITIES is:

An urban energy system represents all functional processes related to the provision and use of energy **service for demands** from an urban population. The energy system comprises from primary energy supply, through conversion, distribution, storage to final use in different sectors (such as buildings and mobility). It requires an increasingly **integration of planning, implementation, operation and management** towards an overall sustainable impact, with interactions between a larger number of **components and actors.**

In principle, **urban energy systems are not fundamentally different from other energy systems in that they need both to satisfy a suite of energy-**

service demands and to mobilize a portfolio of technological options and resources.

However, urban energy systems also have distinguishing characteristics that set them apart:

- A high density of population, activities, that results in energy use and pollution.
- A high degree of openness in terms of exchanges of flows of energy, information, people, and resources.
- A high concentration of economic and human capital resources can be mobilized to institute innovation and transitional change.

The framework is mapped in Figure 1, compromising the needed **resources** (climate, technical, human and stakeholders, economic, environmental and policy measured) **to enable the Urban Energy Systems working under the different phases of the energy chain** (supply, conversion and demand), **which will have a positive impact (co-benefits) and negative implications, into the society, environment and economics.** In between the integrated infrastructure (conversion of energy) and the final energy consumption (demand), there are the **new market players, such as energy communities and prosumers**, which can **take part of both, conversion and demand, and manage energy assets** (with tools such as virtual power plants).

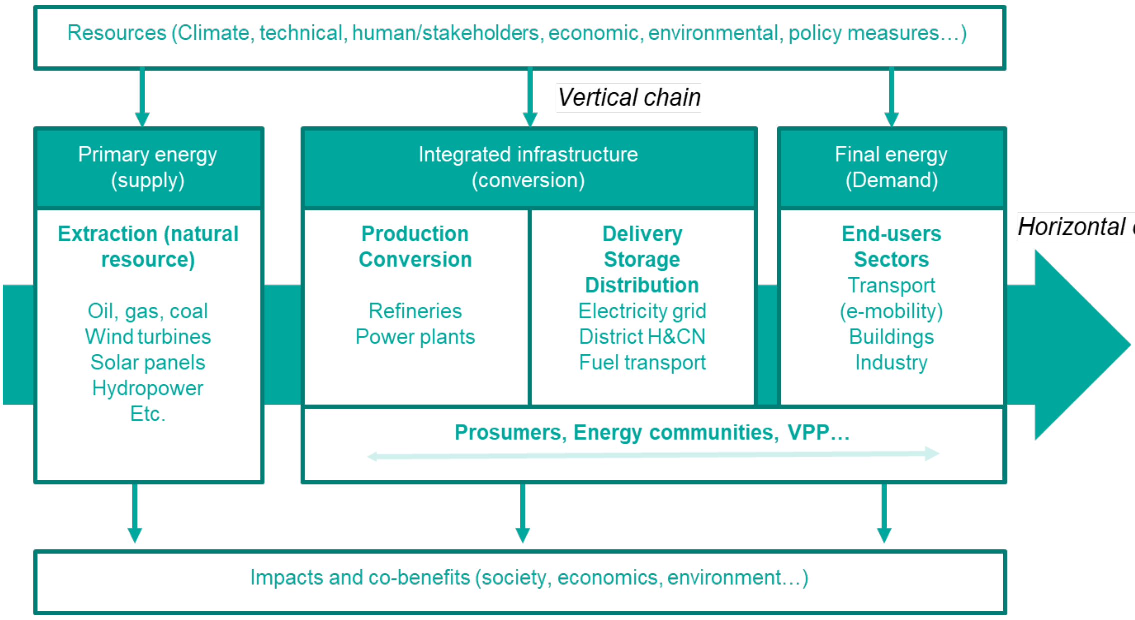

Figure 1 : A revised concept of an urban energy system, based on [11]

3. State of the Art in Digitalisation of Urban Energy Systems

Since 2018, experts were considering the three "D's", i.e. decarbonisation, decentralisation, and digitalisation, as the main drivers for change [12]. According to the latest report of the IEA, **by 2024, 83 billion connected devices and sensors will be creating a diverse range of datasets,** covering issues such as air quality, energy consumption, geospatial data, and traffic patterns [4]. Thus,

"Digital tools can further help combine and analyse this data to provide information and insights that can underpin more effective and sustainable policy-making and urban planning, and create benefits for citizens." [4]

Information can make the Urban Energy System (UES) smarter, as well as help decision-makers make better-informed decisions. The UES already has a complex energy infrastructure to supply energy to the multiple energy-demanding services, which can be observed in the increased electrification of final energy use, distributed generation of variable renewable energy, mainly photovoltaics (PV), and an increased number of players (including citizens) participating not only as consumers but also as suppliers or adding flexibility to the system. The definition of "integrated energy system", which refers to the coordinated planning and operation of the energy system 'as a whole, across multiple energy carriers, infrastructures, and consumption sectors [13] – can be also applied at the urban scale, and we can affirm that the pathway towards an effective, affordable, and deep decarbonization can only be achieved by "integrated urban energy systems".

Digitalisation can facilitate the management and operation of these **new distributed assets,** such as renewable energy generation and storage, through better use of data along with more advanced communication technologies[14]. Digitalisation should also facilitate the participation of customers, users, producers, and different new actors in a "digitalized integrated urban energy system". In this sense, the digitalisation of the urban energy system will merge with many other aspects of the urban digital transition, where there is an enormous potential for the digital transition to improve the quality of life of citizens, as well as to transform the economy [15].

A few countries have started to invest heavily in digitalisation of urban energy systems. For instance, **Belgium** has supported 62 projects firstly with EUR 400 million, and the second programme is providing another EUR 400 million. In **Finland**, 26 projects with a total budget of 45 million EUR have been executed since 2017. **France** is providing financial support with EUR 50 million of the "City of tomorrow" fund for start-ups in the smart city sector. One **German** funding programme, "City of the Future", offered EUR 150 million. An initial budget of EUR 65 million was announced in **Italy** in 2016. A pilot scheme for smart cities in **Slovakia** includes EUR 1 million from the state budget. As of 2017 in the **UK**, GBP 32 million has been spent on the IoT programme; through the Future Cities Demonstrator Programme, Glasgow was awarded GBP 24 million, and Bristol, London and Peterborough were each awarded GBP 3 million. The Smart Cities Initiative in the **USA** promised USD 165 million investment in smart-city solutions, and announced plans to expand the initiative with an additional USD 80 million investments in 2016. The detailed information regarding these countries' initiatives and their investments are appended in Annex 1 [16].

Estimations on future investment on digitalisation are complex as they are normally interlinked with the adoption of other technologies. As an example, in the building sector, the Smart Readiness Indicator (SRI) proposed in the Energy Performance of Buildings Directive (EPBD) [17] is expected to trigger investments in digitalisation. **In a scenario where the SRI is mandatory linked to the energy performance indicator, a high uptake rate of smart ready technologies and services is expected**, with total cumulated investment of EUR 58 billion by 2030 and EUR 181 billion by 2050, considering 80% of the buildings having increased by at least one level of smartness by then [18]. For the mobility sector, the additional investments on **digital bidirectional charging** devices, which could enable flexibility management for EVs, would be in the **order of EUR 55-60 billion by 2030,** assuming 35% adoption rate by 2030 covering circa 19 million vehicles [19]. Following macroeconomic simulations conducted for this report, **by 2030, the cumulative additional GDP contribution of new digital technologies could amount to EUR 2.2 trillion in the EU**, c.a. 14.1% increase from 2017 [20]. **European institutions and governments may need to contribute approximately EUR 75 billion per year** for ICT investment in the coming decade. Additionally, education, upskilling and reskilling of the labour force to manage the digital transition, may **require total investments of EUR 42 billion per year**.

According to Judson et. al, **digitalisation changes have been focusing mainly on software and data processing development, rather than developing physical equipment** [21]. In fact, the digitalisation has been significantly affected by the rollout of physical energy technologies such as e-mobility systems, heat pumps, battery storage, and distributed RES. Specifically, the changes in UES have affected digitalisation in the following way[21]:

- **On the supply side:** The more renewable energy sources (RES) are integrated, the higher the necessity of monitoring and management of these assets, especially if the RES are installed closer to the energy users. Nevertheless, the authors reflected that there is a **necessity to collect and process data in shorter time intervals,** especially if monetization of the energy exchange and flexibility want to be implemented. The electricity sector is not the only one affected by digitalisation and vice versa. The rollout of EV smart chargers, vehicle-to-grid technologies, and prosumers in district heating networks, among others, are also found, which address energy decarbonization and digitalisation beyond the electricity grid.
- **On the conversion side of production:** the rollout of storage, distributed intermittent RES (by means of prosumers or energy communities), distributed energy resources (DER)[1] and flexibility assets have especially impacted digital innovation on energy flow coordination. Flexibility can be offered to Distribution System Operators (DSO), Transmission System Operators (TSO), or supplier/balance responsible parties [22]. But, according to practitioners, the actual rollout of flexibility is not easy because of the complexity to communicate with the DSO, which is not facilitated by the current tools and procedures. Furthermore, participation in flexibility markets by energy communities is hampered due to bid limits, which are too high for a small community (e.g. 1 MW in Spain).

  In the latest workshops on "Digitalisation of the energy system" held from 16 February to 3 March 2022, it was mentioned that a "standardisation registry of energy flexibility assets" was needed but in an easy way so all market players can participate. Furthermore, due to the number of actors in this part of the energy chain, roles are getting diffuse, which makes responsibilities and data ownerships not clear.

  For example, DSOs have access to smart meters data in real-time while citizens and energy community managers do not have access to the data until the next day. According to IRENA, DSOs should enable communication between DERs/aggregators (which can be but is not limited to energy communities) and TSOs. The communication could be done through platforms or by facilitating common interoperable standards (at physical and information and communication technology level) and Application Programming Interfaces (APIs).

[1] DER: Distributed energy resources (DERs) are small or medium-sized resources, directly connected to the distribution network. They include distributed generation, energy storage (small-scale batteries) and controllable loads, such as electric vehicles (EVs), heat pumps or demand response.

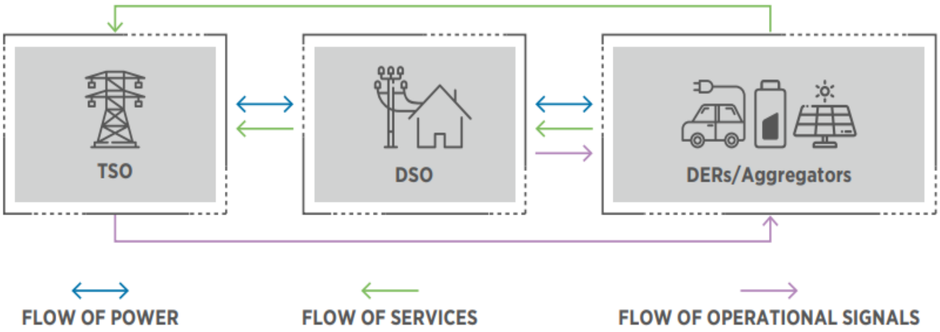

Figure 2 : Flow of power, services, and operational signals among TSO, DSO, and DERs [23]

- **In the final use:** energy efficiency measures contribute to reducing the energy demand, whether they are smart (e.g., smart thermostats) or not (e.g., building retrofit). The installation of IoT, smart meters, demand-side flexibility, etc. can help to reduce and shift energy demand peaks to support grid balancing. To enable this, citizen engagement is needed to allow the user to decide on how the data is used and whether they want to shift some loads to another time. Citizen engagement can be facilitated through digital tools as well, such as phone apps or platforms.
- **Cross-sectoral**: digital tools can help system integration across sectors, such as the heating and cooling sector and the electric one. Power-to-heat technologies integrated in digitally-facilitated demand-response will help to make this link. Furthermore, digital tools allow new ways to optimize the use and planning of both networks and distributed RES.

The key processing functions that digital tools offer in UES are mainly **monitoring, prediction, and control of energy assets, flows, consumption, and system variables** (voltage or frequency). Digitalisation also allows for **automation functions across the system** such as energy management and demand-side response. The most important digital tools and techniques that have been used include, but are not limited to: "optimisation algorithms, 'big data' handling techniques, blockchain, flexibility-enabling software, forecasting, machine learning, AI advances, cloud computing, edge processing, cybersecurity improvements, and smart meter data flows". **Tools and techniques facilitate automation and granularity of flexibility,** allowing to add of new moveable loads, such as an electric vehicle (EV) chargers or heat pumps in the UES and **disrupting or even democratizing certain elements of the systems to allow new market players to participate in,** with revenue-generation (P2P: peer to peer) and decision-making opportunities.

Among these processes**, cybersecurity and privacy issues are the main challenges**. Digitalisation creates significant risks as an increased exposure to cyberattacks and cybersecurity incidents potentially jeopardises the security of energy supply and the privacy of consumer data. **A comprehensive legislative framework** has already been built by the European Commission [24], such as the 'EU Cybersecurity strategy (JOIN (2013)01 final)', the 'Directive on Security of Network and Information Systems (the NIS Directive) (EU) 2016/1148', and the 'Cybersecurity Package (JOIN (2017) 450 final)'. Furthermore, the Commission adopted sector-specific guidance in April 2019, and the 'Clean energy for all Europeans package' will help reinforce cybersecurity of the digital transformation in the energy sector. The Regulation on gas security of supply ((EU) 2017/1938) also includes provisions to consider cybersecurity. The 'Electricity Regulation' requires the Commission to develop a network code on cybersecurity of cross-border electricity flows.

In addition to this legal framework, **digitalisation of urban energy systems requires particular attention to real-time/fast response, cascading effects, and interaction with the most recent equipment for automation and control**. For instance, there are mainly three threats on the smart grids: (i) attacks targeting availability, also called denial-of-service (DoS) attacks, attempt to delay, block or corrupt the communication in the Smart Grid; (ii) attacks targeting integrity aim at deliberately and illegally modifying or disrupting data exchange in the Smart Grid; and (iii) attacks targeting confidentiality intend to acquire unauthorised information from network resources in the Smart Grid. There are **existing approaches to handle such security and data privacy/anonymity**, e.g., the Trusted Platform Module (TPM) standard, which is a dedicated hardware module for cryptographic processing operations. It is usually deployed as a co-processor and is used for cryptographic random number generation, secure boot, attestation, and data sealing [25].

In general, there are **a few innovations** that can potentially **mitigate the challenges in cybersecurity** [26]: (1) **Blockchain**, coupled with software-defined networks (SDN), can significantly virtualize the platform, hence contributing to the practicality of decentralised implementations of energy systems (then reducing the cascading risk). (2) **Game theory** can be used to study the effects of new business trading models (e.g. pricing, biding etc), government's policies on corporates' decision to invest in security and privacy features of their products (for example, paying premiums for security features vs. monetarily penalising vendors for cyber-attacks and security breaches). (3) **Semantic Sensor Network** (SSN) ontology receives raw (even real-time) data from sensors and converts them to interoperable semantics to increase the interaction and synergies of all components in the energy system. and (4) **the evolution of authentication and authorization based on behavioural and biometrics-based techniques** can accelerate the real-time response.

3.1. Role of the citizens and local innovation ecosystems

Until now, supply-side management was mainly the issue for energy efficiency and security of urban energy systems. The end-user perspective was not broadly considered in the earlier SCC projects. Nevertheless, **bottom-up approaches and demand-side management** (concerning management of energy demand for reducing the overall paid cost) **must be supported to sustain the energy transition.** Advanced applications of the digitalisation process may unlock several opportunities for the energy sector, such as demand-side opportunities. The INTENSYS4EU project mentions that the power sector landscape is changing:

Historically, the supply-side (generation and networks) was adapted to meet demand. In the power system of the future the role of supply and demand will change with demand being modulated to adapt to the higher variability of renewable resources. Digital technologies enable power systems to forecast demand side resource availability, and to leverage these to provide benefit for climate, power system resilience and consumers [27].

In parallel with this change in the power sector landscape and the integration of digitalisation in this new concept, the **role of the citizens and citizen organizations has gained much attention among scientists, local policy makers, and the private sector** [28]. Through engaging and facilitating citizen participation, the **role of the citizen is changing from a passive consumer to an active participant** in the transition as, for instance, the initiator of new, local, energy initiatives, becoming a member of such an initiative or by changing from consumer to prosumer. An example of this is the collaborative project **DECIDIM**, which provides a digital open-source participatory platform to the citizens of Barcelona to contribute to and express support for new proposals and policies developed by the city. The platform was created for the Municipal Action Plan campaign "73 neighbourhoods, one Barcelona. Towards a city of rights and opportunities", **Catalonia's first renewable energy co-operative, Som Energia, used the DECIDIM platform to host its 2018 general assembly and various debates with co-operative members and interested citizens** [4].

Diving into this matter from a broader perspective, such as engaging citizens actively in the system**, local innovation ecosystems also play a key role for the digitalisation of urban energy systems since they are enabling environments and infrastructures allowing people to be involved in iterative processes of innovation**. These ecosystems are test beds for generating solutions to local challenges and raising awareness and acceptance by delivering the solution to the end-user. Incubators or accelerators are the most common ones and offer collaboration and funding programmes to start-ups and enterprises to help underpin innovation in cities in various sectors. In Valencia Lanzadera the innovation ecosystem has helped a lot of start-ups to launch in the digitalisation sector, offering a collaborative space to work and funding. An example is "The predictive company" start-up that offers digital tools as a service, such as prediction of energy efficiency in buildings [29]. The new one-stop shop offered by the EU Mission and the NetZeroCities project will map the incubators and accelerators of cities in all sectors (energy, mobility, buildings, circular economy, etc.) which will help cities to know their possibilities for engagement and for setting up specific programmes towards climate neutrality.

Within +CityxChange, cities, citizens, and stakeholders are part of the local energy transition, as they are increasing and integrating local renewables. The citizens gain new roles as co-innovators - explorers, ideators, designers and diffusers - in the co-creation and replication of Positive Energy Blocks and Districts [28]. Citizen observatories in the form of innovation labs and activation of the local innovation ecosystems through innovation playgrounds can be counted as best practices in this project.

Moreover, for ATELIER, co-creation, citizens' energy communities, and behavioural change are the main strategies. The project has established so-called Innovation Ateliers that serve as a multi-stakeholder platform addressing issues coming up amongst the stakeholders during the innovation project, as well as upscaling of specific PED innovations, such as energy communities [30].

Tools that allow to find neighbours are being developed by Energy communities. For instance, JoinEnergy tool allows a citizen to preliminary assess the creation of an energy community in their neighbourhood or house, and share it with its neighbours. Plus, the one-stop shop platforms allows the citizen or manager to manage and administrate documents, create voting polls (to be shared with the members of the community), among other functionalities [31].

Energy communities contribute to increased citizen participation and acceptance of renewable energy projects. They are also recognised as a fertile ground for social innovation [32]. Gamification strategies are promoted within co-created citizen science projects on which most of the decisions of the project are captured by the community. In these types of projects, gamification is utilized for engaging the citizen, regarding defining the problem, designing the study, collecting the samples, analyzing the samples, and interpreting it [33]. For doing so, citizens or communities take role in decision-making processes for designing and developing the projects as data collectors, providers and analysers.

Gamification in SCC:

VTT Technical Research Centre of Finland designed the **CITYOPT Planning Tool**, which was developed to meet the needs of energy experts and investors, enables optimisation of the energy planning of large-scale urban and regional systems. The tool provides alternative plans with cost and functional evaluations, also providing holistic solutions instead of partial optimisation. Over the long-term, the benefits of urban planning are also passed on to the tax payer [34]. The tool has been piloted in Helsinki and Vienna. Vienna case study is using Planning tool to study the possibilities of combining energy systems of three existing buildings, utilising waste heat and ground source heat pump systems in optimal way. Helsinki Case includes small scale testing and simulations of use cases of Environment Building electrical storages. Optimal planning at the case locations achieved reductions of around 15% in energy costs and 30% in CO2 emissions. The planning tool also markedly reduces the time required for planning.

3.2. Limits of digitalisation of urban energy sector

This section provides the challenges and limits of digitalisation that have been found in the framework of UES (see Figure 1).

3.2.1. Resources

- **Climate data:** The **design and implementation of policy are yet to be improved.** Climate data and its implications are **not always understood** by decision makers and processing this amount of information is a challenge in itself due to the skills it requires. Funding accurate and advanced climate modelling can also be a challenge, mainly in small communities. In addition, the **concerns of privacy, security, transparency** are often raised and constitute a major break to the development of digitalisation [35].
- **Technical aspects:** There is a strong technical limitation in **data interoperability.** The tele-communication technique also **constrains the real-time data transmission and optimised control and management** of energy systems. **ICT coverage is a limit** to how effective digital tools can be.
- **Human aspects:** Educational **or technological skills** are also a barrier to the use of those tools. There is a strong need in **enhancing** the education of the **related skilled labour for the digitalisation value chain** [4] .

- **Economic aspects:** Many municipalities are **not able to fully invest in large-scale digitization of urban energy systems**. There is **no clear guidance** on how to access the existing clear energy or climate finance support.
- **Environmental aspects:** Large implementations of sensor networks have a great **impact on the environment from its life-cycle point of view** - including extraction of raw materials, manufacturing processes, energy demand and 'e-waste' [21]. It **lacks dedicated information to reuse sensor networks** to reduce their carbon footprint.

3.2.2. Primary energy carriers (supply)

At the primary energy supply, the following limitations have been found:

- **Traditional fuels**: Existing and **old infrastructures** (mainly for oil, coal, and gas) are **not** compatible **with digitalisation**. Investments in high-carbon resources may not make sense [36].
- **Renewable energy sources:** The intermittent characteristic of renewables requires high-resolution data transmission and the related interpretation so that the urban energy system could adapt to short-time variations. Current **limitation** lies mostly **in the interpretation of the energy data and the corresponding control response** to the urban energy system. In addition, it **lacks the regulatory support and the practical business models** for energy trading at regional or local city and community levels.

3.2.3. Integrated infrastructure (conversion)

At the integrated infrastructure, the following limitations have been found:

- **Production conversion:** Commercial **confidentiality** makes obtaining data complicated, reducing the potential of improvement in planning of power systems. Large projects are capital intensive and take years to develop, making the system not up to date, as **technologies evolve rapidly**. **Cyber security is a risk** for energy security when systems incorporate digitised monitoring and controls, especially in power plants, grid/network assets and storage facilities, which is mainly depending on policy makers to ensure ongoing improvements in the cyber resilience [37].
- **Delivery, storage and distribution:** The efficiency of the storage and distribution systems relies on real time monitoring and control that comes from digitalisation. Limited **policy** exists to support distributed energy storage and distribution. **Ownership** of distributed energy systems **is not clearly defined, which further influences the business models and investment.**

- **Prosumers, energy communities:** The **digitalisation infrastructure is missing or disconnected** in most prosumers and energy communities. It is thus a challenge to autonomously connect all prosumers, both together with the centralised plants, to better regulate and optimise the energy generation and create an overall balanced and efficient energy flow.

3.2.4. Final Energy (demand)

Digital technologies and applications face a variety of barriers to adoption and use, and their impacts on energy use differ across demand sectors. The digitalisation trends/strategies included in the figure 3 are not intended to be exhaustive. "Magnitude of potential change to energy demand" indicates the potential impact of digitalisation on energy demand in absolute terms, which may be positive or negative. "Barriers to digitalisation" include technological, regulatory and public perception components. The quadrants are illustrative only and intended to give a sense of relative magnitude.

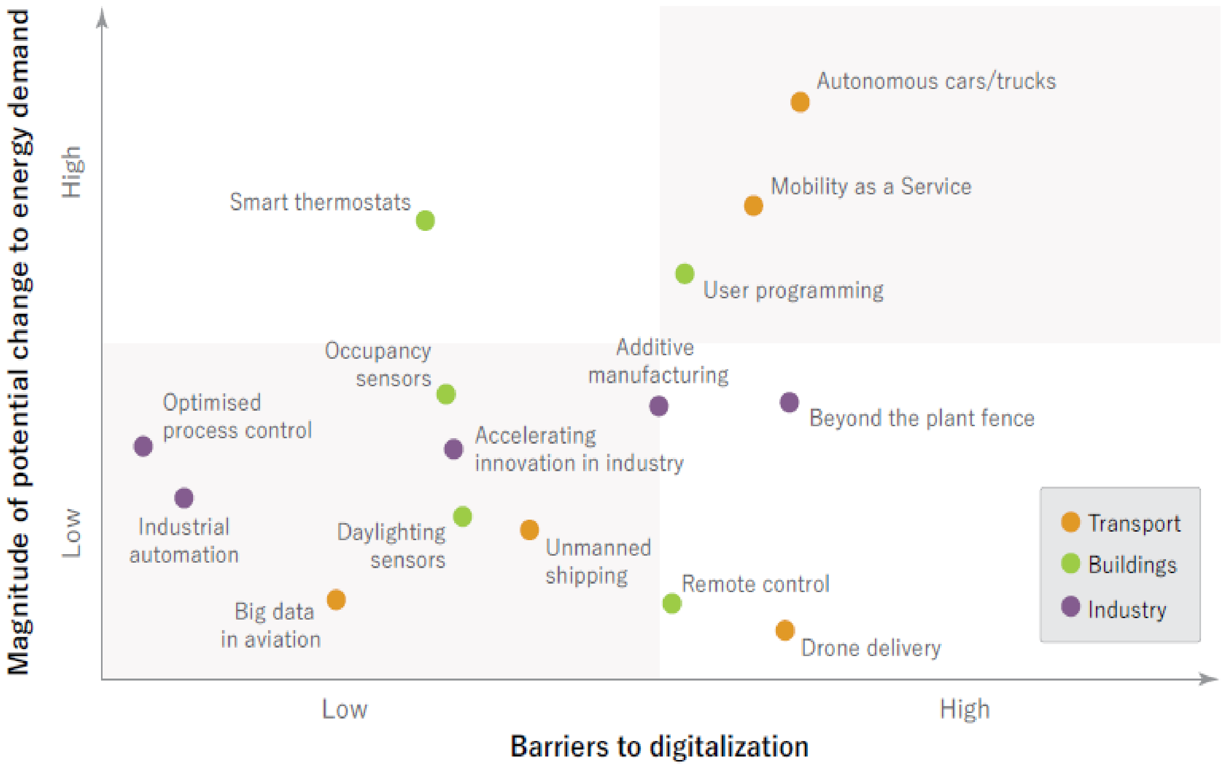

Figure 3 : Digitalisation's potential impact on transport, buildings, and industry [36]

- **Transport:** Many **limitations**, such as technical, regulatory, moral, and ethical considerations, exist regarding mostly connected and automated vehicles. Questions about **vehicle and software certification, liability, cybersecurity, data privacy, and employment** will need to be addressed [38]. Old regulations do not encourage competition and facilitate trials.

Different **data protocols** make travel difficult across borders. Improvements in freight logistics is limited by the **lack of sharing of information** across the supply chain. There is an **absence of well-maintained and accessible databases** that could promote innovative mobility services and foster multimodality. Government policies and regulations are not strong enough in directing the deployment of digital technologies in transport, as well as steering developments towards lower energy and emissions pathways [36].

- **Buildings:** There are **great concerns about privacy, technical and economic considerations, which weaken the digitalisation's effect**. **Standards to assure interoperability** are needed across technologies (open source or compatible software in the devices), as well as user **friendliness and product operability** (design, interface, and ergonomics). These factors hinder the deployment of smart building energy management tools and devices. Limited cases are found for utilities to offer financial incentives and introduce innovative tariff schemes to encourage building owners and occupants to adopt digital technologies, given the potential network cost savings from optimised energy use in buildings. **Limited business models** are designed for energy services, while mostly they are targeting for measurement of energy amount. **Supportive policy frameworks**, such as bulk procurement of energy-efficient technologies and white certificates, **are needed** for wide replication of new products [36].
- **Industry: Lack of accurate information, shortcomings in technical expertise and cultural barriers** may limit the potential for further digitalisation. So far, technology and service providers have been the main source of digitalisation information. Small and medium-sized enterprises often have **limited resources** for digital technology. It **lacks clear policy and regulators** for industrial firms to participate in demand response to connect to electricity grids and district heating networks and harness innovative business models. **Connectivity, data privacy and cybersecurity** need to be improved inside firms, supply chains and industrial sectors [36].

3.2.5. Iteration of limitations for different phases of urban energy systems

- **Conception and planning:** Tools for planning for urban energy systems are limited. For instance, there are many **tools** for urban planning, but very **limited** ones are found **for urban energy system planning**[2].

[2] This statement is experts' own finding during literature review.

Communication for all phases is difficult without the existence of a common process that would enable better management and coordination of development at different departments and levels within cities and between them as well [39]. An **effective digital support or guidance must be developed** with the ability to be replicated, so the cities redirect their focus on digital solutions.

- **Design:** **Limited interoperability** among various sub energy systems is found during the design phase. It **lacks information flow** among each sector and raises an issue in scalability. The insecurity created by the unknown external control of the digital devices is another break to the deployment. The age-friendly environment for digital tools is needed to increase the efforts to the empowerment of all population groups [40]. There are tools established by researchers for detailed design of urban energy systems but few of them are used in daily practice.
- **Implementation/construction:** The construction of smart cities comes with security challenges increased by the complexity of the installations, where that information is not well shared or synchronised. The **number of technical devices and their diversity creates a difficulty in maintaining safe networks.** The "smart" characteristic of a city cannot be reached in a single attempt. The scale of such constructions implies a slow, step-by-step development.
- **Operation and management:** There are **many platforms for city** (energy) data in operational stages, **but they are mostly used for gathering and monitoring data** with few management applications**.** The operation faces other challenges due to the **diversity of existing tools and protocols, and by the lack of education and technical skills to use those tools** [37]. Management is mainly limited by privacy concerns and the lack of clear ownership regulations regarding data.

3.2.6. Limitation of evaluation on the impact

There is a **lack of systematic method for evaluation of impact of digitalisation**. There are existing key performance indicators (KPIs) that have been identified for both quantitative and qualitative evaluation, but there is **no significant breakthrough on the overall evaluation of the impact of digitalisation of urban energy systems in smart cities**. **Insufficient data** is one of the potential limitations, as digitalisation is generally implemented together with other physical interventions such as electrification, and specific impact due to digitalisation is difficult to measure.

3.2.7. Other limitations

Digitalisation outside the energy sector, such as e-commerce, e-materialisation (e.g. e-books, DVDs to streaming video), and teleworking, could also change energy use patterns through a range of efficiency, substitution, and rebound effects. Few examples have been discussed [36]. However, this is not the main scope of this study.

3.2.8. Summary

A short summary is made by the below table.

Table 1 : Summary of limitations for both horizontal and vertical chains, adapted from [37]

LIMITATIONS ON DUES		HORIZONTAL CHAIN	VERTICAL CHAIN
Data challenges	• Limited use of existing data, while most data is only stored and visualised • Limited access to data as data ownership is not clear • Limited data sharing • Insufficient data interoperability • Limited by privacy and security concerns • Insufficient data for quantitative evaluation	→ **Primary energy (mostly renewable energies)** → **Integrated infrastructure** → **Prosumer, energy communities** → **Final energy**	➢ **Resources** ➢ **Energy supply chain** ➢ **Different phases of smart cities** ➢ **Impacts**
Insufficient coordination and integration	• Lack of dialogue and mechanism between different levels of government • Lack of cross-departmental collaboration • Lack of coordination and management resource throughout the chains • Lack of the integration of digitalisation at each step of the chains • Lack of regulatory support • Limited compatibility among different digitalisation infrastructure • Culture and context barriers	→ **Primary energy (mostly renewable energies)** → **Integrated infrastructure** → **Prosumer, energy communities** → **Final energy**	➢ **Resources** ➢ **Energy supply chain** ➢ **Different phases of smart cities**

Lack of capacity	• Lack of knowledge and related support for education • Limited access to digitalisation skills and capacity • Limited use of big-data techniques • Limited telecommunication infrastructure • Limited digitalisation tool across the whole chains • Limited compatibility with existing UES infrastructure • Lack of systematic evaluation methods	→ **Primary energy (mostly renewable energies)** → **Integrated infrastructure** → **Prosumer, energy communities** → **Final energy**	➢ **Resources** ➢ **Energy supply chain** ➢ **Different phases of smart cities** ➢ **Impacts**
Access to finance	• Limited investment on digitalisation infrastructure • Limited economic return • Lack of business models for development of investment-grade projects • Limited access to green finances	→ **Primary energy (mostly renewable energies)** → **Integrated infrastructure** → **Prosumer, energy communities** → **Final energy**	➢ **Resources** ➢ **Energy supply chain** ➢ **Different phases of smart cities**
Digitalisation risks	• Cybersecurity • Environmental impact on digitalisation infrastructure (embodied energy is often ignored) • Lack of equitable access or inclusivity	→ **Primary energy (mostly renewable energies)** → **Integrated infrastructure** → **Prosumer, energy communities** → **Final energy**	➢ **Resources** ➢ **Energy supply chain** ➢ **Different phases of smart cities** ➢ **Impacts**

In order to further compact the information, the same information is also visualised in the following diagram:

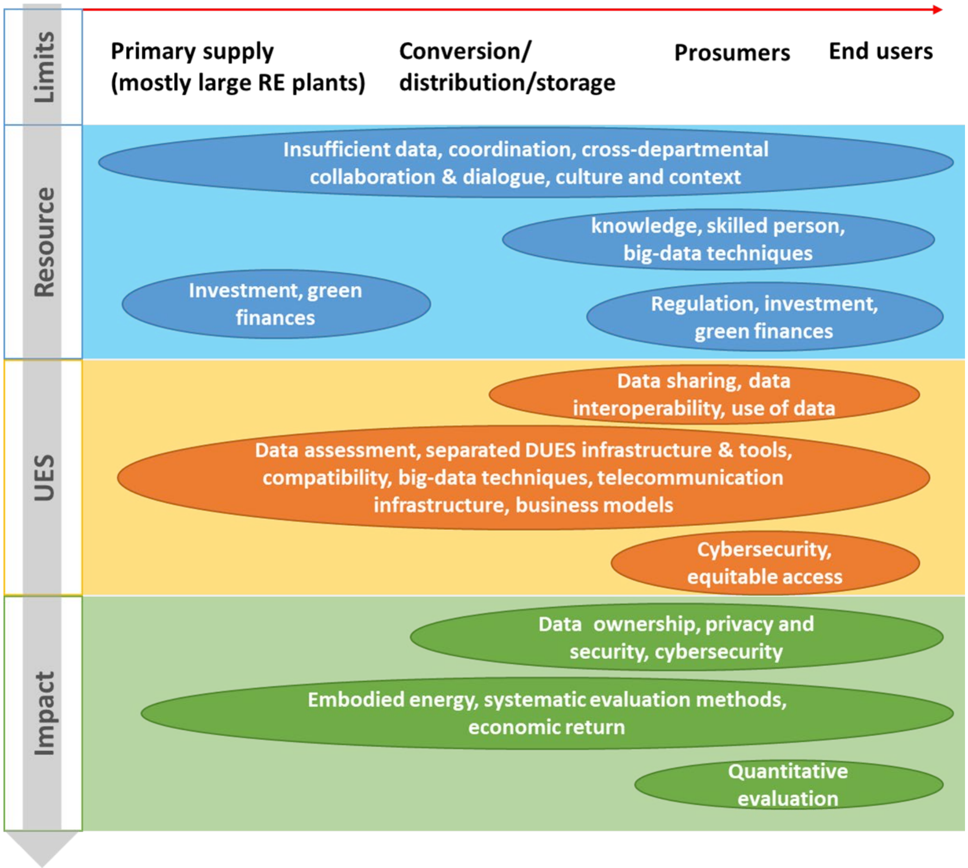

Figure 4 : Summary of limitations of DUES through the supply chain

4. Replicable Technologies & Tools

As mentioned in section 3, data analysed can make smarter UES, helping to make better decisions in all the system phases: planning, design, and operation. **Digital tools and techniques are facilitators to make that happen.** Digital tools and techniques can be found along the supply chain of the UES, from resource and primary energy (input) to the final energy use (output). In this section, Smart Cities and Communities (SCC) projects are reviewed to identify which solutions have been used and where they match with the framework defined in this document (see **Figure 1**).

According to the Strategic Implementation Plan of the European Innovation Partnership on Smart Cities and Communities (EIP-SCC), Smart cities are understood as *"systems of people interacting with and using flows of energy, materials, services, and financing to catalyze sustainable economic development, resilience and high quality of life; these flows and interactions become smart* *through making strategic use of information and communication infrastructure and services in a process of transparent urban planning and management that is responsive to the social and economic needs of society"* [41]. Later on, SCC projects have included not only the concept of Smart Cities or nearly zero energy districts, but also, "Positive Energy Districts" (PED) which can also include digital solutions to monitor the energy flows (imports and exports) to control them (when to store energy, when to export it and when to use it within the boundaries), monetise the exports (through P2P trading or selling it to the grids), or engage with citizens (showing them information or making them participants).

As it has been highlighted, digital tools can underpin multiple synergies between sectors and UES of a city. The following review will help to analyse where these tools have been applied, and which impacts and barriers have been found so far.

Figure 5 : All Smart Cities and Communities projects in the EU

4.1. Digital technologies and platforms

In Smart City and Communities (SCC) projects, the main technologies, and tools, found in the literature review, have been grouped according to their functionality (e.g. energy monitoring or operation and management), sector (buildings, transport, etc.), and type of tool (sensor, load balancing, etc.). **More than 100 tools have been found in SCC projects** and Figure 6 summarizes where the tools and techniques are applied.

Figure 6 shows that most of the efforts in these European projects have been focused on the smart appliances (mainly buildings, vehicles, lighting), urban digital platforms, and techniques for energy management (at the building or district level), and optimisation (e.g. of district heating networks). Some load balancing and demand-response have been applied as well.

4.1.1. Primary energy (supply)

On the primary energy side, the main application of digital tools is mostly gathering information of sensors implemented to monitor the production of RES integrated into the project. The sensors can be included in **Energy Management Systems** (EMS) to allow control and optimisation of energy assets. The RES integration in UES can help to have a reliable and secure energy supply in cities. But to ensure that, digitalisation is needed to optimize the RES use and reduce curtailment by means of storage. Furthermore, advanced analytics such as predictive maintenance, applied at the supply level, can help **minimize the risk of a power failure and generate early warnings before a problem has occurred** [42]. These advanced techniques have not been applied yet in these projects. Instead, in Renewable Energy Communities projects, such as LocalRES, control algorithms, and blackout strategies are being considered, to define the order of restarting different electric entities in a blackout event. Furthermore, by means of a **Multi-vector Virtual Power Plant** (MVPP), services of voltage control will be provided to the grid [43].

Substation or distribution automation, as well as measuring power quality of the grid (voltage, frequency control, etc.) are not found in SCC projects. At global level, digital substations are being applied. For example, in India the Swiss engineering group ABB has installed **digital substations, that are more compact, flexible and reliable, and that allow to gather local data.** Furthermore, using fibre optic cabling, the "digital substation will also enable the drive for power management efficiencies by turning real time data into **actionable intelligence and bringing cost efficiencies**" [44].

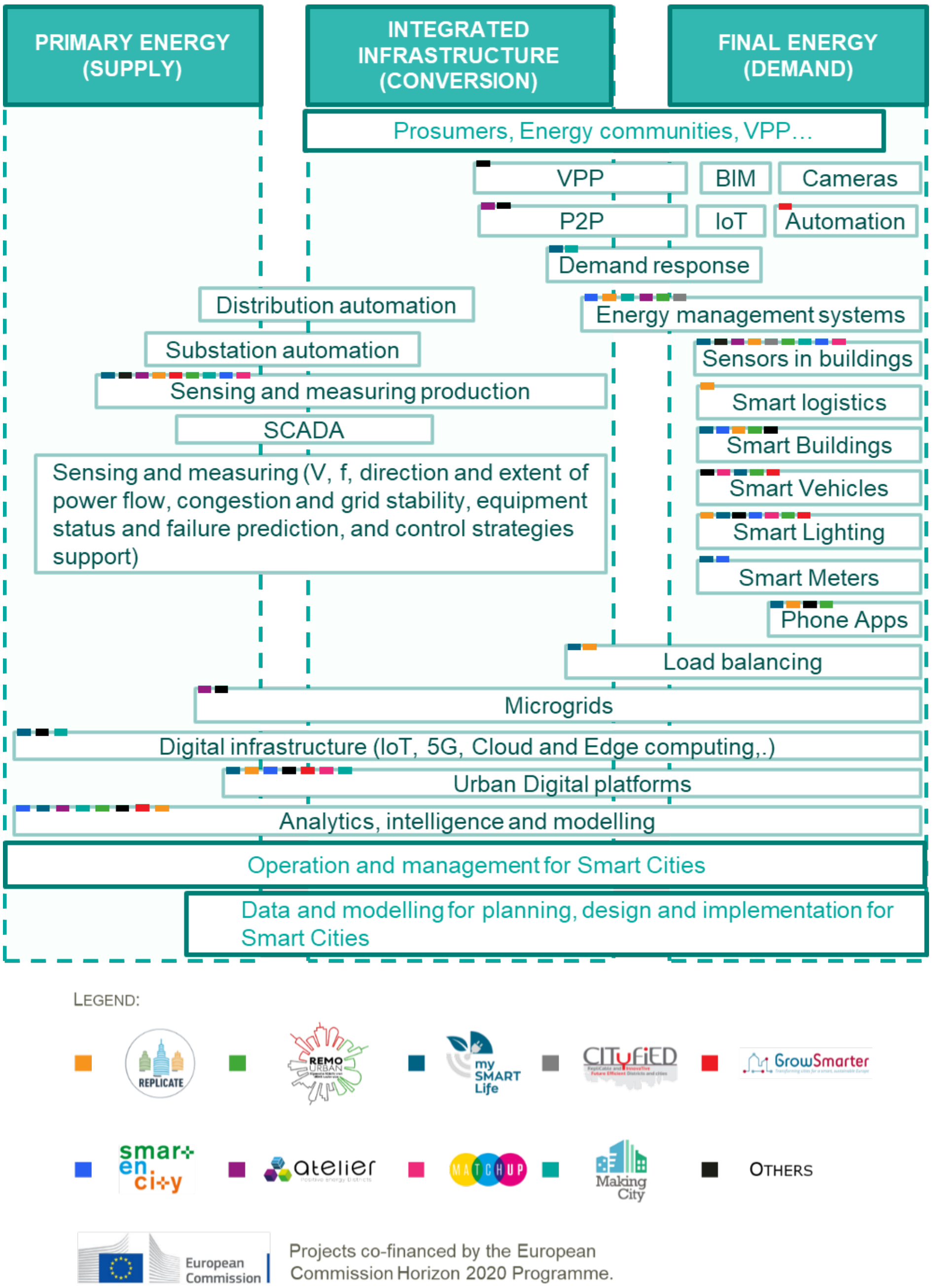

Figure 6 : Technologies reviewed within UES framework[3]

[3] The logos of SCC projects indicate which ones have been reviewed. The category of "Others" includes municipal projects (e.g. City of Vienna) and international catalogues (such as CityXCity Catalogue)

At primary energy supply, digitalisation can help to:

- Increase reliability and quality energy supply of the system;
- Improve maintenance (e.g., by means of proactive and predictive maintenance) and reduce power failures;
- Offer services to TSOs such as voltage control.

4.1.2. Integrated infrastructures (conversion)

The **integrated infrastructure** includes the flows from production conversion (power plants, refineries) to the delivery, storage, and distribution of energy (in grids: power grid, district heating and cooling networks, fuel transport, etc.). As there are new market players in the traditional horizontal chain of energy supply, such as prosumers, aggregators, or energy communities, these stakeholders and its associated technologies can also be found in this part. The **tools and techniques** found are similar to the previous section but more of them **focused on monitoring, prediction, and control of flows** (from power plants to energy supply or to storage) and production (decide which power plant needs to supply first). The monetization of the flows is also found and is described in section 4.2. From SCC projects, **PEDs play a key role in this part of the horizontal chain as PEDs need to manage the energy flows exchange with external grids and within the boundaries**.

The POCITYF project integrates P2P, energy storage and RES in Evora and Alkmaar. In Evora, 2nd life residential batteries are used together with a **P2P energy trading platform and control algorithms for the provisioning of flexibility and market services** [45]. At Alkmaar there are centralized solutions at city level (a city energy management system) for offering flexibility services and a decentralized trading energy platform for P2P [46]. Furthermore, a **HeatMatcher** is applied to make an optimal balance of heating and cooling provision. The HeatMatcher is also found in the MAKING-CITY project in Groningen, which helps **optimising across multiple energy producing components** – such as heat pumps with thermal storage, solar collectors and gas heaters. Groningen also includes **demand response algorithms, using the available energy flexibility within the PEDs** (e.g. storage, time, shifting, etc.) **to optimise the energy productions and consumption** within the PEDs. Lighting control is also found in PEDs such as Oulu, where **LoRa (Long Range) wireless network** and activity sensors is applied to optimize the lighting level in evening and night time using 50 controllers and 50 activity sensors [47].

In the case of the ATELIER project, a large-scale deployment of local PV will be achieved. Furthermore, one of the areas included in the PED boundaries is a **smart grid,** which allows P2P trading, and participation in the Buiksloterham Energy Community [48]. This concept of the smart grid will be deployed in the building blocks of Republic and Poppies, which will also **integrate demand-response to**

reduce peak loads and congestion management, and local storage to reduce the curtailment of RES [49].

As a summary, the conversion part of the energy chain, digitalisation can help to:

- Optimise flows in a bottom-up approach, and improve load local balancing; which can reduce peaks, and therefore, primary energy consumption that usually comes from fossil fuels[4] generators;
- Allow more flexibility providers, and therefore, allow direct load control, which can offer a more attractive, clean and cost-efficient spinning reserve loads [50].

4.1.3. Final energy (demand)

The majority of the tools are related to final energy use. Sensors are applied at building and city level to gather information. For example, in Hamburg floor sensors in parking lots allow to improve the service provided by phone applications for smart clean mobility, which allows to increase confidence of EV drivers and EV use [51]. In Vienna 111 households take part in the ASCR research program. They agreed to provide their energy consumption and home data (electricity, hot water, cold water, room temperature, indoor air quality, etc.) for research purposes [52].

Smart buildings, smart vehicles, smart meters, and smart lighting are widely applied in SCC projects. These smart appliances **allow for monitoring and remote management**, and, once they are connected to the cloud, then they can be considered IoT[5]. These IoT can also **integrate sensors for different purposes**, such as the Viennese traffic signal systems that are being equipped with a total of ten thousand weather and environmental sensors, which help to recognise the heat island effect. IoT and smart appliances can also help to **reduce the impact on urban energy systems (grids) thanks to linking them with cloud data.** For instance, in Helsinki, a Smart personal EV charger was developed to create a solution for personal EV charging considering grid load balancing and variable price of electricity [53]. In Tepebaşı, an intelligent lighting system was introduced in four streets. Changing the system from high pressure sodium (HPS) lamps to light-emitting diodes (LED) only would have saved 37.5% only, but thanks to smart lighting (which dims the lights by 80% with no activity) savings of 85.33% were achieved [54]. Lastly, IoT can **improve and/or develop new services thanks to data availability**, such as in New York City Smart traffic signal systems are connected with buses (that are geolocated) to reduce commute times and improve public transport [55]. In San Sebastian, advanced data

[4] Traditionally, in electricity networks when demand and supply need to be adjusted in a short time interval of time, the operating reserve systems (fast-start generators, spinning reserve,etc.) start to generate the extra capacity needed.

[5] Internet of Things (IoT) are the suite of technologies enabling the connection of physical objects to the internet

analytics methods can provide very exact aggregated information about mobility of people in the city as mobility heat points, origin-destiny matrix, etc.

When analysing IoT implementation, it is **difficult to quantify the impact, as it is needed to compare the impacts with not only the baseline but also with the same solution without the smart component**. IoT and smart appliances can in a general way:

- Monitor the city in a holistic and integrated way;
- Increase demand-side flexibility (of aggregated smart IoTs);
- Reduce peaks (and impact on the grids), which can lead to a reduction of primary energy and fossil fuels and prioritize non-flexible demands.

Other tools that are found in the final energy use are citizen engagement digital tools, which are described in section 4.2.

4.1.4. Cross-sectoral tools

According to Mckinsey, to make a smart city the layers of smartness are needed. The first layer needs **networks (1G to 5G), connected devices (smartphones), and sensors** [7]. Different types of sensors were previously mentioned. Sensors, together with high speed networks, IoTs and data coming from smartphones or applications (see section 4.3 for citizen engagement apps that allow to collect data), **can help cities to improve their services** (e.g. using digital signage or mobile apps to deliver real-time information about public transport delays) and the **wellbeing of citizens** (e.g. in Vienna the traffic signals and sensors allows to improve traffic flow and reduce commute time; in Beijing when pollution is detected the traffic is regulated). Real data from sensors can also **allow reducing the uncertainty of energy models, tools and enable the development of digital twins. It can also help, if applied with AI, tp bring disruptive technologies closer to market,** such as autonomous vehicles, which can ultimately offer clean mobility, and faster commute times [56]. In Oulu, a 5G network is being implemented at city level and also within the PED as part of the MAKING-CITY project, **increasing the speed of data sharing and reliability.** At the PED, the wireless data transfer network will cover the whole area for control and data aggregation.

The second layer of smartness is the **change of behaviour**, which **can be promoted through the use of platforms and phone applications.** For example, in Sweden "City as a platform" is a **collaborative space** that gathers 18 municipalities in Sweden to tackle data sharing, and interoperability issues, among others, and agree on data models and Application Programming Interfaces (APIs) [57]. Others, like Amsterdam, are setting collaborative spaces among researchers and public entities, such as Open Research Amsterdam to share what is being researched in Amsterdam (under open data principles) and to connect researchers. Although stakeholder platforms are useful for a city to potentially create new services and connect people, there is **a lot of data available and unutilized potential that can be used to actually help shape cities** [58]. More citizen engagement digital tools can be found in section 4.2.

The last layer covers **smart applications and data analysis capabilities,** which help **translate data into alerts, services, and tools** that can be used by stakeholders, citizens, and municipal actors.

Urban data platforms

"An urban data platform (UDP) enables digital technologies that can bring together and integrate data flows via open standards within and across city systems and city infrastructure of the public and private sector. It also makes the development of data resources and information tools accessible for further exploitation, visualization, and modelling in a comprehensive, reliable and affordable way"

In 2015 the EIP-SCC set a goal to 'serve 300 million Europeans with urban data platforms in their cities by 2025'. According to the Erasmus Centre for Data Analytics (ECDA), which researched the efforts of 80 European cities using UDP developments, found that still 44% of the 80 cities are starting exploring UDPs, and **only 31% are actually using UDP operationally**.

The involvement of stakeholders in UDPs varies from city to city: 19% are developing an internal data platform within the municipality, 45% include data from their municipality and other business stakeholders, and 16% have an urban data platform governed by an external stakeholder that does not include data from the municipality. According to ECDA, the main challenges the cities found are [59]:

- developing extra capacities in their teams, which includes data management across silos (communicate between city departments) and new agile governance;
- contractual complexities and legislation (such as privacy and procurement)
- cyber security risks;
- data ethics and societal concerns;
- digital literacy;
- skills of end-users.

In general, "usage of the operational **UDPs** in terms of connected data sources, actual end users and applications that run on top of the UDP is still low". But there are some good practices. For instance, 3D Helsinki Energy and Climate Atlas allows seeing calculated data of water, DHN and electricity consumption, solar and geothermal potential which can potentially help stakeholders to **evaluate scenarios, to find areas for potential investments, or optimization of urban system networks**, such as district heating [60]. Furthermore, UDPs can help to improve and/or develop new services thanks to data availability and to gather people's feedback. **Lyon data platform provides open data sets for**

citizens and private companies. The later ones develop new citizen services thanks to this. Lyon also provided a tool for a multimodal route planner[61].

Generally speaking:

"UDPs can help a city make better decisions in a more holistic way (in energy and other sectors), encourage energy efficiency, and reduces energy costs (thanks to optimization and better management). "

Nevertheless, ECDA comments that "although there has been progress in implementing urban data platforms in cities, there is a long way to go before the real potential is realised and before we reach the goal set by the EIP-SCC" [59].

Urban energy planning and design tools

Urban energy planning is a complex discipline that implies a combined analysis of multiple inputs, from varied areas such as spatial urban analysis, energy system engineering, social and behavioural science, or policy and regulatory elements.

Digitalisation is playing an important role in general urban planning, where data and processes have been digitalized around the world, and vast amounts of geospatial data are used within cities' planning departments. An increasing share of that data is also made openly available through data portals, on topics such as urban planning, tourism, and increasingly real-time data in the transport and mobility area, such as datasets on available parking spots, public transport or bike schemes. Use of these **data** by citizens or other private or public stakeholders **can help to tackle typical urban challenges such as congestion and pollution, and to improve the quality of urban public services and the interactivity between the local government and citizens** [62].

The use of this **data for urban energy planning is however not very common and requires additional efforts to treat, process, and combine with other data sources.** In the REMOURBAN project. Nottingham's City Information Platform [63] gathered datasets relating to different intervention areas, and the major challenge was to manage and interpret the data from all the devices, as there were many variables to monitor and the data retrieved came in different protocols and forms. **Big data techniques and standard formats should be integrated in the sensors as a "plug and play" system embedded to speed the data analytics and its integration into larger systems (clouds, platforms, etc.).**

Urban energy data is currently scarcely available. Access to disaggregated energy data (e.g., at building level) is generally not available for privacy and data protection issues, or because it has not been digitalized.

There are however various EU initiatives that can facilitate access to GIS energy data for urban areas where there is no current data available. As an example, with the HOTMAPS tool, cities can estimate current heating and cooling demand, identify renewable energy or calculate the optimal energy mix for district heating supply within a certain area [64].

The Pan-European Thermal Atlas (Peta), which initially included only data about thermal demand and potential supply, is being extended through the sEEnergies project as a cross-sectoral mapping platform, to include geospatial information on energy efficiency and infrastructures in the building, transport, and industry sectors [65].

More detailed models at urban scale also have been developed in the last decades, with modelling tools and practices searching for different ways to generate missing data, and enable a better representation for urban areas, for example gathering data from energy certificates, or developing building stock energy models.

Urban energy system models are formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area [66]. **These models can describe in detail demand and supply at district or city scale, and providing both simulation and optimization. While been a potentially powerful tool both for planning and design, those details models, as reviewed by Sola et al., are however mainly used by academia** [67]**.**

Building stock energy models (BSEMs) need a special mention on the spectrum of urban energy system modelling. These models are widely extended, and as main characteristics **can (a) represent multiple buildings** - often geographically co-located; **(b) produce energy use metrics as an output; and (c) generate out-of-sample predictions** [68]. Feeding from different detailed georeferenced data available at building scale, such as cadastral data of Energy Performance Certificates, the energy models are **generally built through a bottom-up approach**, using building archetypes or representative buildings to map the energy use of the building stock.

Simulated results for the building stock of an urban area can be as detailed as showing energy use and type of energy system for each building. This simulated **data can be calibrated** depending on the availability of real data, which commonly is provided from Distribution System Operators (DSO) and supplied only for whole urban area or at district level.

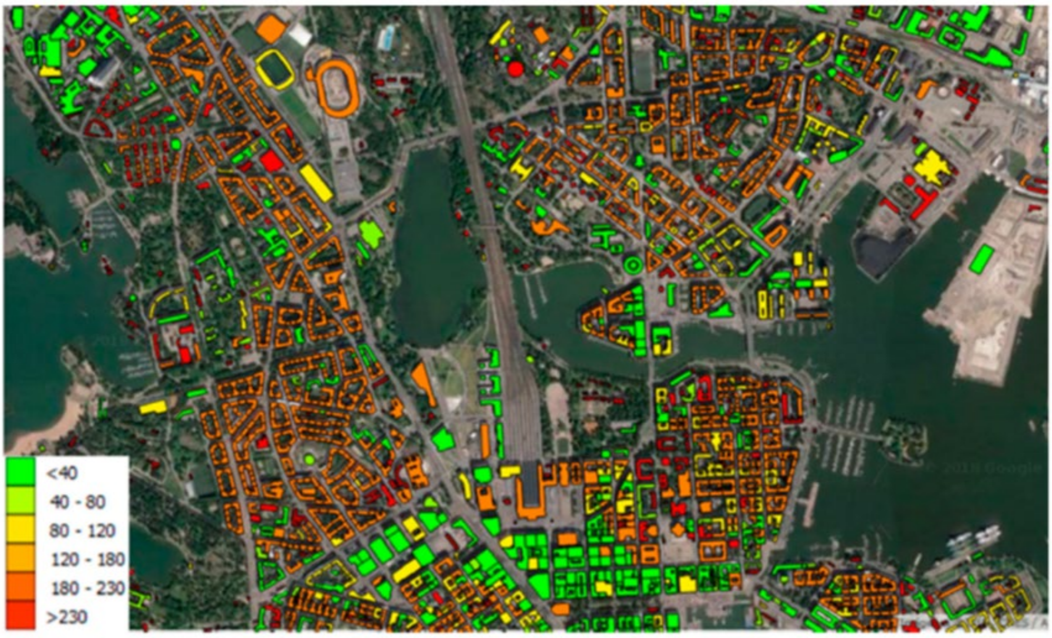

Figure 7 : Example modelling results for the heating demand (kWh/m² year) of the buildings of Helsinki [69].

For **building stock data models to be widely used in urban energy system design, its development and access to data needs to be further standardised and made open**. There are some advances in this area, with the most common data format for storing and exchanging information in building energy models being the **CityGML** format, which has several Application Domain Extensions (ADEs) that can enrich the data model with new feature classes and attributes, while preserving the semantic structure of CityGML [70].

There is a large potential for using building stock models in combination with other tools for simulating other sectors (electricity grid, mobility, thermal grids), in order to develop digital twins of urban energy systems, which could be a key tool for energy planning and urban energy system design. Zhang et al. reviewed several successful applications of digital PED twins, acknowledging its potential and discovering further challenges and opportunities in relation to data analysis, semantic interoperability, business models, data security, and management [71]**.**

Digital Twins

A digital PED twin usually consists of four important components: (1) a virtual model of PED, (2) sensor network integration, (3) data analytics, and (4) stakeholder layer, which combines capacities of a virtual model, data management, analytics, simulation, system controls, visualization, and information sharing. Figure 8 displays a schematic of how a digital PED twin is made. A digital twin is a combination of several modules, such as a computer model, a physical model, communication services, and data analytics. These modules work in synchronization to monitor, learn, and optimize the complete system operation.

Until 2020, there were several digital twin developments [72]. A **digital twin project in Helsinki** has been developed on CityGML, which is a semantic, expandable information Open Geospatial Consortium model [73]. **Rennes, France, has established a digital 3D model** for various urban studies (such as for urban mediation with citizens) and for urban development purposes (such as sunshine simulation, noise modeling, and tree shadow impact on buildings) [74]. **Rotterdam, Holland, applies a digital twin for managing the city's infrastructure assets** [72]. **Pasadena**, California, in the USA, has developed a useful **supervisory tool for the city's public sector players**. Meanwhile, **Portland,** Oregon, in the USA, plans to **construct a digital transportation system** activated by residents' cellular data [75]. The **waterfront in Toronto**, Canada, is using digital twin technology to **launch a public advocate of waterfront revitalization, along with the urban innovation organization Sidewalk Labs** [76].

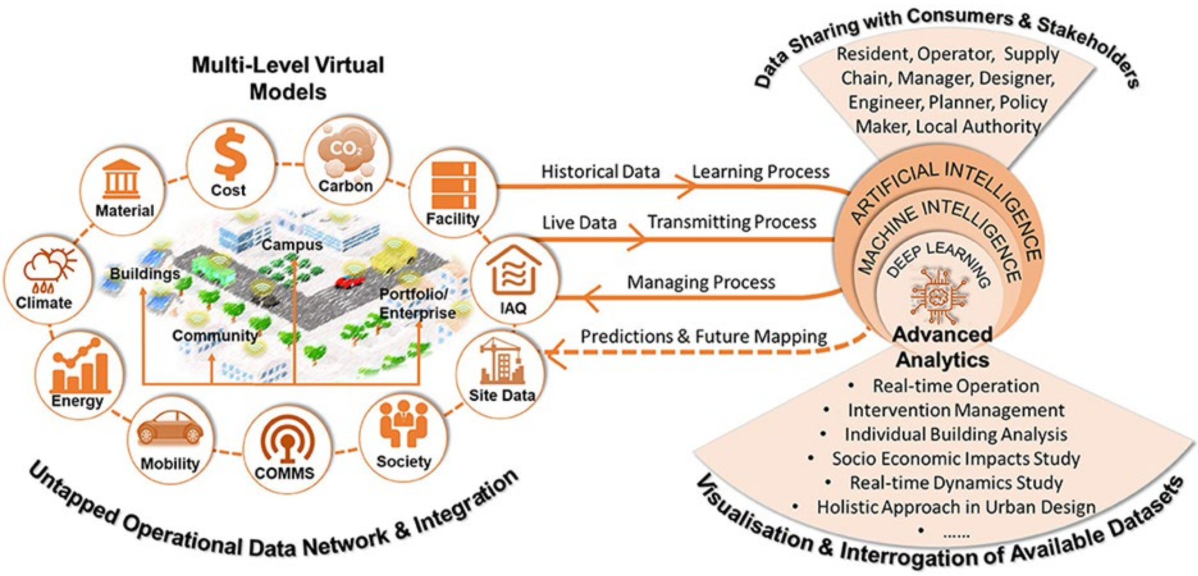

Figure 8 : Schematic design of key components in a digital twin [71].

A project **in Dubai focuses on users' experience** by using a digital twin. Jaipur, India, is using a digital twin project for urban planning and supervision [72] (Research Markets, 2020). In **Shanghai, China, immersive digital twins** in railway engineering have established new practices to deliver a sewage treatment plant [77].

Some lessons and observations are gained that **digital twins can be categorized in three tiers**: (1) an enhanced version of Building information modelling (BIM) model only, (2) semantic platforms for data flow, and (3) AI-enabled agents for data analysis and feedback operation. Most of the **projects/cities are in the first two steps to support planning** of the urban energy system, while the third step requires further development in order to operate and manage cities in the optimized way. Temporally segmented **daily efficiency metrics integrated into digital twin–enabled energy management platforms can transform approaches to energy management across a portfolio of buildings** [78] **and help across the different phases of the city** (planning, design, and operation), as integrates a reliable model (calibrated with real-time data) and spatial analysis.

CASE STUDY: Helsinki Digital twin

The Finnish capital of Helsinki is currently in the process of developing a digital twin city. They are developing a three-dimensional representation of the city (a model) by geo-referencing the data and feeding the model with data (energy, water, transport, security, buildings and healthcare). Everything will be shared as open data to encourage different stakeholders to use it to produce new products and new innovations [79].

To create the 3D representation the city has used laser scanning and oblique photogrammetry. They have two models: a city information model based on cityGML and ContextCapture. They used ProjectWise to connect data with the digital twin. They also have a pilot project portfolio to integrate these models into processes. They used serious games to let citizens simulate scenarios in the 3D model, such as increasing green areas [80].

4.2. Business models that drive the urban energy transition

UES are being rapidly affected with new value propositions and new market players emerging around aggregation or individual energy trading. Section 4.2.1 explains the main digital technologies that facilitate the monetization of energy trading, whereas section 4.2.2 deals with the types of energy trading schemes. Both sections set the context to finally describe the type of business models and the technologies used in section 4.2.3. Section 4.2.4 highlights some good practices in Europe.

4.2.1. Technologies for energy trading

The **main technologies for energy trading** are firstly reviewed and summarised as below. Table 2 compiles the main characteristics for these technologies.

- **Artificial intelligence** (AI) - an advanced approach to understand the past, optimise the present and predict the future.
  - Currently intelligent systems can be used in electricity markets in different applications: (1) alarm processing, diagnosis, and post-fault restoration, (2) forecasting and (3) security assessment [81].
- **Machine learning** - one of the ways to implement AI.
  - Mostly they are clustering, regression and classification approaches
  - Applied for customer segmentation, pricing forecasting, fraud detection, and predictive maintenance and operation [82].
- **Deep learning** - one of the tools of achieving machine learning.
  - Deep networks for unsupervised or generative learning: to conduct pattern analysis of the observed data and capture the correlation between datasets when no information about target class labels is available.
  - Deep networks for supervised learning: to directly capture the correlation of observations for pattern classification purposes with distributions of classes on the captured data available.
  - Hybrid deep networks: to achieve pattern discrimination with data assistance and produce the outcomes of generative unsupervised deep networks.
- **Blockchain** - a distributed chronological ledger that is able to record, validate and store transaction information within a 'node' network instead of using a single centralized authority.
  - Greatly shorten the operation period by removing this central validation, and make transactions happen almost instantly [83].
  - Blockchain can initiate the shift of the trading ecosystem from a centralized to decentralized one [84] by:
    - removing the dependence on intermediaries through direct end-to-end energy trading;
    - enabling individuals and communities to start energy production with initial investment gained through crowdfunding;

- packaging a number of energy services (e.g., billing, supplier switching) as an integrated solution at a generally lower price;
- providing a platform to allow energy initiatives such as an integrated system to consolidate a household's daily energy consumption, which might include washing, HVAC and vehicle battery charging.

It can be used at different levels of the energy system value chain (e.g., investments in assets, tokenization of energy assets, registering transactions, and direct payments etc.).

- **Internet of things (IoT)** - integrate smart appliances for energy services

4.2.2. Types of energy trading scheme

The different types of **energy trading schemes are** summarised as below [83], which are further visualized by Figure 9.

- **Traditional energy trading scheme**
  - Bilateral contracts [85].
  - Hour (or day) ahead markets [86].
  - Ancillary services markets [83].
  - Capacity markets [87].
- **Feed-in-Tariffs (FITs)** - paid for electricity generated from renewable sources fed back into the electricity grid.
  - It removes the need for the prosumer to actively 'trade' their electricity because they are offered a fixed price for it which does not vary in time or with network conditions.
- **Flexibility aggregator** (also known as distributed system platform or energy hub) - it pools the flexibility and offers flexibility to balance energy markets or to a grid operator, and meanwhile stimulate investment, innovation and improve customer choices. When the flexibility is activated, the aggregator receives revenue from the provided flexibility service. The aggregator redistributes some of the revenue in the form of a premium to the flexible prosumers [88][89][90].
  - Some supplier or a third-party operator can offer aggregation services (e.g., trading, balancing, and network services) in markets, such as **Virtual Power Plants (VPP)**.

    - In most cases, "independent aggregator" enables distribution system users to actively participate in electricity markets either implicitly or explicitly, such as **demand response (DR)**.

- **Peer-to-Peer (P2P) trading** - producers can also be consumers and the energy produced by one prosumer (function as both producer and consumer) can be shared with another prosumer. P2P trading usually contains a few characteristics as below:
    - Some P2P energy markets are **designed with blockchain** where all transactions will be validated by every node of the network and stored permanently without the involvement of a central authority.
    - **Smart energy contracts** are available through the integration of blockchain with energy trading.
    - **P2P energy trading can bring additional flexibility to the system** in the energy market by:
        - **Innovative tariffs**: flexible and innovative tariff designed to suit the new patterns of the energy market;
        - **Smart home devices**: using the Internet of Things (IoT) to connect the online flexibility market with flexible energy equipment;
        - **Energy storage technologies**: saving electricity to bridge the gap between demand peaks and valleys, as well as increasing flexibility and liquidity;
        - **Consumer data collection and forecasting using machine learning**: applying digital technology to analyse consumer data and better match available supply and demand.
        - **Connection with flexibility aggregator**: providing energy to other communities/cities via grid.

4.2.3. Types of business models

In this report, we define 5 categories of business models for DUES, which are:

- **Savings** - revenue through energy and cost savings;
- **Software** - sale of software or application of tool/platform;
- **Products** - materials, hardware (smart plugs, batteries, meters or other components;
- **Services** - analysis, energy balance, other data related activities;
- **Energy** - direct sale of energy.

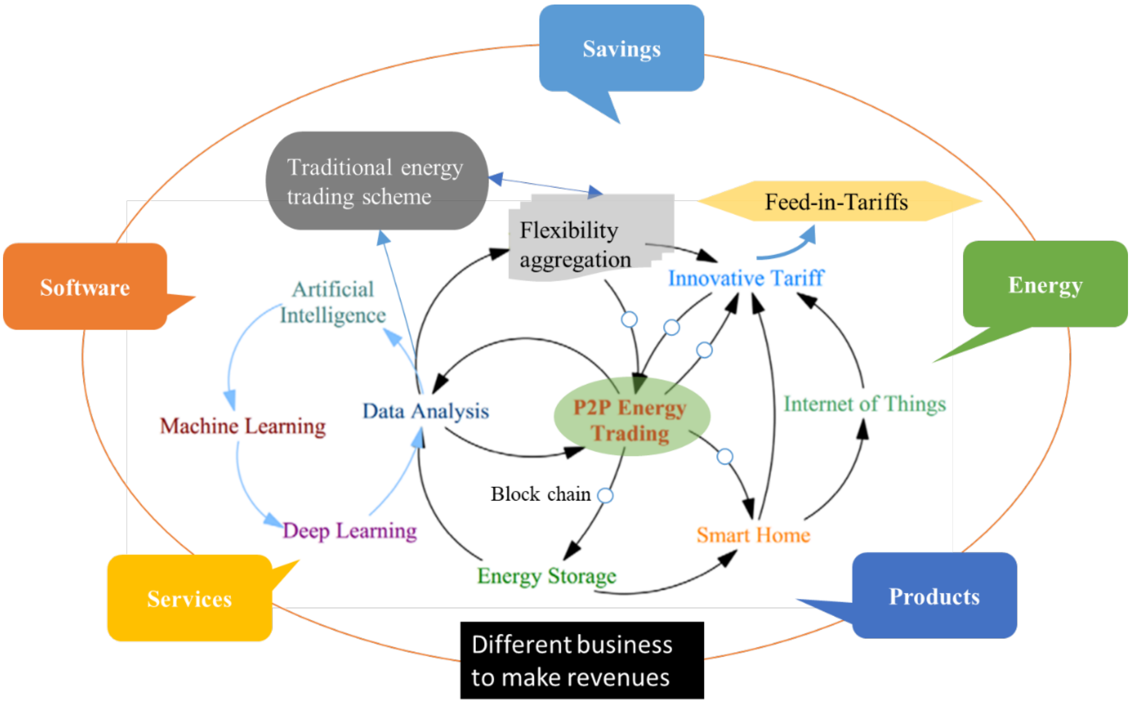

Figure 9 : Flexible urban energy market ecosystem (revised based on [83])

Table 2 : Summary of technologies for business models

Technology	Used for	Description	Enablers	Barriers
Artificial Intelligence	• Carbon management • Energy efficiency • EVs management • Grids services • Platforms & P2P • Smart metering	Optimization and prediction using past data	• Large amount of available data and algorithm • Complexity in energy system • Optimising resource utilisation	• Existing market mechanism • Depend on data resource • Lack of previous experience
Machine Learning		Analytical tool enabling AI		
Deep Learning		Accurate energy consumption forecasts production tool		
Blockchain	• Carbon management • Energy efficiency • EVs management • Grids services • Platforms & P2P • Smart metering	Distributed ledger	• Tedious trading process • Need in increasing trading efficiency • Trading from a centralized to decentralised one • Reducing unnecessary	• Slow transaction due to proof of concept • Lack of regulations • Energy-intensive computation • Lack of previous experience • Conflicts of interest of

			financial burdens • Engage market participants • Build trust among prosumers	established trading schemes • Challenge in local energy market
Internet of Things	• Energy efficiency • EVs management • Grids services • Platforms & P2P	Integrate smart appliances for energy services	• Engage market participants • Demand response • Improving grid service • Collection of data	• Relying on sensors • Limited by data interpretation • Lack of guidance for use engagement

A short survey was conducted for different business models in 48 companies/projects (details are listed in Annex 2). Further, in Table 3, we analysed all these business models and their business areas according to the survey. It is found that **P2P trading models have a potential to bring benefits to the overall energy system** by offering customers more options, increasing trading efficiency and optimising resource utilisation, reducing unnecessary financial burdens, introducing more market participants, building trust among prosumers, and making the transaction procedure simpler. It **brings a relatively high number of actors** in the business service for P2P trading by **using the new technology such as blockchain**.

Table 3 : Summary of business models and their business areas

Business models	BUSINESS AREAS: Carbon management	Data analysis and management	Energy efficiency, energy savings, domestic applications	EVs and fleet management, smart charging and parking	Grid services, grid performance and monitoring	Platforms, P2P energy trade, flexibility, storage	Smart metering, billing, and switching
Savings	2	1	2	2	1	1	2
Software	n/a	n/a	5	n/a	2	4	n/a
Products	1	2	3	1	n/a	2	n/a
Services	2	3	8	3	5	15	1
Energy	n/a	n/a	1	3	n/a	6	1

4.2.4. Case studies using digital business models

An energy trading case study is found below, which uses a platform for P2P and data for traceability of the guarantee of origin.

CASE STUDY: Vienna's energy community of OurPower

In Vienna the non-profit European Cooperative (SCE) OurPower has created a peer-to-peer marketplace for RES electricity generated by its members. OurPower handles the online matching services as well as the whole process of electricity supply and billing. Now, prosumers instead of feeding electricity anonymously into the grid at low market prices, they sell electricity to the communities at a fairer price (for consumers and for producers). The OurPower marketplace brings buyers and sellers together and ensures that all energy and payment processes are transparent and secure. This ensures you a long-term, stable, and fair price for your green electricity and makes you independent of electricity exchanges.

OurPower has authorization to the electricity meters of producers to E-Control guarantee of origin database [91].

Other business models, such as **car sharing,** affect the digitalisation of the mobility sector as well. Several car sharing programs already operate all-electric fleets, including car2go (Stuttgart, Amsterdam, Madrid, Paris), and DriveNow (Copenhagen). The business model of car2go is that it only enables people to book a car 20 minutes in advance, whereas DriveNow offers free parking anywhere and there is no need to end the rental period when the vehicle is parked. **Generally, they rely in phone apps** mainly to make the rental of the cars. **Sometimes they are charged by a small subscription fee plus rates based on time and kilometres driven, while others are only paid when they are used.** Car2go and DriveNow is a **free-floating** service and they operate in an indicated area (allows to go from point A to B), while **others need pool stations** (Autolib, Bluetorino, etc.) **and others need to be returned** to the zone or station from which they started (Ubeeqo, Cambio, Greenwheels, Io Guido need roundtrips) [92]. Lastly, **P2P platforms** are also appearing such as "CarAmigo" in Belgium that allow **members of the system to rent their cars without obligation**. The car owner receives requests directly to your email address or by SMS [93].

Another example of business model is a **"sustainable business model" in which there is no profit** and it embraces a different array of value propositions. A great example is Vienna's culture token, **where the value is the CO_2 reduction which is incentivized by exchanging the token for cultural services.** Indirectly, it **improves social wellbeing** (e.g. healthier lifestyle, less noise, etc.) and **air quality** (due to the reduction of car use) [94].

CASE STUDY: Vienna's Kultur-Token

Vienna has launched a research project in which citizens can obtain rewards for climate-friendly behaviour, called "culture-token". The app allows to visualize, tokenize and reward sustainable mobility behaviour. Citizens provide information and allow the app to use motion tracking to measure the distances users travel. Then, it calculates their personal CO2 balance (CO_2 saved by walking, cycling or using public transport compared to travelling the same distance by car) [94].

4.3. Digital tools and technologies for citizen engagement

Access to urban digital platforms, digital policy measures, dedicated platforms for citizen engagement, Phone apps, citizens cards, digital education allow to:

- **Include services to be provided to citizens**: besides including sensor data and KPIs calculation, Urban digital platforms and urban data platforms can also include services and models in the backend to allow the user to test different scenarios in the city (or in their house). For instance, the Urban Data Platform in Nantes has an algorithm for optimizing electricity contracts, as well as a tool for diagnosing the most important opportunities for energy reduction in public buildings [95].

- **Inform citizens and stakeholders**, set a collaborative space that allows to share and engage with them and between them. For instance, the Smart city platforms of Vienna [52] and Amsterdam [96] allow to share projects, initiatives, ideas, etc. between stakeholders, and keywords are used to ease the search. Open Research Amsterdam [58] follows a similar approach but open data is mandatory and it is aimed at academia and the public sector.
- Phone apps **for sharing experiences**, or **data collection** as citizen sensing approaches. For instance, the "Serious games for energy saving" in Nottingham [97] allow players of the game to share and compare their energy use. Another example in Valencia [98]- residents can communicate directly with the city and also receive notifications and information related to works, events, Covid-related news, etc. The Valencian app can also be used to foster public participation and offers real-time information on public transportation.

CASE STUDY: Carbon Ego mobile application in Helsinki

Carbon Ego mobile application is a mobile app to show different statistics to the user. User can select their house and see their estimated carbon footprint, as well as perform a test and engage in challenges with neighbours. More in: MYSMARTLIFE Helsinki [99]

Citizen engagement activities frequently include workshops with residents, experts, and policymakers around the topic of digital rights, and related opportunities and challenges. These serve to widen the impacts of citizen-engagement such as:

- **Support for the implementation of public policies;**
- **Realise savings by adjusting our electricity contracts to actual consumption;**
- **Inform citizens and stakeholders;**
- **Safeguarding digital rights in cities.**

Citizens can be part of the data collection processes, such as the Telraam project. Notify directly when there is a problem in the city (e.g. AppValencia) and answer to them in real time (through chatbots like in Vienna [52]).

CASE STUDY: Telraam project

Within the Telraam project, Transport & Mobility Leuven co-developed an integrated application based on low-cost hardware and a public online platform allowing citizens to perform traffic counts. Citizens can put a small metering device and a microcomputer near their window to take part.

Pedestrians, cyclists, cars, and heavy vehicles are each counted individually when passing along the traffic count sensor. The resulting traffic data can be used to perform traffic engineering studies. Like this, citizens and citizen platforms collect objective data, allowing them to engage in a dialogue with their local government. This can potentially result in actions such as a modification of the driving direction, the re-design of the public space, an improvement of the cycling conditions, or a modification of the parking facilities. In the European project, WeCount the traffic counting data with Telraam are linked, for example, to air quality measurements. More on: telraam.net [100]

4.4. Impact on energy sector

World population is growing, and cities are rapidly increasing in size and complexity. For instance, electric mobility connects transport and energy sector operation, and at the same time, new players enter the market, such as prosumers. **Managing the platforms and data required to keep this system operating effectively becomes a central part of the new energy economy, as does mitigating associated cybersecurity and data privacy risks** [36]. According to the last Global Enabling Sustainability Initiative (GeSI) report on Digital solutions for climate action, "Information and communication technologies (ICTs) are a contributor to greenhouse gas emissions [6], but their impact is much more in terms of its mitigating effect on the highly energy-intensive and polluting sectors such energy generation, transportation and buildings, and in helping efforts to adapt to climate change".

In the mobility sector, digitalisation is intrinsic to the deployment of connected and autonomous vehicles, and of the rise of on-demand mobility or mobility as a service (MaaS). These, together with the electrification, will bring radical changes to the urban energy system, that can result in substantial but uncertain energy and emissions impacts [36]. Furthermore, according to this report, **digitalisation could cut total energy use in residential and commercial buildings by around 10% to 2040.**

These estimated savings are however very uncertain as they will greatly depend on building user acceptance and changing behaviour. More optimistic estimations specific for the heating and cooling sector indicate that **models to predict building behaviour, will lead to 5-70 % of energy savings and 10-40 % of peak power savings** [101]. However, new services and comforts brought about by digitalisation – as well as greater use of standby power by idle devices and appliances – could offset potential savings. Figure 10 shows a summary of potential impact of digital tools in different sectors and its savings (in energy, water, commute time and waste). Details explanations can be found in sections 5.4.2, 5.4.3 and 5.4.4.

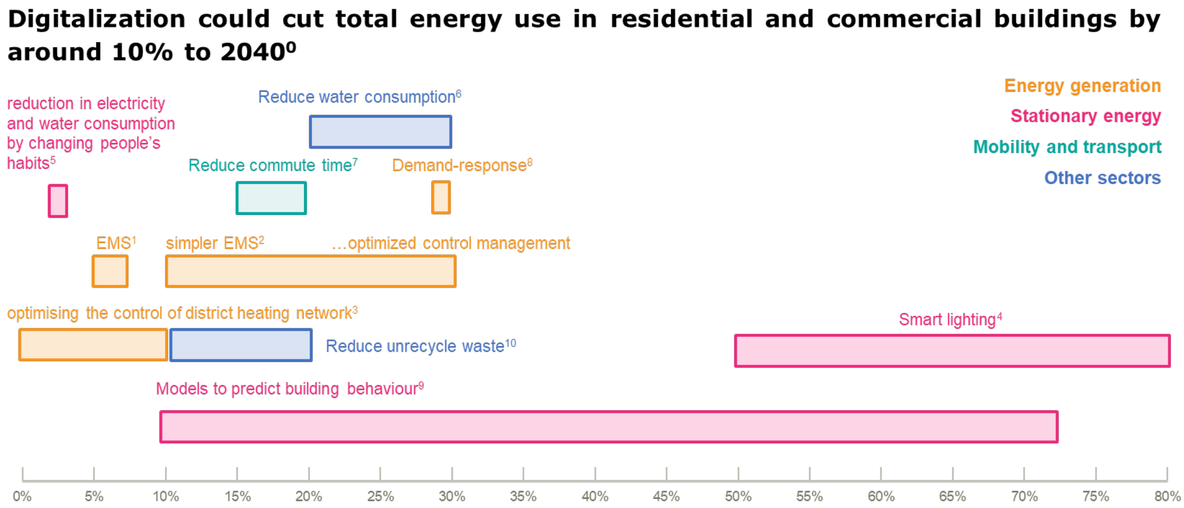

Figure 10 : Summary of digital tools impact potential

*References in figure: 0-*IEA, 2017 [36]; *1-REMOURBAN* [63]; *2-Al-Ghaili et al., 2021* [102]; *3-CITYFIED project* [103]; *4-Tepebaşı* [54]; *5-My Sustainability Living Program at DEWA*[104]; *6 and 7-*McKinsey [7]; *8- Making-City project* [47]; *9-Lyons,L., 2019* [101]; *10-New York City Smart traffic signal systems* [55]

4.4.1. Impact evaluation frameworks for digitalisation in urban energy systems

Over the last decade, many initiatives have proposed different monitoring and assessment frameworks for evaluating impact of smart city solutions. The CITYKEYs project [105] already compiled numerous initiatives and frameworks, and promoted harmonisation of indicators for the assessment. The Smart Cities Information System (SCIS), a knowledge platform to exchange data, experience and know-how and to collaborate on the creation of smart cities, developed a framework and indicators for assessment departing from CityKeys and a number of other initiatives. The SCIS collects KPIs from different 'smart city projects' at different aggregation levels (e.g. building, set of buildings, energy supply unit, set of energy supply units, neighbourhood). Some of the KPIs at the upper levels can be calculated from simple addition of the lower levels, while some other KPIs are specific to each level.

The **information and KPIs included in SCIS framework** for evaluation of digitalisation could give a good overview of the technical economic, environmental and social performance of the different digitalisation actions within the smart city projects. However, the reviewed information from the current database available at the Smart Cities Marketplace [106] is still **not sufficiently robust to allow an impact assessment of digitalisation.**

As an alternative, a review of case studies from Smart City projects, together with general commentary on different solutions, has been performed to give a clear illustration of the potential carbon abatement afforded by digital solutions and also the co-benefits that can come with it (co-benefits for the social structure, social well-being, economics, etc.).

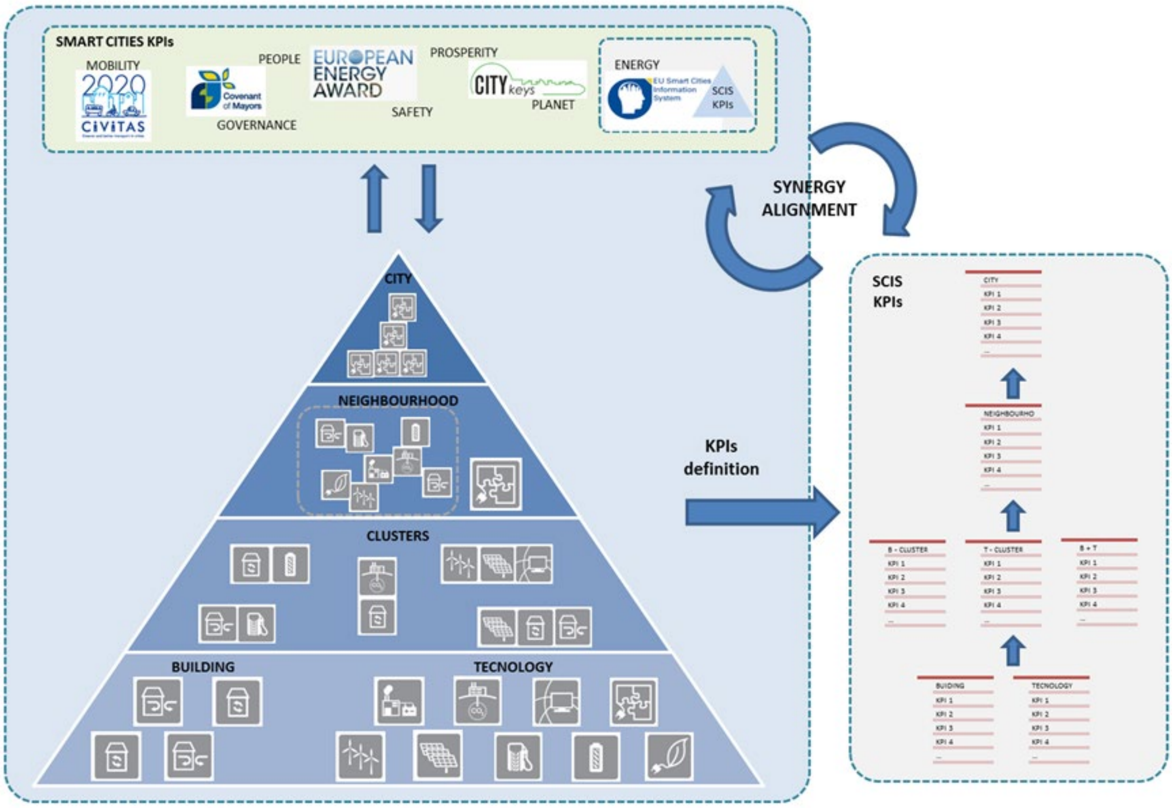

Figure 11 : 10 SCIS indicator framework development [106].

4.4.2. Impacts of digitalisation in the mobility sector

In the mobility sector, a key economic impact of digitalisation in cities will be the reduction of the cost with the advent of autonomous vehicles, which could result in Mobility as a Service (MaaS) being up to 40% cheaper than private vehicle ownership [107]. Applications such as Volvero [108] in Brussels, OpenMove [109] in Trentino or Instant System [110] in Biot already promote renting and sharing of vehicles instead of property.

Electric mobility is key for improving air quality in the cities, and also for reducing overall CO_2 emissions. There are also many opportunities to improve the performance of electric vehicles (EV) **through digitalisation,** resulting in economic and GHG savings. Public electric buses can **reduce their energy use between 10 and 15%** by using specific software and sensors to determine eco-driving patterns and achieve larger battery life. **Smart load management and smart charging stations**, as implemented in Valencia in the MAtchUP project [111], can **facilitate vehicle battery storage to provide building-level electricity demand management services, can reduce peak demand, and assist with the integration of decentralised electricity generation, providing both financial and GHG benefits.**

New digitally enabled services such as **smart bikes** [112] or bike sharing [54] **can also result in cost savings** on mobility for the citizens. Cargo bikes [113] also offer the possibility of delivering large items by bike instead of a car.

Data platforms such as Florence's Smart City Control Room or San Sebastian Smart Mobility Platform (REPLICATE project [114]) **allow a better understanding of a city's mobility issues and result in management strategies that reduce overall mobility costs and GHG emissions in the city.**

Social impacts of mobility are manifold. Digitalisation should facilitate affordable access to a more efficient and sustainable mobility, including for those communities which currently have more difficult access. However, there is an **actual risk of further divides between social groups with different approaches and access to mobility.** Particularly for those urban areas with potential social disadvantages, digitalisation of mobility should consider aspects such as ease of use, flexibility, safety, travel time and affordability. Public-private understanding and common approaches to mobility solutions will be needed to ensure that advances digitalisation brings to mobility can contribute to removing social and economic barriers between citizens.

The disruptive changes that digitalisation is bringing to the mobility sector will likely mean job losses, for example for commercial drivers with the advent of autonomous driving. It is important that a fair redistribution of jobs is ensured. Reskilling, public engagement, awareness and training exercises should be widely adopted by the stakeholders that need to effectively manage this transition [115].

4.4.3. Impacts of digitalisation in the building sector

Digitalisation in the building sector affects all the life cycle phases of construction, from design and construction phases, to operation and maintenance. As an example, BIM, currently being increasingly used during design and construction phases, can be further updated with sensor-based information, forming digital twins of a building that **could optimize performance through the operation and maintenance phases.**

This section, relating to the urban energy system framework described, will focus on the impact of digitalisation on a building's operational phase, and particularly on the potential of digitalisation for energy and cost savings, and its associated environmental and social impacts.

On a general global review by the International Energy Agency, **digitalisation could cut total energy use in residential and commercial buildings by around 10% to 2040** [36]. However, new services and comforts brought about by digitalisation – as well as greater use of standby power by idle devices and appliances – could offset potential savings. Beyond this general number there is a great uncertainty on how digitalisation affects different types of buildings and buildings inhabitants.

From the review of Smart City projects, some estimations of the impact of individual digitalisation tools are extracted. **Energy savings of about 5% are estimated from the use of dedicated platforms for citizen engagement, which only provide visualization of energy use** (CITYFIED project [103], Soma and Lund demo sites). Similar results are reported by the My Sustainability Living Program at DEWA [104], where Dubai achieved a between **2% and 3% reduction in electricity and water consumption by changing people's habits.**

The variety of combinations between building types, occupants, building energy systems and energy management strategies that could be deployed, makes it very difficult to provide an impact assessment of the implementation of building management systems. The review by Al-Ghaili et al. [102] describes a potential high of **30% savings could be achieved in the most optimized control management, while 10% savings could be achieved with simpler management systems.** In the Valladolid site of REMOURBAN [63] project, however a **smaller 5-7% savings was reported from the home energy management system.**

Estimated **savings of 10% can also be achieved from optimising the control of district heating network through data collection and analytics**, as done in Lund demo site for the CityFied [103] project.

4.4.4. Impacts of digitalisation on integrated infrastructure

Digitalisation can make disruptive changes in the management of electricity and heat loads, supporting energy flexibility and the potential integration on the grid of variable renewable energy.

Smart charging of EVs will be the major player in the flexibility market, with users being able to save charging costs if they can choose to charge at times with lowest electricity cost. The combination of EV charging with PV systems for self-consumption, and the V2G (Vehicles to grid) are also important trends that will affect flexibility markets.

The potential for district heating and cooling networks to decouple demand and supply is also very large, and can make a case for economic viability of new district networks. **Demand response management strategies at district scale** have been estimated in Groningen (MAKING-CITY [47] project) as having the **potential to reduce the energy costs by 30%.**

For individual buildings, depending on its characteristics, U-values of building components and climate conditions, **between 17,6% and 35,3% of the heat supplied by heat pumps could have flexibility potential** [19], **and its management could bring benefits both to the final users and the grid.**

Home energy management systems, have also a great potential for managing flexibility. When combining stationary batteries, with rooftop PV systems, and heat pumps, these would make the prosumers important actors in the energy flexibility market, many of them through energy communities. The role of these energy communities in the different parts of the energy value chain, which currently is mainly through shared supply, self-consumption, or P2P trading, will be progressively expanded to the operation on flexibility markets.

4.4.5. Energy use of data

Digitalisation through all the sectors in urban energy systems **requires gathering and management or large amounts of data.** Beyond data regulations, data strategies need to be developed by the different actors, to continuously improve the way to collect and handle the data. To maximize the data accessibility and openness, is a **crucial issue on which consumers, prosumers, TSO and private and public sector in general should agree on following best practices, with "presumed open" reversing the current default for data accessibility from closed to open** [3]. As a principle that most cities adhere, the more Open Data is provided, the more the community can create new insights making the city smarter [62]. This principle can be applied to the urban energy systems, where the openness of data would be in principle directly related to more energy, environmental and economic savings.

The **data usage inherent to digitalisation also has associated direct environmental and economic impacts.** The clearest examples are related to the energy demand of data transmission networks and data centres, and to energy requirements of sensors, actuators and IoT devices.

In relation to the energy use of data centres and transmission networks, while the **global internet traffic has surged in the past years** (more than 40% in 2020), the rapid improvements on energy efficiency have managed to maintain electricity use fairly stable. **Data centres and transmission** networks account each for **about 1% of the global electricity use**. Most of the data usage is however due to video streaming and gaming, expected to account for up to 87% of global consumer internet traffic in 2022 [116].

The amount of data processed in relation to the energy system is comparatively very small in relation to these major data flows. As an example, the **estimated data generation per day for the city of Barcelona is about 8GB,** corresponding mostly to energy and urban parameters monitoring, that need to be transferred through the Smart City network [117].

This **can be considered a very modest amount of data, compared to the average 9,9 GB which is used for each smartphone on average in central and eastern Europe** [118]. In any case, even if data related to urban energy systems is relatively small when compared to other data processes, attention should be given to networks and data centres energy usage, as they could be themselves considered as part of the urban energy systems. Adherence to initiatives as the "Code of conduct for data centres" [119], and exploring the potential for data centres to be further integrated in urban energy system, both as renewable energy electricity users and generators of waste heat for district networks.

In relation to energy requirements of sensors, actuators and IoT devices, while there have also been advances in reducing their associated energy use through efficient communication protocols, their consumption might still be relevant. For example, Gray et al [120] estimated a very large energy use for home energy management systems, with values between 1,460 kWh and 289 kWh per home and year, which would likely offset all potential energy and environmental benefits. There is therefore a clear need for standardization and policies include the principles of Green IoT, focusing on saving and managing energy in IoT networks in order to optimize and reduce the energy consumption and prolong the IoT networks lifetime [121].

5. Learning Processes & Knowledge Sharing

This research on "Digitalisation of Urban Energy Systems" follows a **participative approach throughout the process for development of the Outlook 2025,**

2030 and 2040. Learning from different experts (both from theory and practice), conducting online digital forum, workshops, interviews and deep literature review on the results of a diverse set of Smart cities and Communities projects prepare the ground for multi directional learning and knowledge and experience sharing. Aligned with this structure, the activities mainly held under knowledge and experience share are classified in two groups: i) interviews with volunteers from SCC projects and ii) workshops organised as foresight exercises for creating scenarios through 2040.

5.1. Interviews with volunteers

While conducting the literature review to identify the digital tools and technologies developed in SCC projects, several questions arose to understand the barriers, enablers, impacts, gaps and business models of the tools utilised in these projects. Questions below are directed to the volunteers from two SCC projects.

1. How do you involve citizens in the core of the digitalized energy system? As Data providers? As co-planners?
2. How do you use digitalisation (of city/energy services/infrastructure) as a way to engage citizens in the energy transition?
3. What are the feasible business models derived or based on digitalisation of urban energy systems in your projects?
4. What tools do cities have to drive investments in digitalisation of (urban) energy systems? Do you know any examples?
5. What are the main barriers for digitalisation of the urban energy system in your projects, and what are potential solutions?
6. What data would they like to have access to (that is not available now to them or not available in general) to support their work as cities to accelerate/facilitate the energy transition?
7. What are the limitations of digitalisation of the urban energy system in your projects, from aspects of data, coordination/governance, capacity, finance, risks and so on?
8. In your opinion, what should be the measures to make digitalisation happen?
9. Are there any training programmes / schemes in place for Public Authorities to enhance their green & digital skills?

Unfortunately, answers to these questions could not be collected from the volunteers. If the volunteers are more collaborative in the upcoming period, results will be integrated in this report.

5.2. Visioning workshops

The aim of the visioning workshops was to build up synergies for imagining the digitalisation of urban energy systems for the future (short to long term). In order to build a variety of scenarios and imaginations for Outlook 2040, gathering experts from different fields and levels is very important. For this reason, external experts from SMEs, universities, RTOs, industries, NGOs, Renewable Energy Communities specialised on energy, mobility and ICT sectors were identified before the research was initiated to invite for the workshop.

The first Foresight exercise, so called "visioning workshop" was conducted on 1st of April 2022, starting with a narrative that is happening in 2040. The story **[Step 1]** guides experts to imagine this future (set a vision for 2040) via utilizing urban energy systems (from supply, towards integrated infrastructures and demand side). After a while, the facilitator directs a few questions (as follows) to shape participant's visions.

Step 1 - Narratives for Future - What is your vision?

Please close your eyes.

Imagine it is 2040 and you're in your "smart home" in a "smart city". It's is a sunny day and you will make a morning coffee. You just pressed the coffee machine button and hmm where is the energy coming from? What is its source? Then, you realized that you don't have so much spare time and you leave the house to meet some friends outside. How are you travelling? You meet in an urban park. It is green everywhere; you're calm in nature (urban natural environment) and smiling.

- Do you foresee any technology there?
- How do you picture a 2040?
- What kind of energy systems do you utilise? Any digitised features?
- What will be the realistic urban energy systems in the next few decades Regarding supply, conversion, distribution and final use of energy?

Participants tried to set a vision by taking notes on black circles and dragged them inside the clouds. Next step is the individual writing session for testing the big steps towards the vision **[Step 2]**. In doing so, questions below were directed to the participants to understand the potential gaps, barriers, tools, engagement strategies, business models and expected impact of their scenarios through the vision.

1. What will be a possible pathway to achieve this future urban energy system? Is digitalisation inevitable? If this future is not digitised (or less digitised) - is it possible to compare it with the first scenario?
2. Is this future a running business for all? What new business models could we have?
3. Until now, supply-side management was mainly the issue for energy efficiency and security. How about the end-user perspective? How to involve the demand side in future systems? How to involve citizens directly in the urban energy systems?
4. What are the gaps, barriers of the developed digital tools and digital technologies in general? Any experience from outside the EU?
5. What could be the positive implications of digitalisation in different sectors of urban energy systems? What could be the negative implications of digitalisation to avoid risks?

The contributions regarding each question may be seen in **Annex 3** in radar diagrams for pathways, business models, how to involve citizens and barriers/gaps through visions set by participants. Next step is the clustering for common vision **[Step 3]**. Several common themes were identified from the visions in discussions of the participants and 6 clusters were developed, namely: i) Autonomous local energy systems, ii) human centric approaches, iii) more intelligence, iv) holistic approach - urban energy planning – circularity, v) sharing economy and vi) not everything is digitised (Table 4).

Finally, last step is to set a common vision statement for 2040. The contributions are as follows:

Table 4 : Workshop Vision's summary

VISIONS – Step 1	VISION CLUSTERS – Step 3	VISION STATEMENTS – Conclusions
Self-consumption	**Autonomous local energy system**	• The urban energy system will be clean, resilient, interoperable, efficient, trustable and share by all the actors, one without giving away autonomy. • Citizens are participative in the urban energy system
Neighbourhood Energy		
Shared RES generation		
e-Mobility and PV-based charging		
e-Mobility and wind-based charging		

<table>
<tr><td>BIPV and high-quality architectural design</td><td rowspan="5"></td><td rowspan="22">and they can make informed decisions.
• Cities are being shaped in a holistic way connecting sectors and different layers of the system (including data, citizens, stakeholders).
• Digitalisation does not need to be everywhere and everything looks natural. Without giving away autonomy.
• Technologies are not slaves but accelerators, and it is being used in a smart way.
• Urban Energy Systems must be holistic and integrated approaches consisting of several different layers – The process is important and adds different actors.
• Cities shape connected sectors. Digitalisation as natural aspects – human-centric approach.</td></tr>
<tr><td>No visible digital technology</td></tr>
<tr><td>Circularity of energy</td></tr>
<tr><td>No visible heating/cooling systems</td></tr>
<tr><td>Autonomous e-mobility</td></tr>
<tr><td>Interaction based on holograms</td><td rowspan="7">More intelligence</td></tr>
<tr><td>Digitalized natural resources</td></tr>
<tr><td>Affordable energy</td></tr>
<tr><td>Home energy system management</td></tr>
<tr><td>Informed decisions and choices by Actionable intelligence</td></tr>
<tr><td>Environmental footprint awareness</td></tr>
<tr><td>Energy Security</td></tr>
<tr><td>Integrated and human-centred energy systems</td><td rowspan="2">Human Centric Approach</td></tr>
<tr><td>Undisturbed natural environment</td></tr>
<tr><td>Standard mobility</td><td rowspan="2">Not everything is digitalized</td></tr>
<tr><td>No digital world</td></tr>
<tr><td>P2P energy sharing</td><td rowspan="3">Sharing economy</td></tr>
<tr><td>Energy communities</td></tr>
<tr><td>Shared e-mobility</td></tr>
<tr><td>Last mile</td><td rowspan="3">Holistic approach - Urban energy planning - circularity</td></tr>
<tr><td>Carbon Capture - home gardens</td></tr>
<tr><td>Landscape / Urbanscape integrated PV</td></tr>
</table>

The second **Visioning Workshop was held on 27th of April to present the results of the first workshop**. The visions and the vision statements set at the **first workshop were benefited to form scenarios towards 2025, 2030 and**

2040 (detailed in Section 6.2). Three scenarios based on this research were presented to the external experts. **A voting session was conducted in order to prioritise a scenario among three. The third scenario, so called "Open, trusted, efficient digitalised UES" was promoted between the experts.** More information regarding this scenario may be found in Section 6.2. Afterwards, the audience was directed to provide recommendations to their identified scenario in terms of **data, coordination, capacity, finance and digitalization aspects**. The results are included in Section 7 under Recommendations for future table, together with the identified recommendations derived as a result of this research. As a result of the two visioning workshops, the participants provided very good feedbacks for this research but also the format of the workshops. A foresight exercise to imagine the future helped the external experts brainstorming easily and they were dedicated to achieve results and recommendations.

6. Digitalisation leads to Energy Outlook 2025, 2030, 2040

6.1. Fill in the gaps for future

Drivers and barriers to implement renewable energy systems in urban areas are summarized in Table 5. The potentials of digital technologies to contribute to some of the barriers are also mentioned with examples of solutions.

Table 5 : Summary of the main drivers and barriers to the implementation of RE [122]; [123]; [124]; [125]; [126]; [127]; [128].

	Drivers	Barriers	Digital opportunities
ECONOMIC	**Business models:** Investment in RE is encouraged with advantageous models (e.g. tax, regulation, grants, quotas, subsidies, trading).	**Innovation:** Possible new discoveries are breaks to investment in existing RE technologies: a new component or a more optimal way to use an existing one can make past investments useless and considered as wasted.	Digital tools can be used to promote RE investments through platforms (e.g. Solar As a Service at the Messukeskus Solar Power Plant[129])
	Feed-in tariffs: Electric utilities are compelled to pay above-market rates for RE.	**Competitiveness:** Non-renewable resources of energy often present financial advantages that slow down the investments.	

SOCIAL	**Fairness:** Respecting a procedural and distributional justice (fair planning and costs/benefits share) increases social acceptance of RE projects.	**Landscape**: Visual impact of RE are often rejected by citizens.	BiblioTech project[130] in Tirana or Connectem Barcelona, allow to offer a space to use internet and computers as well as teach them how to use it, reducing the social gaps.
	New job opportunities: RE industry represents new opportunities for jobs and related tax/revenue increase locally.	**Involvement**: Lack of data access for the consumers to manage their consumption and the origin of their energy.	De Energiecentrale [131] (The Energyhub) in Gent is a **one-stop shop for advice and guidance** on energy efficiency. This created **660 new jobs.**
	Quality of life: A higher life quality generally leads to higuer energy needs and its flexibility.	**Awareness:** End-users do not always have the knowledge of the potential for RE and available financial help.	Helen [132] is an energy utility with public shares that provides information of production and consumption in a narrative way in the platform of Suvilahti district so it is understandable for everyone.
	Energy democracy: Request in control of own energy supply and use is increasing.	**Traditional energy industry**: Fossil-fuel market is often a large part of a country's income. Abandoning it will reduce the associated collected taxes by the government.	OurPower [91] is an energy cooperative that allows citizens to sell their energy and buy it from their neighbours in its one-stop shop

POLITICAL	**Long term policies**: Long term strategies help developing sustainable energy system and encourage research.	**Industry**: Many industries rely on fossil fuels and have a strong influence in the policy making process.	Nantes Energy Data Lab [95] data from buildings is obtained which maps demand and clusters of the city, and also DHN to support a decision aiding tool (for operators, for optimisation, etc.).
	Quotas: Obligation for electricity producers to justify that a determined part comes from renewable sources.	**Leadership:** Lack of motivation from the policy makers to encourage behavioural changes and development of RE systems.	
TECHNICAL	**Geography**: Presence of resources (wind, solar, hydro, and geothermal enables the development of RE production. **Hybrid systems**: RE systems are often weather relevant. The combination of two sources can compensate for the intermittence and encourage the development of new RE.	**Geography:** Absence of resources (wind, solar, hydro, and geothermal prevents the development of RE production. **Generation system**: Existing infrastructures without generation (e.g. dams with no hydropower generation) decreases the part of available sources of RE.	**Platforms** such as Windcentrale [133] can help you invest in RE production even though there are not located close to your house.
TECHNICAL	**Digitalisation**: Provides better control and management that improves the effectiveness of energy systems.	**Skills**: The lack of technical skills and qualified manpower slows down the expansion of RE systems.	With **digital education** the barriers could disappear. **Collaborative platforms** like City As a platform [57], allows cities with lower resources to exchange information and knowledge with bigger cities

	Smart designs: Smart technologies enable better use of electricity, improving the overall efficiency of RE systems and encouraging development.	**Curtailment:** RE are not always connected to the grid and the production cannot be used efficiently.	**Curtailment** can be reduced thanks to smart grids or storage optimisation [63].
ENVIRONMENTAL	**Decarbonisation:** Energy production through RE has a lower carbon footprint and less impact on climate change.	**Side-impact**: Implementation of new RE facilities (e.g. hydropower) raises environmental concerns, such as the destruction of ecosystems (flooding).	E-waste and life cycle of materials of RE and digital tools should be considered. Smart waste techniques could be also used to inform citizens and reduce impact of waste. See more in here [134]
	Recycling: High improvements in the recycling process have increased the environmental benefits of RE compared to combustion plants.	**Materials:** Clean energy technologies, especially with wind and solar, increase the mineral demand and the load on extraction mines.	

* The main drivers and barriers are categorised according to the supply chain of urban energy systems. Each of the step has its own individual colour as represented in the table: Primary energy (supply), Integrated infrastructure (conversion), Final energy (demand), Cross-section

(a)

(b)

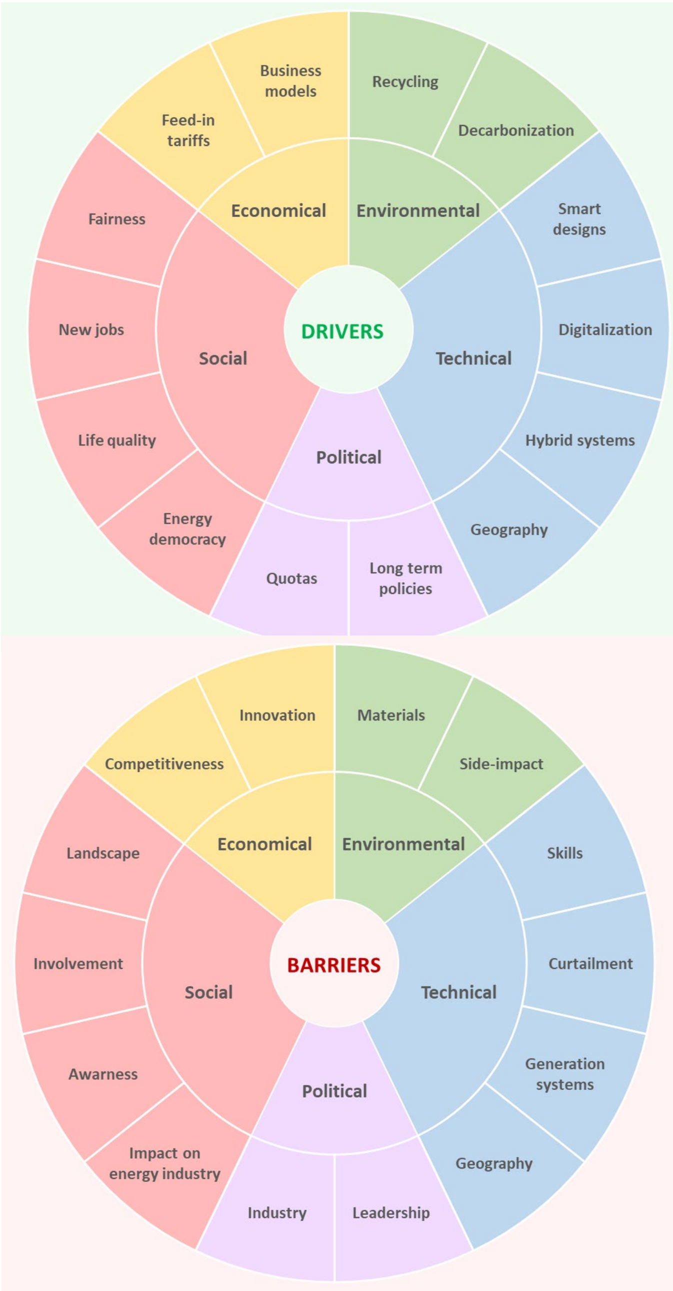

Figure 12 : Drivers (a) and barriers (b) of renewable energy systems, based on table 5.

6.2. Outlook 2025, 2030, 2040

The potential implications of digitalisation in urban energy systems are currently very uncertain. As it has been described in the report, there are several limitations and barriers in different aspects such as data, coordination and integration within public and private sectors, knowledge and capacity, finance, citizen engagement, etc. To discuss the various paths that citizens, private and public sector could take to embrace and implement digitalisation in urban settings, and describe potential implications and impacts, a scenario approach is used in this section to present an outlook for 2025, 2030 and 2040.

From this outlook, recommendations to progress to the most desired scenario will be drawn, supported by the inputs at the 2nd workshop, and will be summarised in the conclusion section as an input to the EC Action Plan on the Digitalisation of the Energy System.

The following figure summarizes the three scenarios and the implications in each sector of UES framework. More details can be found in the description of each scenario.

	Scenario 1. Slow and reluctant digitalisation of UES.	Scenario 2. Private sector reaps digitalisation benefits	Scenario 3. Open, trusted, efficient digitalised UES
BUILDINGS (DEMAND AND SUPPLY SIDE)	**Slow digitalisation** due to concerns on data privacy, mistrust on AI, and difficulty of participation in energy markets. **RES have been adopted but** are **not** being **optimised**	Private companies have service contracts in most buildings, and have **optimised efficiency**, **renewable energy production** and **flexibility management**, with no upfront costs for building owners.	SRI has triggered investments in **buildings' digitalisation**. Widely adopted solutions for **renewable energy integration** and **participation in energy markets, including flexibility**.
MOBILITY (DEMAND SIDE)	Traditional **active mobility** (cycling, walking) and **car-free zones** are increasingly adopted in cities. **Digitalised** mobility solutions are mostly used for **public transport**.	Cost effective **private MaaS** is displacing public transport. Complex management of urban mobility as the pace of **digitalisation within the public sector** is comparatively very **slow**.	Cities operate efficient **urban mobility platforms**. Very successful and cost effective **MaaS solutions** have been deployed and widely in use, together with **multimodal solutions** for public transport.
INTEGRATED INFRASTRUCTURE	**Slow** penetration of **distributed storage and flexibility solutions**, and **low participation** of citizens in **energy markets**.	ESCOs and large utilities have control of most of the **UES** through **service contracts**. They efficiently manage **renewables, storage, flexibility assets**.	**Citizens fully participating in the energy market**. **High rate of distributed RES and storage**, 100s GW **flexible capacity** in operation in cities.
CITIZEN ENGAGEMENT	Low	Medium	High
DATA AVAILABILITY AND DATA ACCESS	Low	Medium	High

Figure 13 : Scenario summary

6.2.1. Scenario 1. Slow and reluctant digitalisation of UES

In this scenario, there is **limited data openness and exchange, and citizens' concerns regarding data privacy and cybersecurity**. The digital divide is a reality with complex cultural and socioeconomic variants, with sectors of the society being explicitly reluctant to adopt digitalised solutions for their mobility or home energy systems.

The smart city "digital twin" concept is not being useful for city energy planning and management, as **lack of standardisation** has led to deployment of sensors and devices platforms by private actors with their own protocols, and most of them with proprietary access, not being openly available.

- **Buildings**

In 2025 and 2030, there is slow progress on the adoption of smart solutions for the building sector. **Households mistrust the many products in the market**, which are not standardised and offer dubious energy savings. In the absence of clear guidelines and regulations, energy use of sensors, actuators, data transfer and storage, together with other life cycle impacts of product materials and production are suspected by citizens to outweigh the potential benefits of digitalisation in the urban energy system.

By 2040, all **buildings have smart metering and technology is really developed for every user to participate in the energy system**. The **digitalisation however** has not resulted in energy and cost savings for the citizens, as interaction and interoperability of smart metering, IoT devices and home energy management system **is not optimised**. The multiple existing brands and platforms, which in cases are installed to justify a better score for the Smart Readiness Indicator (SRI), are not easy to use and do not offer clear benefits to the users. There are also **concerns about data privacy and mistrust in AI to manage private homes,** so the **uptake of digitalisation** in the residential sector beyond smart metering is **slow**.

- **Mobility**

In 2025 and even 2030, **cities lack skills and do not have the capacity to capture, process and use data to improve mobility within the city**. The smart **mobility platforms are rarely being implemented**, as lack of standardisation has led to somehow chaotic deployment of sensors and devices in many cities, most of them with proprietary data access, and with no centralised data management from the city. As a positive feature, there is a **consistent trend to active mobility**, with more and more citizens embracing walking and cycling, and local authorities working towards visions of car-free cities.

By 2040, **few private companies have deployed Mobility as a Service (MaaS)** mostly based on autonomous vehicles which are popular in some sectors of the society. The coexistence of those with the non-autonomous vehicle, and the public transport, in the absence of clear European or national guidelines and standards, is difficult to manage and regulate for many local authorities. In some cities it has resulted in **additional problems and protests in relation to rights and responsibilities of human drivers**, and particularly taxi drivers who face job losses. The car-free cities movement is growing and is seen by many as the best option to improve quality of life in cities, and more and more cities move towards active mobility, with very **limited access to vehicles within urban areas**. This is resulting in **increased public space and green areas** for the citizens, and more efficient public transport, which has adopted popular multimodality solutions.

- **Integrated Infrastructure**

In 2025 and 2030, there is a **rapid uptake of distributed RES solutions** (mainly PV) for self-consumption. However, **digitalisation has still not favoured the participation of the small installations from citizens in the energy market**, and there are only pilot experiences in P2P trading, virtual power plants and energy communities offering flexibility services.

By 2040, flexibility assets associated to renewable energy installations, district heating networks or non-residential buildings **are still under-exploited**. Demand aggregators and users have difficulties with accessing and managing data, and cannot fully exploit their benefits and compete in the flexibility market. For the citizens, there are **few platforms** that intend to empower citizens and make them participants in the energy market, but are **complex and the cost-benefit is uncertain**, **so few citizens are engaged**. The **citizen investment in storage systems is still small**, which prevents a higher penetration of variable RES.

6.2.2. Scenario 2. Private sector reaps digitalisation benefits

In this scenario data ownership is centred in few (mostly private) actors, which are the main beneficiaries and they do use the data to improve energy system and create new business opportunities in renewable energy or mobility. Business opportunities emerge, with several technologies and tools being deployed and offered to the citizens. While digitalisation is present in the day to day and has brought down the costs of heat, electricity, or mobility, still the benefits are not clearly seen or understood by many, as all is offered through the private sector with the citizen only role being as a client or final user.

- **Buildings**

In 2025, an increasing number of non-residential buildings are being approached by **ESCOs and utilities and installing more sophisticated energy management systems.** They are also being offered investments on renewable energy production and storage, and given the possibility to **participate in emerging platforms** to reduce energy costs through demand response, and **some incipient participation in flexibility markets**. Most of the benefits of this digitalisation are reaped by these ESCOs and utilities and their contracts with DSOs and TSOs by improving grid management. In the domestic sector, there are a **wide variety of sensors, actuators, applications and services offered to the citizens,** in cases with **no very transparent information** on their data policies or their implications on energy use. This makes it **difficult to assess the potential benefits versus the costs of digitalisation** in the urban energy context. To overcome this and reap the benefits of the residential sector, **by 2030**, ESCOs and utilities are developing new business models linked to long term contracts offering a full energy service including **'Heating as a Service' (HaaS) and demand management.** They offer investment on storage solutions and renewable energies under these contracts, so they start having a good portfolio of distributed generation and storage, and a large base of energy service contracts to be able to manage loads.

By 2040, **building management has really improved** overall energy efficiency particularly in non-domestic buildings, with more sensors and controls linked to AI. Building owners and managers are mostly enjoying service contracts through **large utilities and ESCOs**, which **cover the different energy services** in the buildings from heating, electricity and demand side management, renewable energy generation and operation of storage, linking also with EVs charging. This way, no upfront payments are generally needed and **digital solutions and AI are broadly implemented.** The overall **efficiency** of the buildings **has generally improved,** with large energy service providers really benefiting from the buildings' energy flexibility, operating jointly with demand response aggregators in the energy market, as **clear regulation and relationship with DSOs is still not present**. Overall, while the private sector has created business models for shared self-consumption or for flexibility management for homes, benefits for the citizens are generally small and uncertain. **The full potential to exploit flexibility directly by citizens or energy communities has yet to be realised**.

- **Mobility**

In 2025 and even 2030, the **private sector is really exploiting the benefits of digitalisation, and increased number of platforms** for Mobility as a Service

(MaaS) have emerged and are fiercely competing with public transport. **The public sector tries to increase efficiency** of public transport through digitalisation and particularly working in multimodality, **but lacks the resources and capacity** to reach the citizens who look for quick and cost-effective mobility solutions.

By 2040, **public transport networks are in decline, as private companies offer all possible kinds of options for private and shared mobility, starting at very competitive prices.** MaaS, frequently based on autonomous vehicles, is the norm and has generally brought down mobility costs, while resulting in a lucrative business models for private companies. Cities struggle to cope with the changes and to manage mobility within the cities. They face difficult decisions to discontinue some public transport networks, particularly bus routes, or to regulate and limit the access of private and MaaS vehicles to parts of the city.

- **Integrated Infrastructure**

In 2025 and 2030, business models have emerged so **PV self-consumption** installations, **heat pumps (through HaaS models),** and **storage solutions are being quickly implemented.** Together with EVs from mobility service providers, are efficiently managed by the large service providers, which are starting to manage a large part of the cities' energy use.

By 2040, **large ESCOs and utilities have control of most of the city's energy resources**, manage a large portion of the demand and large flexible capacity including distributed storage solutions, EVs, heat pumps and district heating and cooling networks. They are very successful in exploiting the urban energy system flexibility in the energy market. Private vehicle fleets of major MaaS providers have deployed optimised bidirectional charging networks for their EVs, and have set major agreements and contracts with TSO and DSO for provision of flexibility services. This **has brought economic growth and benefits to these major companies**, has triggered further renewable energy projects and storage, and overall, the environmental impact of the urban energy system has greatly reduced.

6.2.3. Scenario 3. Open, trusted, efficient digitalised UES

In this scenario there is a **well-established data policy, with citizens being the key beneficiaries**, having information that help them reduce the energy use and energy costs in their homes and mobility, while ensuring data protection, privacy and security. They are also able to actively participate in the energy market as prosumers or providers of flexibility services, both as individuals and as part of energy communities. New business opportunities for improving efficiency of the urban energy system emerge and are embraced, with very successful examples such as Mobility as a Service (MaaS) or Heating as a service (HaaS). There is clear regulation on energy efficiency and circularity for IoT, data transmission and data centres, which ensure that their relative energy use and environmental impact is very small, in relation to their benefits.

The requirement of the Energie Performance of Buildings Directive (EPBD) to set up databases of the energy performance of buildings in each Member State has been a key input to improve energy planning practices. These databases, particularly as include real energy data collected by digital tools in hourly or sub-hourly steps, allow evaluation of potential interventions at building, district and city level, combining energy use for building and electric vehicles. These newly available databases provide a trusted source to plan urban energy systems, to maximise the use of on-site renewable energy, increase urban energy system flexibility, and reduce overall cost of energy services for the citizens. The cities have invested in capacity building and digital twins are proving a valuable tool for energy planning and management.

- **Buildings**

By 2025, the **market for home energy management systems and digitalised homes is rapidly growing.** New **regulations ensuring interoperability and data access and ownership, are helping to break barriers towards citizen engagement.** Efficiency in non-residential building is rapidly improving through the combination of electrification and digitalisation, with building energy management systems allowing demand side response and optimisation of on-site renewable energy generation.

By 2030, the Smart Readiness Indicator for buildings has really had an effect on raising awareness, and the penetration of energy management systems is very wide. **Digital divide has been mostly overcome by large engagement and empowerment campaigns.** Most of the energy end uses in non-residential buildings, and increasingly in homes are digitalised. Together with the completed **roll-out of** smart metering, and very well-developed **tools** that allow demand response to pricing, digitalisation of energy at home has been massively adopted by citizens and can offer significant savings. There are also very **successful business models of ESCOs and utilities** that offer HaaS (Heating as a service), so the **full synergies of electrification and digitalisation of heat, including flexibility management, are being exploited.**

In 2040, almost all energy uses **in buildings are digitalised, with standardised communication and interoperability** between them and with the smart meters, which are present in all buildings. **Costs can be optimized through demand side management, and buildings can also provide flexibility** services, particularly those with heat pumps and storage.

AI plays a major role in improving energy efficiency, and to provide those flexibility services. AI has not ignored a human-centric approach, and specifically in residential buildings, citizen engagement tools have succeeded to make energy awareness widespread, so human decisions to override AI controls are made consciously.

- **Mobility**

In 2025, cities are investing in capacity building and start developing enhanced mobility data platforms mobility planning and management. Paper free **multimodal mobility,** powered by easy-to-use mobile applications, **is becoming the norm** in most European cities.

The **market for MaaS is growing** with various vehicle sharing platforms emerging, and regulatory efforts ensure cooperation between stakeholders and considering user needs and choices.

By 2030, cities are making the **best of the open mobility data and have developed Sustainable Urban Mobility Plans**, which sets the path towards a sustainable mobility for 2040.

Multimodality in urban areas has been a success, with easy-to-use public tools which facilitate use of different public mobility solutions. **These coexist with private MaaS solutions and collaborative mobility platforms.** AI is becoming an essential tool as autonomous vehicles are becoming a reality. Multiple regulatory efforts are in place to ensure efficient transition of the autonomous vehicles in the mobility ecosystem, including policies for data availability, access and exchange.

In 2040, cities have managed to **optimize mobility** through the use of mobility platforms which feed from a wealth of data available from digitalised vehicles, mobile network data and city-wide sensors. **A variety of smart electric mobility** solutions are offered by various companies, coexisting with non-digital active mobility (walking, cycling), and multimodal solutions for public transport, making for a sustainable eco-system. The system is effectively reproduced in the **digital twin of the mobility platform,** allowing to make predictions and taking quick decisions for improvements or to solve specific mobility problems. Autonomous vehicles have been effectively regulated resolving cybersecurity, data privacy and liability, and very cost-effective MaaS have resulted in a reduced number of private cars, with better traffic management and parking space has been liberated for **active mobility and new green areas** within the city.

- **Integrated Infrastructure**

In 2025, digitalisation is rapidly advancing to help manage renewable energy systems and flexible loads through the urban energy systems. Bidirectional charging stations are becoming extremely popular as the additional investment can be recovered in few years for most users. **By 2030**, it is common for **citizens to be familiar with platforms** to optimize their overall energy use, through joint management of building and EV charging. They **increasingly trust systems** and AI to manage their energy assets through demand response and offering **flexibility services linked to other citizens within energy communities.**

In 2040, energy citizenship is a reality, with most households being active players in the energy system, either individually or through energy communities, using demand response to reduce cost of energy, sharing renewable energy for self-consumption and participating in the flexibility markets. **Easy-to-use standardised platforms facilitate this participation,** as it is mandatory for retailers and installers to ensure compatibility to access to these platforms when a new energy management system, storage system or EV is purchased. This contributes to the success of the flexibility market in Europe, which by now has hundreds of GW of flexible capacity operating in cities. The majority of this capacity is associated with **bidirectional charging of EVs**, which have become mandatory, but also to district heating and cooling networks and Virtual Power Plants with dispatchable energy resources.

7. Summary, Conclusions & Recommendations

This report has provided a review of digitalisation of urban energy systems, including limitations, tools and technologies, business models and potential impacts. From this review, and supported by knowledge sharing activities such as workshops, an outlook for 2025, 2030 & 2040 has been prepared and recommendations drafted.

The review firstly **explores the concept of the 'urban energy system'(UES)** to achieve a common understanding of the concept and boundaries for the study.

The **state of the art of digitalisation of UES been presented**, including how digitalisation affects the different sectors identified in the boundaries by considering the supply chain from energy production to final use. This review has highlighted how digitalisation is key in managing distributed generation, storage and final use to enable a decarbonised urban energy system with high inputs of variable renewable energies. Present and future investments needs, as well as the key importance of cybersecurity and privacy issues, have been included in this review. The important role of local innovation ecosystems, as enabling environments and infrastructures allowing citizens to be involved in iterative processes of innovation, together with other public and private stakeholders, has also been highlighted in the review.

A great number of limitations of current digitalisation are found at each step of the supply chain for urban energy systems, such as data challenges, insufficient coordination and integration, lack of capacity, limited access to finance, and digitalisation risks. Besides, limitations exist at different phases of urban energy systems, from conception/planning to operation and management.

Tools and technologies for the digitalisation of UES have been identified, mainly from current and past Smart Cities and Communities (SCC) projects funded by the Horizon 2020 programme. In the supply side, energy monitoring and management systems, digital substations and virtual power plants (VPP), through advanced data analytics can increase reliability and quality of the energy supply system, improve maintenance and offer services such as voltage control. Tools focusing on monitoring, prediction and control of flows can also optimize the use of integrated infrastructure including district heating and cooling networks or storage, improving load balancing and allow more flexibility providers to enter in the market. The majority of tools and technologies are however being deployed for the final energy users, as digital solutions which are part of **smart buildings, smart vehicles, smart meters, and smart lighting** projects, improving efficiency, increasing demand-side flexibility and reducing costs for the users, while reducing peak loads of the grid. The data from those implementations can be a powerful source of data for **urban data platforms, urban energy planning tools and digital twins.** These cross-sectoral tools have the potential for **improving efficiency of urban energy systems, from design to operation and maintenance**. However, the full potential of those tools is yet to be realised. As an example, building stock and urban energy system models can describe in detail demand and supply at district or city scale, and provide both simulation and optimization**. While being a potentially powerful tool both for planning and design, those detailed models are still mainly used by academia.**

Efforts on **capacity building** in the public sector are **needed for these tools to successfully implemented**, and to ensure an efficient work and data flow from design and planning stage through operation of the urban energy system.

It is found that P2P trading models have a potential to bring benefits to the overall energy system by offering customers more options, increasing trading efficiency and optimising resource utilisation, reducing unnecessary financial burdens, introducing more market participants, building trust among prosumers, and making the transaction procedure simpler. It brings a relatively high number of actors in the business service for P2P trading by using the new technology such as blockchain.

Drivers and barriers to implement renewable energy systems in urban areas, as well as potential digital solutions, **are summarised in terms of economic, social, political, technical, and environmental aspects.** It is found that social and technical aspects are being considered more than the other aspects at the moment. There is a need to better understand the political, economic and environmental impacts of digital solutions on the urban energy system.

These **impacts of digitalisation** in the different sectors of an urban energy system are currently **very uncertain but potentially disrupting**, with great potential **for energy efficiency and resource efficiency**.

Mobility as a service (MaaS) and collaborative mobility platforms are a clear example on how digitalisation, together with electrification, can completely change one sector, with radical changes that could have profound impacts on the urban energy system, by reducing the number of private cars, improving overall efficiency and reducing energy use, CO_2 emissions and pollution. The advent of autonomous cars could intensify these impacts, and bring together new challenges for the cities regarding regulation, competitiveness of public transport, or potential job losses (e.g., taxi and commercial drivers). Data-driven sustainable urban mobility planning should ensure that all components of the urban mobility system are efficiently integrated, and improve efficiency of public transport solutions, for example embracing and facilitating multimodality through digital tools.

For the **building sector**, digitalisation is also expected to have multiple impacts, with tools and technologies like building information modelling (BIM) being capable of improving efficiency from planning and design state, through construction and operation through the end of life. Building management systems (BMS), linked to **a variety of sensors and actuators and optimized through AI, can greatly reduce building energy use in building operation**. While the effect is very uncertain and various sources provide different estimates, **potential savings in the building sector due to digitalisation could be of 10-20% by 2040**. There is however a **strong need for standardisation** of **sensors, actuators and IoT devices** in buildings, to optimize communication and management and **reduce as much as possible their associated energy and resource use**.

Urban **infrastructures** such as district heating and cooling networks can also improve efficiency through better management, enabled with data collection and analytics. They can also have important flexibility potential when heating for this network is supplied by heat pumps. Together with digital enabled flexibility of EVs charging, building energy systems, and other urban energy infrastructures, this flexibility can reduce final costs via demand response and enable the integration of further RES in the energy system. For the citizens, clear data policies will need to be put in place to protect and empower them if their participation in the energy market wants to be realised. This participation of citizens could be individually or through energy communities, materializing in shared-self consumption, P2P trading or virtual power plants.

Regarding the **impact of the data on energy use**, it has to be considered that amount of data related to urban energy systems is **relatively very small in relation to other data streams** such as online video or gaming. In any case, focus needs to be maintained in the efficiency of communication networks and data centres, and when located within urban areas, to their integration within the energy system (e.g., as renewable energy users and waste heat providers).

Considering these impacts together with the discussed limitations of the digitalisation within urban energy systems, and the review of tools and technologies, an **outlook for 2025, 2030 and 2040 has been prepared taken a scenario approach**. Three scenarios have been considered, taking into account the uncertain impacts of digitalisation in urban energy systems and exploring potential implications in the different sectors.

Scenario 1 describes a slow and reluctant digitalisation of the UES, with low access to data and low citizen engagement. Scenario 2 describes a higher level of digitalisation, driven by the private sector who controls most of the data, and which develops successful business models. Scenario 3 depicts a future high data access and availability, and digitalisation rapidly being successful not only for the private sector but also enabling 'energy citizenship' and an efficient participation of citizens and energy communities in the energy market.

Following the discussion of these scenarios, and supported by the inputs collected on a second stakeholder workshop, recommendations have been drawn.

A few recommendations are listed in Table 6, respectively for 2025, 2030 and 2040. They are categorised into 'data', 'coordination', 'capacity', 'finance' and 'digitalisation', which are in line with the limitations of DUES. Each recommendation is associated with its related governmental level for potential implementation.

Table 6 : Recommendations for 2025, 2030 and 2040, adapted from [37]

YEAR	RECOMMENDATIONS		GOVERNMENTAL LEVEL
2025	Data	Further develop the legal and strategic framework for facilitating data storage, usage access, sharing and securityH	EU
		Strengthen support from public authorities	City
		Promote data-sharing tools and platforms across different stages for cities	EU & National
	Coordination	Develop communities of practice	City
		Set up of a central unit or a core group in local government to oversee the overall development. to identify potential synergy and facilitate the coordination	City
		Engage local stakeholders in digitalisation of urban energy systems, through various ways, such as workshops, popular science, exhibitions etc.	City
	Capacity	Extend opportunities for knowledge exchange through existing initiatives, such as IEA, Cost Actions, JPI Urban Europe etc.	EU
		Increase investment from public sector in capacity building	National & City
		Increase level of energy literacy & consciousness among citizens	National & City
	Finance	Enable participation of public/private sectors and citizens in those interventions with clear financial benefits	City
		Stimulate public-private partnerships, especially in investment on renewable energy systems (such as solar parks, wind farms etc)	National
		Enhance the awareness among citizens of possible financing/ subsidy mechanisms	City
		Reduce burdens by regulating the opportunities for peer-to-peer energy trading	EU & National

	Digitalisation	Strengthen the application of cyber security frameworks and guidelines	EU
		Digitalize the energy system infrastructure in different sectors and promote the development of first layer of digital twin	EU & National
		Promote wide application of urban energy system modelling	EU & National
		Ensure transparency to citizens about the values from sharing data	City
		Follows the local needs and not blindly following the trend	City
2030	Data	Accelerate data communication by improving data transmission infrastructure	National
		Strengthen transparency in use of data	EU
		Ensure the achievement of open application programming interfaces (API)	EU
		Promote requirements for improving interoperability (e.g. common data models, communication protocols etc.)	EU
	Coordination	Create cross-cutting networks for co-creation	City
		Build up special purpose vehicle	City
	Capacity	Develop new initiatives to attract capacity and skills	National
		Develop training and upskilling programmes	National
	Finance	Encourage development of new business models	EU
		Introduce training to develop bankable projects	EU
		Clear financial guidance for prioritisation of interventions and optimised use of resources	National & City
		Ensure fair contracting to public and private companies	City
	Digitalisation	Promotion of Green IoT design, Eco-labelling	EU
		Strengthen digitalisation on the energy service and promote the development of second layer of digital twin	National
		Build low-threshold solutions and develop step-by-step digitalisation guidelines for different stakeholders	EU
2040	Data	Optimize urban energy system using large sets of data, and strengthen 3rd layer of digital twin for cities' operation and management	National
	Coordination	Develop coordination framework across city levels and departments	City
		Encourage trustworthy/neutral actor to coordinate	City

	Capacity	Extend training and upskilling programmes in different levels of education system	National
		"Enlightened" municipalities to take the lead and update HR/training systems	City
	Finance	Redirect funding and develop dedicated financing vehicles	National
		De-risk investments or reduce cash flow needs for faster transformation	National
		Support the development of new instrument, such as green bonds	National
	Digitalisation	Build capacity and develop inclusive policies	EU
		Ensure just and fair transition and profit sharing	EU
		Digitalize urban energy system as a whole	EU
		Align with European standards and roadmaps on digitalisation, and push vendor-independent solutions for easier integration and scale up	EU

References

[1] United Nations, "The World 's Cities in 2018," *World's Cities 2018 - Data Bookl. (ST/ESA/ SER.A/417)*, 2018.

[2] United Nation, "UN-HABITAT STRATEGIC PLAN 2020-2023," 2020.

[3] L. Sandys, R. Dobson, E. Brown, G. Graham, R. Lane, and J. Verma, "Energy Data Taskforce: A Strategy for a Modern Digitalised Energy System - Energy Systems Catapult," *Energy Data Taskforce Rep.*, 2019.

[4] International Energy Agency, "Empowering Cities for a Net Zero Future: Unlocking resilient, smart, sustainable urban energy systems," 2021. Accessed: Mar. 01, 2022. [Online]. Available: https://iea.blob.core.windows.net/assets/4d5c939d-9c37-490b-bb53-2c0d23f2cf3d/G20EmpoweringCitiesforaNetZeroFuture.pdf.

[5] Digital Europe, "A digital investment plan for Europe," 2020. Accessed: Apr. 27, 2022. [Online]. Available: https://www.digitaleurope.org/wp/wp-content/uploads/2020/10/DIGITALEUROPE_How-to-spend-it_A-digital-investment-plan-for-Europe.pdf.

[6] Global Enabling Sustainability Initiative, "Digital solutions for climate action." https://www.gesi.org/events/report-launch-digital-solutions-for-climate-action (accessed Mar. 09, 2022).

[7] McKinsey, "Smart Cities: Digital Solutions for a More Livable Future," *McKinsey Co.*, no. June, 2018, Accessed: Mar. 07, 2022. [Online]. Available: https://www.mckinsey.com/~/media/McKinsey/Industries/Public and Social

Sector/Our Insights/Smart cities Digital solutions for a more livable future/MGI-Smart-Cities-Executive-summary.pdf.

[8] N. ten Caat, L. Graamans, M. Tenpierik, and A. Van der Dobbelsteen, "Towards Fossil Free Cities—A Supermarket, Greenhouse & Dwelling Integrated Energy System as an Alternative to District Heating: Amsterdam Case Study," *Energies*, vol. 14, p. 347, 2021, doi: https://doi.org/10.3390/en14020347.

[9] P. Rutter and J. Keirstead, "A brief history and the possible future of urban energy systems," *Energy Policy*, vol. 50, 2012, doi: 10.1016/j.enpol.2012.03.072.

[10] A. Grubler *et al.*, "Urban Energy Systems," in *Global Energy Assessment: Toward a Sustainable Future*, Global Energy Assessment Writing Team, Ed. Cambridge: Cambridge University Press, 2012, pp. 1307–1400.

[11] J. Rosales Carreón and E. Worrell, "Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism," *Resour. Conserv. Recycl.*, vol. 132, 2018, doi: 10.1016/j.resconrec.2017.08.004.

[12] M. L. Di Silvestre, S. Favuzza, E. Riva Sanseverino, and G. Zizzo, "How Decarbonization, Digitalization and Decentralization are changing key power infrastructures," *Renewable and Sustainable Energy Reviews*, vol. 93. 2018, doi: 10.1016/j.rser.2018.05.068.

[13] European Commission, "Powering a climate-neutral economy: an EU strategy for energy system integration," 2020.

[14] M. Webb, A. Scott, I. Gençsü, and D. Broekhoff, "Urban energy and the climate emergency: Achieving decarbonisation via decentralisation and digitalization," *Coalition for Urban Transitions, London and Washington, DC*, 2020. https://urbantransitions.global/wp-content/uploads/2020/03/Urban_Energy_and_the_Climate_Emergency_web_FINAL.pdf (accessed Apr. 10, 2022).

[15] U. A. for the EU., "Digital transition action plan.," 2018.

[16] OECD, "ENHANCING THE CONTRIBUTION OF DIGITALISATION TO THE SMART CITIES OF THE FUTURE," 2019. https://www.oecd.org/cfe/regionaldevelopment/Smart-Cities-FINAL.pdf (accessed Apr. 21, 2022).

[17] E. Commission, "Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast) COM/2021/802 final." 2021.

[18] E. Commission, "Directorate-General for Energy, Verbeke, S., Aerts, D., Reynders, G., et al., Final report on the technical support to the development of a smart readiness indicator for buildings : final report," *Publ. Off. Eur. Union*, 2020, [Online]. Available: https://data.europa.eu/doi/10.2833/41100.

[19] C. Europea *et al.*, *Digitalisation of energy flexibility*. 2022.

[20] European Commission, "SHAPING THE DIGITAL TRANSFORMATION IN EUROPE," 2020. https://www.ospi.es/export/sites/ospi/documents/documentos/Sstudy_Shaping_the_digital_transformation_in_Europe_Final_report_202009.pdf (accessed Apr. 27, 2022).

[21] E. Judson, I. Soutar, and C. Mitchell, "Governance Challenges Emerging from Energy Digitalisation," 2020.

[22] E.DSO, "DSOs as facilitators for energy communities," *2021*. https://www.edsoforsmartgrids.eu/wp-content/uploads/E.DSO-Position-Paper-on-Energy-communities-FINAL.pdf (accessed Apr. 08, 2022).

[23] IRENA, "Innovation landscape brief: Co-operation between transmission and distribution system operators," 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_TS%0AO-DSO_co-operation_2020.pdf?la=en&hash=5D78444F4339DC130204A0F9A99A30753368AABC (accessed Apr. 10, 2022).

[24] EC, "Tackling cybersecurity challenges in energy: Commission adopts recommendation on cybersecurity in the energy sector," 2019. https://ec.europa.eu/info/news/tackling-cybersecurity-challenges-energy-commission-adopts-recommendation-cybersecurity-energy-sector-2019-apr-03_en (accessed Apr. 21, 2022).

[25] POCITYF, "D11.12 Cyber Data security managament plans," 2020. https://pocityf.eu/wp-content/uploads/2020/09/POCITYF-864400_D11.12_Cyber-Data-Security-Management-Plans.pdf.

[26] H. Habibzadeh, B. H. Nussbaum, F. Anjomshoa, B. Kantarci, and T. Soyata, "A survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in smart cities," *Sustain. Cities Soc.*, vol. 50, p. 101660, Oct. 2019, doi: 10.1016/J.SCS.2019.101660.

[27] E. SNET, "DIGITALIZATION OF THE ENERGY SYSTEM AND CUSTOMER PARTICIPATION: Description and recommendations of Technologies, Use Cases and Cybersecurity," 2018. https://www.etip-snet.eu/wp-content/uploads/2018/11/ETIP-SNET-Position-Paper-on-Digitalisation-short-for-web.pdf.

[28] M. Van Wees *et al.*, "Energy Citizenship in New Energy Concepts †," *Environ. Sci*, doi: 10.3390/environsciproc2021011027.

[29] LANZADERA, "The predictive company," 2022. https://lanzadera.es/proyecto/the-predictive-company/ (accessed Apr. 27, 2022).

[30] J. Zuo *et al.*, "Energy Citizenship in Positive Energy Districts-Towards a Transdisciplinary Approach to Impact Assessment," 2022, doi: 10.3390/buildings12020186.

[31] AIGUASOL, "JoinEnergy Tool," 2022. https://www.joinenergy.eu/ (accessed Apr. 27, 2022).

[32] E. Cities, "community Energy: A practical guide to reclaiming power," 2020. https://energy-cities.eu/wp-content/uploads/2020/10/Community-Energy-Guide-web.pdf.

[33] E. Velis, D. Torres, and G. Caballero, "Gamification for social perception: Introducing scientific literacy to dabblers in citizen science," *J. Sci. Commun.*, vol. 20, no. 6, 2021, doi: 10.22323/2.20060208.

[34] M. R. Zica, A. C. Ionica, and M. Leba, "Gamification in the context of smart cities," in *IOP Conference Series: Materials Science and Engineering*, 2018, vol. 294, no. 1, doi: 10.1088/1757-899X/294/1/012045.

[35] A. L. Balogun *et al.*, "Assessing the Potentials of Digitalization as a Tool for Climate Change Adaptation and Sustainable Development in Urban Centres," *Sustain. Cities Soc.*, vol. 53, 2020, doi: 10.1016/j.scs.2019.101888.

[36] IEA, "International Energy Agency - Digitalization & Energy," *Digitalization & Energy*. 2017.

[37] International Energy Agency, "Net Zero by 2050: A Roadmap for the Global Energy Sector," 2021.

[38] A. Hern, "Assume self-driving cars are a hacker's dream? Think again," *The guardian*, 2017. www.theguardian.com/technology/2017/aug/30/self-driving-cars-hackerssecurity. (accessed Mar. 02, 2022).

[39] V. Cities, "Digitalisation strategy and digital tools for conversion to climate-neutral cities," 2021. https://static1.squarespace.com/static/5dd54ca29c9179411df12b85/t/616ed6f31e2fc310b32e9d48/1634653940238/20211019_Digitalisering_och_digitala_verktyg.pdf (accessed Mar. 02, 2022).

[40] C. S. Lai *et al.*, "A Review of Technical Standards for Smart Cities," *Clean Technol.*, vol. 2, no. 3, 2020, doi: 10.3390/cleantechnol2030019.

[41] EC, "European Innovation Partnership on Smart Cities and Communities: Strategic Implementation Plan.," 2013.

[42] A. Ptak, "Smart city management in the context of electricity consumption savings," *Energies*, vol. 14, no. 19, 2021, doi: 10.3390/en14196170.

[43] LocalRES, "LocalRES website: Ollersdorf," 2022. https://www.localres.eu/demonstration-sites/ollersdorf/ (accessed Apr. 10, 2022).

[44] SmartCitiesWorld, "ABB installs digital substation in Kerala.," 2017. https://www.smartcitiesworld.net/news/news/abb-installs-digital-substation-in-kerala-1406 (accessed Apr. 10, 2022).

[45] Pocityf, "Pocityf Evora solutions," 2018. https://pocityf.eu/city/evora/#solutions (accessed Apr. 10, 2022).

[46] Pocityf, "Pocityf Alkmaar solutions," 2018. https://pocityf.eu/city/alkmaar/#solutions (accessed Apr. 10, 2022).

[47] MAKING-CITY, "MAKING-CITY website," 2018. https://makingcity.eu/ (accessed Apr. 04, 2022).

[48] JPI Urban Europe / SET Plan Action 3.2, “Europe Towards Positive Energy Districts,” *PED Bookl.*, no. February, 2020.

[49] ATELIER, “Amsterdam Lighthouse,” 2018. https://smartcity-atelier.eu/about/lighthouse-cities/amsterdam/general-information/ (accessed Apr. 09, 2022).

[50] T. Hesser and S. Succar, “Renewables Integration Through Direct Load Control and Demand Response,” in *Smart Grid*, 2012.

[51] MySMARTLife, “Paring space detectionin Hamburg,” 2019. https://www.mysmartlife.eu/fileadmin/user_upload/Info_packs/info-packs_pdf/PSD_SNH.pdf (accessed Apr. 14, 2022).

[52] OASC, “Vienna the capital of digitalisation,” 2022. https://catalogue.city/en/cities/vienna (accessed Apr. 10, 2022).

[53] MySMARTLife, “Smart Personal EV charger system in Helsinki,” 2019. https://www.mysmartlife.eu/fileadmin/user_upload/Info_packs/info-packs_pdf/Smart_personal_EV_Charger_System.pdf (accessed Apr. 10, 2022).

[54] REMOURBAN, “Best practices and lessons learnt,” 2020. http://www.remourban.eu/kdocs/1986507/REMOURBAN_BestPractices.pdf (accessed Apr. 10, 2022).

[55] M. Engelhardt, “IoT improves the quality of our lives.” https://new.siemens.com/global/en/company/stories/infrastructure/2019/internet-of-things-interview-with-wef-expert-jeff-merritt.html (accessed Apr. 10, 2022).

[56] G. Kamiya and J. Teter, “Shared, automated… and electric?,” *International Energy Agency*, 2019. https://www.iea.org/commentaries/shared-automated-and-electric (accessed Apr. 27, 2022).

[57] CityAsAPlatform, “City As a Platform,” 2021. https://cityasaplatform.se/ (accessed Apr. 04, 2022).

[58] O. R. Amsterdam, “Open Research Amsterdam,” 2018. https://openresearch.amsterdam/ (accessed Apr. 10, 2022).

[59] ECDA, “Digitally managed cities of the future – how close are we?,” 2020. https://ecda.eur.nl/2020/04/17/digitally-managed-cities-of-the-future-how-close-are-we/ (accessed Apr. 27, 2022).

[60] Kartta, “Helsinki energy and climate Atlas.” https://kartta.hel.fi/3d/atlas/#/ (accessed Apr. 10, 2022).

[61] GrandLyon, “Open data Grand Lyon.,” 2022. https://data.grandlyon.com/actualites/les-communes-mobilisees-pour-developper-lopen-data (accessed Apr. 10, 2022).

[62] O. de Publicaciones, J. Berends, W. Carrara, and H. Vollers, *Open data in cities 2*. Publications Office, 2020.

[63] REMOURBAN, “Info-Package Nr.2,” 2019. http://www.remourban.eu/technical-insights/infopacks/building-

integrated-photovoltaics-bipv--energy-storage-and-smart-grid-management.kl (accessed Apr. 10, 2022).

[64] T. U. Wien, "THE HOTMAPS TOOLBOX suppor ting strategic heating & cooling planning at local leve," 2020.

[65] SEEnergies, "D5.3 Online web map application and first set of map layers," 2019. https://seenergies.eu/.

[66] J. Keirstead, M. Jennings, and A. Sivakumar, "A review of urban energy system models: Approaches, challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6. 2012, doi: 10.1016/j.rser.2012.02.047.

[67] A. Sola, C. Corchero, J. Salom, and M. Sanmarti, "Multi-domain urban-scale energy modelling tools: A review," *Sustainable Cities and Society*, vol. 54. 2020, doi: 10.1016/j.scs.2019.101872.

[68] C. Nägeli *et al.*, "Best practice reporting guideline for building stock energy models," *Energy Build.*, vol. 260, p. 111904, Apr. 2022, doi: 10.1016/J.ENBUILD.2022.111904.

[69] E. Arrizabalaga *et al.*, "Methodology for the Advanced Integrated Urban Energy Planning †," *Proceedings*, pp. 5–7, 2019, doi: 10.3390/proceedings2019020017.

[70] F. Biljecki, K. Kumar, and C. Nagel, "Open Geospatial Data, Software and Standards CityGML Application Domain Extension (ADE): overview of developments," doi: 10.1186/s40965-018-0055-6.

[71] X. Zhang *et al.*, "Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications," *Frontiers in Sustainable Cities*, vol. 3. 2021, doi: 10.3389/frsc.2021.663269.

[72] R. and Markets, "Digital Twin Cities. 2020: The Global Ecosystem, City-backed Projects, Main Application Sectors, and Solution Suppliers, s.l," 2020.

[73] A. Heiskanen, "Helsinki is Building a Digital Twin of the City," 2019. https://aec-business.com/helsinki-is-building-a-digital-twin-of-the-city/ (accessed Apr. 10, 2022).

[74] S. Poppe, "Digital 3D Modelling of Rennes Metropole.," 2016. https://sharingcities.eu/eurocities/allcontent/Digital-3D-modelling-of-Rennes-Metropole-WSPO-A8JDUM (accessed Mar. 31, 2022).

[75] R. Fischer, "Digital Transportation: The Future of Urban Mobility," 2019. https://usgtima.org/perspectives/digital-transportation-the-future-of-urban-mobility/ (accessed Apr. 14, 2022).

[76] S. (IET) Doyle, "Digital urban planning: twins help make sense of smart cities," *Eng. Technol.*, vol. 14, no. 1, 2019.

[77] A. Parrott and D. L. Warshaw, "Industry 4.0 and the digital twin Manufacturing meets its match," 2017.

[78] A. Francisco, N. Mohammadi, and J. E. Taylor, "Smart City Digital Twin–

Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking," *J. Manag. Eng.*, vol. 36, no. 2, 2020, doi: 10.1061/(asce)me.1943-5479.0000741.

[79] Bentley, "City of Helsinki Expands Digitalization with Citywide Digital Twin." https://assets.ctfassets.net/pnliwdxhy0tx/3QXa4p03pq5qJ6VEeq54NW/de3935d8584121636e34d0d64fb280c2/CS_City_of_Helsinki_Citywide_Digital_Twin_LTR_EN_LR.pdf (accessed Apr. 10, 2022).

[80] Bentley, "City of Helsinki: Helsinki 3D+," 2016. https://www.bentley.com/en/project-profiles/city-of-helsinki_helsinki-3d (accessed Apr. 10, 2022).

[81] C. Ramos and C. C. Liu, "AI in power systems and energy markets," *IEEE Intelligent Systems*, vol. 26, no. 2. 2011, doi: 10.1109/MIS.2011.26.

[82] R. Bose, "Advanced analytics: opportunities and challenges," *Ind. Manag. Data Syst.*, vol. 109, no. 2, 2009, doi: 10.1108/02635570910930073.

[83] S. Kufeoğlu, G. Liu, A. Karim, and M. Pollitt, "Digitalisation and New Business Models in Energy Sector," *EPRG Work. Pap. . Energy Policy Res. Group, Univ. Cambridge*, no. December, 2019.

[84] D. W. E. Allen, "Governing the entrepreneurial discovery of blockchain applications," *J. Entrep. Public Policy*, vol. 9, no. 2, 2020, doi: 10.1108/JEPP-03-2019-0017.

[85] G. Gao, K. Lo, and J. Lu, "Risk assessment due to electricity price forecast uncertainty in UK electricity market," in *2017 52nd International Universities Power Engineering Conference, UPEC 2017*, 2017, vol. 2017-January, doi: 10.1109/UPEC.2017.8231903.

[86] G. Zhang, E. Ela, and Q. Wang, "Market Scheduling and Pricing for Primary and Secondary Frequency Reserve," *IEEE Trans. Power Syst.*, vol. 34, no. 4, 2019, doi: 10.1109/TPWRS.2018.2889067.

[87] A. S. M. Khan, R. A. Verzijlbergh, O. C. Sakinci, and L. J. De Vries, "How do demand response and electrical energy storage affect (the need for) a capacity market?," *Appl. Energy*, vol. 214, 2018, doi: 10.1016/j.apenergy.2018.01.057.

[88] M. Kubli and P. Canzi, "Business strategies for flexibility aggregators to steer clear of being 'too small to bid,'" *Renew. Sustain. Energy Rev.*, vol. 143, 2021, doi: 10.1016/j.rser.2021.110908.

[89] M. Zheng, B. Joy Dalmacio, and J. Bo Nørregaard, "Aggregation potential related to business models: A technical report from IEA EBC Annex 67 Energy Flexible Buildings," *International Energy Agency*, 2017. https://www.annex67.org/media/1568/aggregation-potential-related-to-business-models.pdf (accessed Apr. 28, 2022).

[90] M. Beus, I. Pavic, H. Pandzic, T. Capuder, I. Stritof, and I. Androcec, "Evaluating flexibility of business models for distributed energy resource aggregators," in *International Conference on the European Energy Market, EEM*, 2018, vol. 2018-June, doi: 10.1109/EEM.2018.8469776.

[91] OurPower, "OurPower," 2022. https://www.ourpower.coop/ (accessed Apr. 10, 2022).

[92] S. Tart, P. Wells, S. Beccaria, and E. Sanvicente, "Deliverable D3.1: Analysis of business models for car sharing.," 2019. http://www.lgi-consulting.com/wp-content/uploads/2019/10/STARS-D3.1.pdf (accessed Apr. 10, 2022).

[93] Car Amigo, "Car Amigo Website." https://www.caramigo.eu/be/fr/commentcamarche/ (accessed Apr. 10, 2022).

[94] G. J. Foster, M. J. Lamura, and J. Hackel, *"Kultur-Token" Sustainable Business Model: Visualizing, Tokenizing, and Rewarding Movility in Vienna, Austria*, no. October. 2020.

[95] MySMARTLife, "Energy data lab in Nantes," 2019. https://www.mysmartlife.eu/fileadmin/user_upload/Energy_Datalab.pdf (accessed Apr. 14, 2022).

[96] Amsterdam City, "Amsterdam City Website." https://amsterdamsmartcity.com/ (accessed Apr. 10, 2022).

[97] REMOURBAN, "Virtual games on energy savings Nottingham," 2019. http://www.remourban.eu/kdocs/1949819/REMOURBAN_IP3_Virtual_games_energy_savings.pdf (accessed Apr. 28, 2022).

[98] R. Garcia, "Valencia invests to become a smart city," 2022. https://eurocities.eu/stories/valencia-invests-to-become-a-smart-city/ (accessed Apr. 10, 2022).

[99] MySMARTLife, "Carbon Ego Mobile application in Helsinki," 2019. https://www.mysmartlife.eu/fileadmin/user_upload/Info_packs/info-packs_pdf/Carbon_Ego_mobile_application_fin_update.pdf (accessed Apr. 14, 2022).

[100] T. Website, "Telraam Website." telraam.net (accessed Apr. 10, 2022).

[101] L. Lyons, "Digitalisation: Opportunities for heating and cooling," 2019.

[102] A. M. Al-Ghaili, H. Kasim, N. M. Al-Hada, B. N. Jorgensen, M. Othman, and W. Jihua, "Energy Management Systems and Strategies in Buildings Sector: A Scoping Review," *IEEE Access*, vol. 9. 2021, doi: 10.1109/ACCESS.2021.3075485.

[103] Cityfied, "Cityfied website," 2022. http://www.cityfied.eu/ (accessed Apr. 28, 2022).

[104] Advizzo, "Case Study: Behavioural Insights-Driven Customer Engagement," *International Energy Agency*, 2019. https://www.iea.org/articles/case-study-behavioural-insights-driven-customer-engagement (accessed Apr. 28, 2022).

[105] P. Bosch and E. Al., "CITYkeys indicators for smart city projects and smart cities.," 2017.

[106] S. C. Marketplace, "Data captured through the Self-Reporting Tool," 2022.

https://smart-cities-marketplace.ec.europa.eu/scis-kpis (accessed Apr. 28, 2022).

[107] C. Simpson, E. Kemp, E. Ataii, and Y. Zhang, "Mobility 2030: Transforming the mobility landscape," *KPMG Int.*, no. September, 2019.

[108] Volvero, "VOLVERO website," 2022. https://volvero.com/ (accessed Apr. 10, 2022).

[109] OpenMobe, "Mobility as a service in trentino." .

[110] I. System, "Instant System Website." https://instant-system.com/ (accessed Apr. 10, 2022).

[111] M. H. Project, "D2.20: New Services on sustainable mobility in Valencia," 2020. https://www.matchup-project.eu (accessed Apr. 10, 2022).

[112] SmartenCity, "SmartenCity," 2020. https://smartencity.eu/about/solutions/public-bike-sharing-system-tartu/ (accessed Apr. 10, 2022).

[113] Wien city, "Graetzlrad Website." https://www.graetzlrad.wien/ (accessed Apr. 10, 2022).

[114] REPLICATE, "REPLICATE project website." https://replicate-project.eu/ (accessed Apr. 04, 2022).

[115] A. Nikitas, A. E. Vitel, and C. Cotet, "Autonomous vehicles and employment: An urban futures revolution or catastrophe?," *Cities*, vol. 114, 2021, doi: 10.1016/j.cities.2021.103203.

[116] International Energy Agency (IEA), "Data Centres and Data Transmission Networks," 2021. https://www.iea.org/reports/data-centres-and-data-transmission-networks (accessed Apr. 28, 2022).

[117] A. Sinaeepourfard *et al.*, "Estimating Smart City sensors data generation," 2016, doi: 10.1109/MedHocNet.2016.7528424.

[118] ERICSSON, "Ericsson Mobility Report," 2021. https://www.ericsson.com/4ad7e9/assets/local/reports-papers/mobility-report/documents/2021/ericsson-mobility-report-november-2021.pdf (accessed Apr. 28, 2022).

[119] Paolo BERTOLDI and P. BERTOLDI, "EC JRC Data Centers - Code of Conduct," *Navigation path European Commission JRC IET*. 2012.

[120] C. Gray, R. Ayre, K. Hinton, and L. Campbell, "'Smart' Is Not Free: Energy Consumption of Consumer Home Automation Systems," *IEEE Trans. Consum. Electron.*, vol. 66, no. 1, 2020, doi: 10.1109/TCE.2019.2962605.

[121] S. Benhamaid, A. Bouabdallah, and H. Lakhlef, "Recent advances in energy management for Green-IoT: An up-to-date and comprehensive survey," *J. Netw. Comput. Appl.*, vol. 198, p. 103257, Feb. 2022, doi: 10.1016/J.JNCA.2021.103257.

[122] EESI, "Hydropower in America: Energy Generation and Jobs Potential," 2011. https://www.eesi.org/briefings/view/hydropower-in-america-energy-generation-and-jobs-potential (accessed Apr. 01, 2022).

[123] R. Madurai Elavarasan, S. Afridhis, R. R. Vijayaraghavan, U. Subramaniam, and M. Nurunnabi, "SWOT analysis: A framework for comprehensive evaluation of drivers and barriers for renewable energy development in significant countries," *Energy Reports*, vol. 6, 2020, doi: 10.1016/j.egyr.2020.07.007.

[124] G. Sherriff, "Drivers of and barriers to urban energy in the UK: A Delphi survey," *Local Environ.*, vol. 19, no. 5, 2014, doi: 10.1080/13549839.2013.836164.

[125] G. J., "The strengths and weaknesses in the Swedish renewable energy sector – an assessment report," 2019. https://www.ltu.se/cms_fs/1.156688!/file/Jonas Grafström - Full text.pdf (accessed Apr. 01, 2022).

[126] G. Lobaccaro *et al.*, "A cross-country perspective on solar energy in urban planning: Lessons learned from international case studies," *Renew. Sustain. Energy Rev.*, vol. 108, 2019, doi: 10.1016/j.rser.2019.03.041.

[127] F. Mosannenzadeh, A. Bisello, C. Diamantini, G. Stellin, and D. Vettorato, "A case-based learning methodology to predict barriers to implementation of smart and sustainable urban energy projects," *Cities*, vol. 60, 2017, doi: 10.1016/j.cities.2016.07.007.

[128] A. Tabi and R. Wüstenhagen, "Keep it local and fish-friendly: Social acceptance of hydropower projects in Switzerland," *Renewable and Sustainable Energy Reviews*, vol. 68. 2017, doi: 10.1016/j.rser.2016.10.006.

[129] Helen, "Solar Powr plant Messukeskus." .

[130] W. Dragonetti, "How to make digital rights a reality," *2022*. https://eurocities.eu/stories/how-to-make-digital-rights-a-reality/ (accessed Apr. 10, 2022).

[131] A. Colclough, "Energising transformation," 2022. https://eurocities.eu/stories/energising-transformation/ (accessed Apr. 10, 2022).

[132] Helen, "Suvilahti energy system." https://www.helen.fi/tasapaino. (accessed Apr. 10, 2022).

[133] W. Centrale, "Windcentrale." https://www.windcentrale.nl/ (accessed Oct. 04, 2022).

[134] P. Buckley, "Smart City- The Smart Bin," 2020. https://business.blogthinkbig.com/waste-management-in-a-smart-city-the-smart-bin/ (accessed Apr. 10, 2022).

Annex 1

Table 6 : Select examples of investment details [16]

Country	Digitalization of urban energy system, or smart city programme	Investment details
Belgium	Belfius (bank) – European Investment Bank (EIB) co-financing programme: "Smart Cities and Sustainable Development" (2014) & "Smart Cities, Climate Action & Circular Economy" (2016)	The first programme supported 62 projects with EUR 400m, and the second programme is providing another EUR 400m. Belfius has a Smart Cities partnership with Agoria, the Belgian federation of the technological industry.
Finland	The Six City Strategy (6Aika) launched in 2014 is an open innovation platform of the six largest cities in Finland (Helsinki, Espoo, Vantaa, Tampere, Oulu and Turku) where stakeholders can share smart solutions and implementation of experimental projects intending to tackle challenges related to urban environment.	The Platform is managed by the Ministry of Economic Affairs and Employment, and companies can freely experiment their innovative solutions in the six cities. All data, experiences and standards are shared between stakeholders. It is funded by the European Regional Development Fund, European Social Fund, the Finnish Government and the participating cities. As of 2017, 26 projects with a total budget of 45 million EUR have been executed ever since.
France	1/ France's research tax credit 2/ Smart grids and connected cities are fully integrated into the "Sustainable City" plan as part of the "New Industrial France (*Nouvelle France Industrielle*; NFI)" project launched in May 2015. 3/ "La French Tech" initiative Created in November 2013	Smart grid and connected city companies conducting research and development in France are eligible for France's research tax credit Within the framework of NFI, Bpifrance, France's public investment bank is providing financial support. (e.g. EUR 50 million of "City of tomorrow" fund for start-ups in the smart city sector) Innovative companies working with smart grids and smart cities receive business development support through "La French Tech" initiative.

Germany	1/ "City of the Future", a funding programme of EUR 150 million operated by the German Ministry of Education and Research (BMBF) 2/ Smart City Charter (June, 2017), developed by the Smart Cities Dialogue Platform 3/ Smart Cities research cluster, established by German Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR)	The "City of the Future" funding is given out for a range of projects that bring local residents, researchers, local government, and municipal utilities together to work out ideas and solutions for cities. The Smart City Charter was developed by the Smart Cities Dialogue Platform established in 2016 by the BMUB. As part of the Platform, representatives from cities, towns, districts and municipalities, local government associations, various ministries, Land-level urban development authorities, the scientific community, professional, economic and social organisations and civil society all came together to discuss smart cities in the context of integrated and sustainable urban development. The Cluster is to understand the impact that societal adoption of digital technologies has on urban development, to repurpose digital and big data methods and instruments for urban development, to rethink action areas in urban policy with digital know-how and to work with professionals from cities, municipalities and businesses.
Italy	Investment budget to support public-private projects for smart electricity grids, broadband computer network infrastructure and the development of smart city services from the Ministry for Economic Development.	Initial budget of EUR 65m was announced in 2016.
Latvia	1/ The Smart Specialisation Strategy 2/ EU Cohesion Fund 2014-2020 3/ Planning document alignment between the stakeholder ministries. 4/ Local Smart city Task Force.	Development of a Research and Innovation strategy for Smart Specialisation (RIS3) is currently a prerequisite in order to receive funding from the European Regional Development Fund (ERDF). Latvian Strategy includes advanced ICT, Smart energy, and Smart materials/technology/engineering. EUR 10 billion from EU Cohesion funds are being used for digitalisation and smart development. Smart city's definition, necessity and possible solution integration in the relevant planning documents of the next EU Cohesion planning period expected to align the activities between ministries and to allocate funding for smart city solution creation and implementation through Smart city collaboration platform. Creation of a local Smart city Task Force (collaboration platform) with stakeholders from academia, public and private sector to identify problems, solutions and opportunities of Smart city environment in Latvia.
Slovak Republic	The pilot scheme of aid aimed to support experimental development and innovations in the build-up of smart cities (2017, Deputy Prime Minister's Office for Investments and Informatisation)	The scheme includes EUR 1 million from the state budget. Subsidies were designed to focus on 1/ Digitalisation of city management, services to inhabitants and public security and 2/ Transport management.

United Kingdom	1/ Innovation investments from the Innovate UK (innovation agency) 2/ Future Cities Demonstrator Competition (2012, Innovate UK)	As of 2017, GBP 32 million has been spent on the UK's IoT programme from the Innovate UK. Through the Future Cities Demonstrator Programme, Glasgow was awarded GBP 24m to implement its proposal, and Bristol, London and Peterborough were each awarded GBP 3m to implement part of their proposed plan.
United States	1/ Smart Cities Initiative (2015, White House) 2/ Smart City Challenge (2015, Department of Transport) 3/ Smart Cities and Communities Task Force, a body under the Networking and Information Technology Research and Development (NITRD) Program	Smart Cities Initiative promised USD 165 million investment in smart-city solutions, and announced to expand the initiative with additional USD 80 million investments in September, 2016. Seven finalists (cities) worked with DOT to realise their ideas to develop a smart transportation system. Coordination with the Department of Transport Smart City Challenge, Green Bonds and loan guarantees by the Department of Housing and Urban Development

Annex 2

Table 7 : A short survey on business models of different companies and projects [83]; [91]; Entsoe, 2022; Blockdata, 2022; EatLocalChallenge, 2021.

Company/Project	Country	Service	Targeted Customers	Used technology	Trading type	Business model
Adaptricity	Switzerland	Power grids optimization and efficiency improvement of repetitive tasks for grid operators	Business	AI, Big Data	Traditional	Software Services
BeeBryte	France and Singapore	Software to reduce energy consumption	Business and End-users	AI	Traditional	Savings
Car eWallet	Germany	Paying platform	End-users	Blockchain	P2P	Savings
Conjoule	Germany	Transaction P2P market platform for renewable energy consumers and producers.	Business and End-users	Blockchain	P2P	Energy
Crowd Charge	UK	EV charging optimization schedule	End-users	ML, AI	Traditional	Energy
Daisee	France	Energy management tool	Business and End-users	IoT, Blockchain	P2P	Services
Dajie	UK	Energy trading platform	Business and End-users	IoT, Blockchain	P2P	Services Product
Drift	USA	Management and trading platform	Business and End-users	ML, AI, Blockchain	Traditional	Energy
Electron	UK	Trading platform	Business and End-users	Blockchain	P2P	Services

Energy Web Foundation	Switzerland	Operating and trading platform	Business and End-users	Blockchain	Traditional	Services
Energo Labs	China	Trading platform	End-users	Blockchain	P2P	Energy
Energy21	Netherlands	Energy market	Business	Blockchain	P2P	Services
EnLedger	USA	Optimization and trading platform	Business and End-users	Blockchain	P2P	Services
EQuota Energy	China	Management services	Business and End-users	AI, Big Data	Traditional	Savings Services
Fresh Energy	Germany	Data analysis	End-users	ML	Traditional	Products
Greenbird	Norway	Data management	Utilities	AI	Traditional	Products
Gridcure	USA	Predictive analytics software	Utilities	ML, Big Data	Traditional	Services
Grid Singularity	Austria	Trading platform	Business	Blockchain	P2P	Services
GridWatch MAC	Ireland	Digital monitoring platform	Utilities	AI	Traditional	Services
BM Energy Blockchain Labs Inc.	China	Management platform	Business	Blockchain	Flexibility aggregator	Savings (CO2)
Jungle AI	Portugal	Performance monitoring	Business	AI, ML	Traditional	Software
Kisensum	USA	Fleet management software platform	End-users	AI	Traditional	Energy Services
LO3 Energy	USA	Energy management and optimization	End-users	Blockchain	P2P	Energy
Motion Werk	Germany	Trading platform for mobility	Business	Blockchain	P2P	Services
OmegaGrid	USA	Energy optimization platform	Business	Blockchain	P2P	Services

Origami Energy	UK	Trading platform, optimization, and management	Business	Big Data, ML	Flexibility aggregator	Software
Orison	USA	Domestic battery storage system	End-users	AI	P2P	Product
Piclo	UK	Marketplace platform	Business	AI	P2P	Services
PONTON	Germany	Energy trading and grid management	Business	Blockchain	P2P	Software
Power Ledger	Australia	Software solutions for energy trading and management	Business and End-users	Blockchain	P2P	Software
PowerPeers	Netherlands	Trading platform	Business and End-users	AI	P2P	Services
PROSUME	Switzerland	Trading and management platform	Business and End-users	Blockchain	Flexibility aggregator	Energy Services
Relectrify	Australia	All-in-one battery system from used EV batteries	Business and End-users	IoT	Traditional	Products
Sensgreen	Turkey	Energy analysis and optimization	Business	AI, DL, IoT	Traditional	Products Services
Slock.it	Germany	Sharing platform	Business and End-users	IoT, Blockchain	P2P	Services
SOLshare	Bangladesh	Solar energy sharing platform	Business and End-users	IoT	P2P	Products
Spectral	Netherlands	Management and trading platform	Business	AI, Blockchain	Flexibility aggregator	Services
Sterblue	France	Inspection and management solution for systems	Business	AI	Traditional	Services
Verv Energy	UK	Energy management tools	End-users	AI, IoT	Traditional	Software Services
WePower	UK	Management and trading platform	Business and End-users	Blockchain	Flexibility aggregator	Services
OurPower	Austria	Electricity trading platform	Business and End-users	Blockchain	P2P	Services
Enervalis	Netherlands	Energy management and optimization	Business and End-users	AI, IoT	Traditional	Product Software Services

EnHelix	USA	Energy management and trading	Business	AI, Blockchain	P2P	Software
FSight	Israel	Energy management and optimization	Business	AI, ML	Traditional	Services
Pebble	Germany	Energy trading platform	Business and End-users	Blockchain	P2P	Services
Interrface	Bulgaria	Energy trading platform	Business	Blockchain	P2P	Services
Restart Energy	Romania	Energy trading platform	Business and End-users	Blockchain	Flexibility aggregator	Energy
ApolloChain	Australia	Energy trading platform	Business and End-users	AI, IoT, Blockchain	P2P	Services

Annex 3

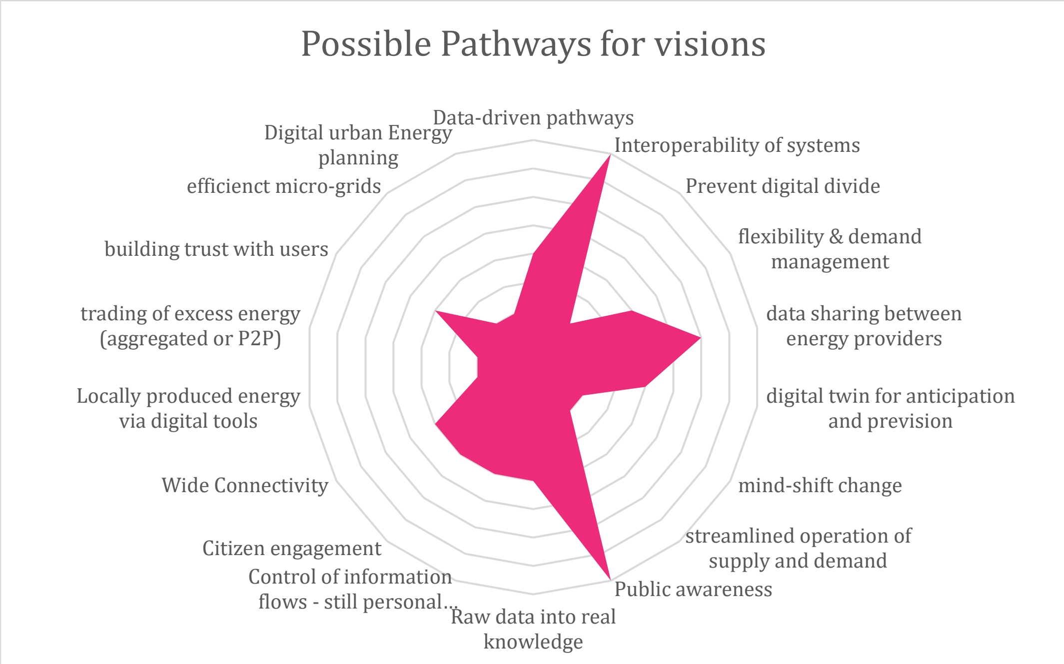

Figure 14 : Visioning workshop results - possible pathways for visions

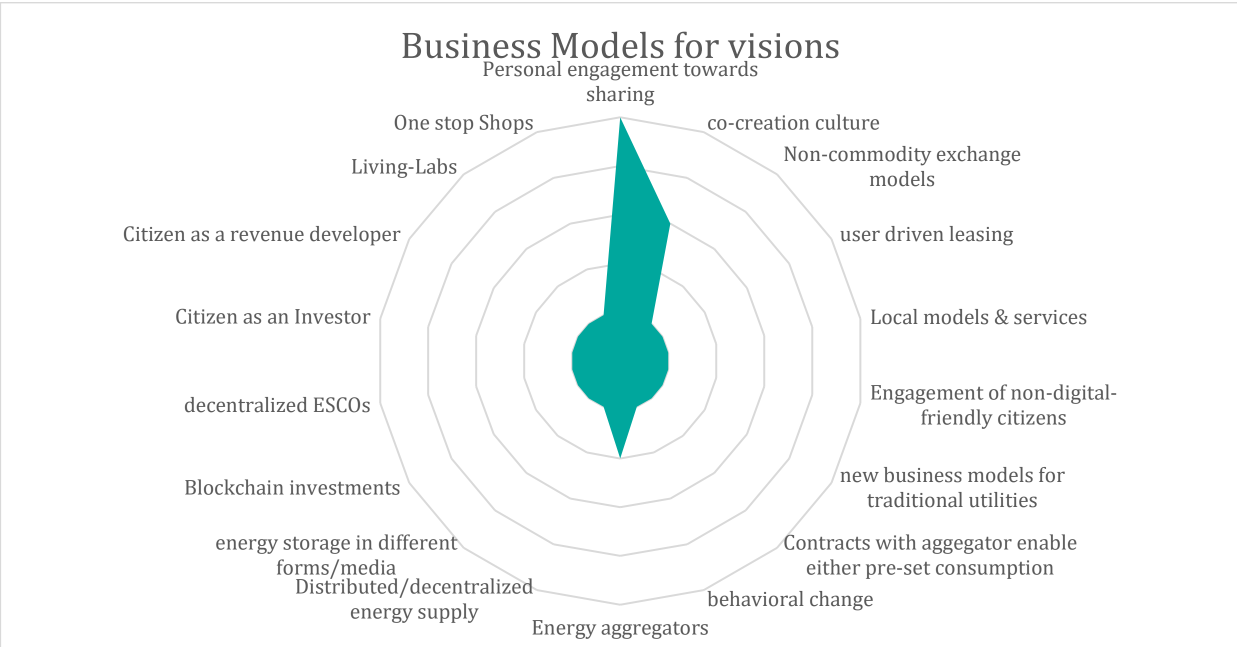

Figure 15 : Visioning workshop results - business models for visions

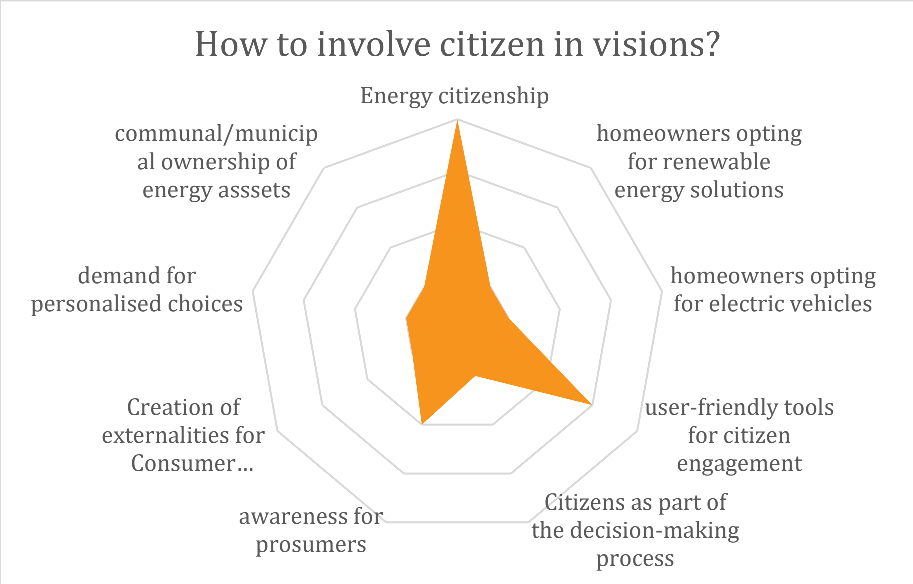

Figure 16 : Visioning workshop results - how to involve citizen in visions?

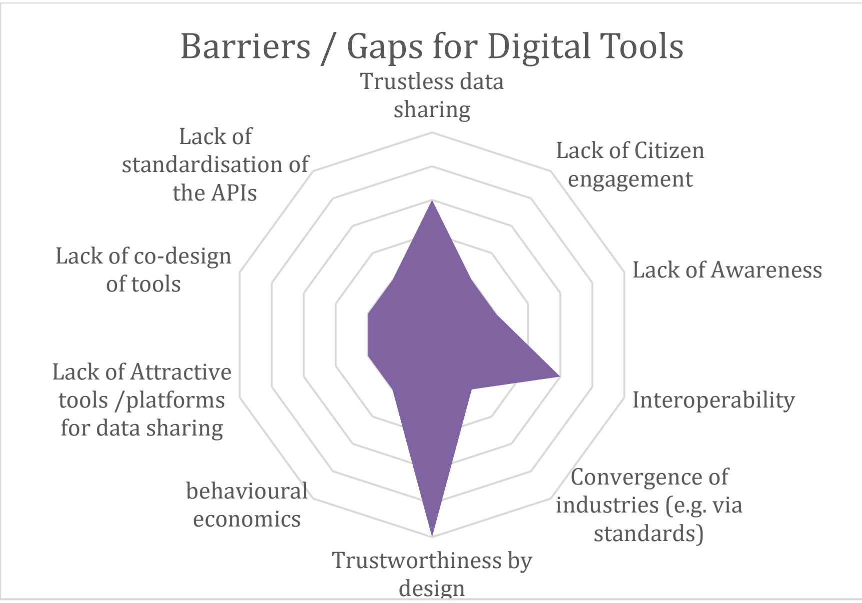

Figure 17 : Visioning workshop results - barriers / gaps for digital tools

Table 9 : Positive and negative implications of digitalization in UES

Positive Implications	Negative Implications
Data-driven business models-based on real data about energy systems real operation	Potential of authorising control depending on political system and cultural aspects
Local optimisation improving efficiency of transports, energy	having all digital requires equipment that increases the energy demand
Efficiency of system operation	Dependency on the system. What happens if it fails?
Availability of techniques to allow mass participation in decision making	Digital energy system may be more vulnerable to attacks
Digitalisation makes things more convenient, more reliable, smarter control	Perception of excessive control, learned data-sharing helplessness
Digitalization: more optimisation	Vulnerability; cybersecurity breaches
Optimised & more effective urban processes	Too much AI, take away decision making from end users
More efficiency	Increasing energy consumption of bigger and bigger ICT systems
	Security problems

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