Comparing Smart Cities Concepts

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***Abstract*—Urban areas cause 70% of global CO_2-emissions already today. This share is continuously growing, mainly due to a general urbanization trend. This makes cities one of the major addressees with regards to CO_2 reduction policies. A potential framework to deal with the challenges of radically reducing energy demand while grounding it mainly on renewable energy sources is the *smart energy city (SEC)* concept. This work provides an overview of the SEC concept by comparing three SEC models regarding their central characteristics and synthesizing them into a common approach. This comparison finds that all three models regard infrastructure, buildings, and transport as the main areas of intervention, such as upgrading the legacy grid into a smart grid or substituting vehicle fuels. Extending these findings, a unified smart energy city model (USECM) is proposed, which can serve for decision-makers as a basis for the conceptualization of SEC initiatives and directing their attention to critical aspects of SEC development.**

I. Introduction

Today, cities are responsible for approximately 70% of global CO_2-emission [1]. Just 100 cities account for 18% of global CO_2-emissions. Thus, coordinated and targeted measures by local governments can have a large impact on global CO_2-emissions [2]. Due to this great weight of cities smart solutions need to be found, which face the challenges of at the same time reducing urban energy demand while increase the share of renewable energy sources. The *smart energy city (SEC)* concept addresses these challenges, while also improving the quality of life of its citizens [3].

Various definitions for the concept of the smart city have been provided, focusing on different aspects, such as human, technological, and institutional factors [4], [5]. *Information and communication technology (ICT)* plays a crucial role in smart city development [6]. *ICT* is seen as a major tool to "enhance the lives of [...] citizens and optimize territorial, economic, and environmental resources". A smart city thus addresses urban challenges and assures the quality of life of its citizens, using technology, and *ICT* in particular, rendering all areas of city development *smart*, nurturing stakeholder collaboration and integration of domains [5]. Providing a *smart* energy system that grounds on renewable energy sources (RES) [7] is a key challenge within the domains of smart environment and smart transport, as well as a precondition for a smart economy and for smart living. This indicates why SEC is at the core of the smart city concept.

This work proposes the following SEC definition as a summary of what was previously stated:
SEC is a concept at the core of the smart city, that uses technology, including ICT, to address the challenges of increasing urban energy demand and climate change, while ensuring the quality of life of its citizens. The SEC uses ICT to integrate different domains, resulting in a holistic view of the energy system.
This definition reflects the central view of this work on the SEC concept, namely being part of the larger concept of smart city and using ICT to solve urban energy challenges.

This work gives insights on the main SEC concepts in order to synthesize and extend them, thus developing a unified smart energy city model (USECM). For this purpose, section II compares three conceptual SEC models and section III explains the main determinants for a USECM.

II. Comparison of SEC models

The three SEC models were selected in an extensive literature review based on three criteria. First, the model should focus on smart energy cities and not merely describe smart energy as a subcomponent of the smart city model. Second, the model should have the intention to present the SEC concept holistically. Third, the model should attempt to identify, structure and explain the relevant components of the *SEC* concept. In the following sections, the three selected models are compared concerning four criteria.

A. Areas of intervention

Areas of intervention are "key target fields for SEC development activities, investment, and stakeholders' attention" [3]. In this section, the models are compared with regards to areas of intervention. In the subsequent section, it is shown, which kind of technological solutions the models recognize to be the most important within these intervention areas. These two sections are an especially important part because they indicate in which areas of city development to act and through which technological solutions to drive change. They are summarized in *Figure 1*.

Mosannenzadeh *et al.* distinguish between hard and soft domains of intervention, where "hard" refers to tangible assets, such as infrastructure and energy resources, and "soft" stands for intangible assets, such as human capital [3]. Within the hard domain, three target fields are considered that have the largest potential for energy savings, namely *buildings and districts*, *transportation and mobility*, and *energy and ICT infrastructure*. The soft domains include *collaborative planning*, *consumer behavior management*, and *energy and data management*.

Intervention areas

Ref.	[8]	[3]	[9]
Generation	●		
Storage	●		
Infrastructure	●	●	●
Transport	●	●	●
Buildings	●	●	●
Collaborative planning		●	
Consumer behavior management		●	
Energy and data management		●	
Industrial			●

● Enclosed in the model

Technological solutions within intervention areas

	Ref.	[8]	[3]	[9]
Infrastructure	Smart electricity grid	●	●	●
	Thermal grid including district heating		●	●
	Data grid		●	
	Gas grid			●
Transport	Vehicle and fuel shifting	●	●	●
	Efficient public transportation	●	●	
	Change of mobility patterns		●	
	Optimized road traffic		●	
Buildings	Energy-efficient buildings	●	●	●
	Active exchange with the grid	●		●
	Electricity from RES	●	●	●

Fig. 1: Intervention areas and technological solutions within intervention areas

Contrary to tha Calvillo *et al.* identify five intervention areas, namely *generation, storage, infrastructure, facilities, and transport* [8]. This approach could be labeled as an "energy value chain" with generation providing energy, storage securing energy availability, infrastructure distributing energy, and facilities and transport as the final energy consumers. This structure is a more classic representation of the energy system, illustrating a sequence of events from point of generation to point of consumption. Although it is noted that *facilities* and *transport* can be both energy consumers and providers, the sequential representation does not fully account for this fact.

Lund *et al.* divide the energy system into four energy sectors: *Electricity, biomass and transport, buildings, and industrial*. *Electricity* is mainly understood as the electricity infrastructure (i.e. the electric power grid). *Biomass and transport* address the need to power the transport system under the constraint of a sustainable use of biomass. *Buildings* are seen as both energy producers and consumers. *Industrial production* is a further major energy consumer from an energy system's perspective. Lund *et al.* criticize the "state-of-the-art" segmentation of the energy system in current research in that it focuses too heavily on the electricity infrastructure and neglects the thermal and gas infrastructure. Therefore, three *infrastructures* are proposed as the core of an integrated energy system: smart electricity grid, smart thermal grid, and smart gas grid. Following this proposition, the sector *"electricity"* should better be called *"infrastructure"* and should include the electricity, thermal and gas grid.

All three models thus consider the intervention areas of *infrastructure, transport,* and *buildings*. In contrast to Mosannenzadeh *et al.*, Calvillo *et al.* and Lund *et al.* do not consider soft domains of intervention [3], [8], [9]. Additionally, Calvillo *et al.* include generation and storage as separate intervention areas, while the other two models presume that generation and storage can be presented through infrastructure, transport, and buildings. Therefore they do not include them as separate intervention areas. Lund *et al.* also mention the intervention area *industrial*, which the other two models do not consider to be part of the urban energy system.

B. *Technological solutions within areas of intervention*

With technology being one of the major enabling factors of smart city development, all three models draw significant attention to the question of what and how technological solutions can contribute to achieving the goals of SEC. All models classify the proposed technological solutions according to the areas of intervention the solutions apply to. However, as not all models put forward the same intervention areas, these classifications differ. For reasons of comparability, the areas of intervention that are shared by all models, namely *infrastructure, transport, and buildings,* are used to structure the technological solutions put forward by the models. This results in a focus on "hard" domains of intervention, which is not supposed to express, that "soft" domains are less important.

1) Infrastructure: Mosannenzadeh *et al.* divide energy and ICT infrastructure into three critical infrastructures, namely *electricity infrastructure*, *thermal infrastructure*, and *data infrastructure*. Electricity infrastructure is mainly concerned with the smart grid. The *smart grid* uses ICTs and advanced electrical infrastructure to create bidirectional flows of information and energy that are ultimately supposed to facilitate the integration of RES into the energy system [10]–[12]. This is the precondition for demand response schemes such as dynamic pricing, where electricity consumers are incentivized to use electricity when overall availability of energy (i.e. low demand and high generation) is high. It involves technical solutions such as an advanced metering infrastructure and electrical energy storage [3]. Thermal infrastructure relate to technical measures as district heating, cooling, and industrial heat recovery. And finally, the data infrastructure provides the underlying data for optimization, storage and exchange of energy.

Calvillo *et al.* primarily focus on electric infrastructure, more specifically on the smart grid [8]. They argue that, due to the communication infrastructure and control system, the smart grid is a precondition for increasing the share of RES and distributed generation as it helps balancing supply and demand.

As discussed in section II-A, Lund *et al.*, as part of their "state-of-the-art" characterization of the energy system, consider electricity largely as *electricity infrastructure*. Therefore, as Calvillo *et al.*, they also refer mainly to the functionality of the smart grid to compensate the intermittency of RES. Furthermore, the role of the smart grid in managing consumer's demand schedules, for instance through incentives, i.e. demand response schemes, is explained. In addition to the "state-of-the-art" characterization of the energy system, Lund *et al.* propose, as mentioned before in *Section II-A*, the thermal and gas grid as two further infrastructures. The *smart thermal grid*, which mainly consists of district heating and cooling, is supposed to connect and integrate the electricity and heating infrastructures. This can lead to synergies as will be shown in section II-C. The *smart gas grid* on the other hand offers the opportunity to integrate the electricity, heating and transport sectors by using non-natural gas produced from a surplus of RES electricity [9].

We can thus conclude that all models refer to the smart grid as critical infrastructure, that can enable the integration of intermittent RES. Apart from that, they discuss increasing the "smartness" within the thermal and gas grid which makes the introduction of a data infrastructure a necessity. These ideas, however, are not explored in detail.

2) Transport: Mosannenzadeh *et al.* divide mobility and transportation into three sub-domains. First, *vehicle and fuel shifting*, which involves shifting vehicles to alternative energy sources, such as hydrogen, electricity, or biofuels, to reduce their carbon footprint. Second, *multimodality and intermodality* concerns changing the way transportation is used towards shared transportation (e.g. car sharing) and more efficient public transportation. The aim is to both improve the travel experience and reduce environmental impact. Here, the delineation between hard and soft intervention is obviously vague. Third, *mobility and transportation infrastructure*, such as charging points, are needed to enable the other two. Urban transportation is thus transformed regarding, on the one hand, the way vehicles are powered, and on the other hand how urban transport is organized. This results in a necessity to update the existing *transportation infrastructure* to accommodate these changes [3].

Calvillo *et al.* introduce solutions that either *save energy* or represent a *shift towards less polluting fuels*. Energy savings in road traffic can be achieved through travel planners, that plan trips more efficiently, or traffic management tools, such as real-time speed-limit-control and traffic-signal-control. Furthermore, in public transportation energy can be saved using technologies such as regenerative braking systems in metros. The *shift to less polluting fuels* involves replacing fossil-fuels by electricity, hydrogen or biofuels. This concerns both individual mobility and public transport. In contrast to Mosannenzadeh *et al.*, Calvillo *et al.* do not address changing behavioral mobility patterns towards more energy-efficient modes of transport. However, they address technologies that could promote a shift in the way mobility is consumed, such as increasing user comfort in public transportation.

Lund *et al.* mainly discuss what Mosannenzadeh *et al.* call *"vehicle and fuel shifting"*, pointing out that a combination of several technologies is needed to transform the transportation sector because for different types of vehicles different kinds of technologies are most suitable. While light vehicles such as cars and vans are predicted to shift to electric engines, for heavy vehicles and aviation, gaseous and liquid fuels most likely cannot be fully substituted [9]. Biofuels, especially electrofuels, are a viable solution for the need for gaseous or liquid fuels [9]. Electrofuels are created in a two-step process. First, hydrogen is produced through electrolysis and carbon is created through the gasification of biomass. Second, electrofuels are synthesized from hydrogen and carbon. Electrofuels thus integrate the electricity, gas, and transport sector by combining hydrogen, produced using electricity, and carbon from biomass gasification to ultimately power the transport sector. This also shows how electrofuels can act as energy storage for excess electricity generation from intermittent RES. Although Lund *et al.* do not address the topics of *energy saving* and *changing mobility patterns*, their lead author extensively discusses these issues in [13].

3) Buildings: Technological solutions mentioned by Mosannenzadeh *et al.* encompass technologies improving the *energy efficiency of buildings*, such as insulation of pipes or adaptive facade systems [3]. In addition to building infrastructure related topics they refer to efficient buildings operation such as improved conditioning systems and thermal storage. If beyond this connecting this smart operation to the electricity grid the integration of RES can be further supported.

According to Calvillo *et al.*, one of the major objectives in the buildings sector is to reduce energy consumption and cost. First of all, this can be achieved by improving the *energy efficiency of buildings*, for instance by using energy-efficient lighting and building envelopes. Additionally, buildings can consume *energy from RES* from district energy networks such as district heating and cooling or distributed electricity generation grids. Lastly, buildings can take an *active role within the energy grid* by exchanging both energy and data with the grid. Supplying electricity generated by its photovoltaic (PV) panels in times of high energy prices buildings can thus help balance the load [8].

When reviewing the state-of-the-art of technological solutions within the buildings sector, Lund *et al.* find that "the predominant paradigm is that solutions for the integration of fluctuating renewable energy should be found within the individual building" [9]. Regarding the individual building, the concept of the Net Zero Energy Building (NZEB) is frequently addressed. The *NZEB* is highly energy-efficient, capable of generating energy from RES, and able to engage in a two-way exchange with the grid, leading to a net zero energy consumption. With regards to buildings as consumers of heating and cooling Lund *et al.* refer to a combination of savings and efficient heating technologies such as district heating.

All models have in common that they stress the *prosumer* role of buildings, i.e. both consuming *and* producing electricity. Furthermore, Calvillo *et al.* and Lund *et al.* stress that buildings should engage in a two-way exchange of information and energy with the grid.

C. Synergies among intervention areas

Due to the interdependency of the intervention areas, they should not be examined in isolation but as a whole to take advantage of synergies between the areas of intervention and prevent inconsistencies. Mosannenzadeh *et al.* define "cross-cutting domains", that "include the integration of all domains and their communication". Despite this recognition of the necessity to identify synergies, Mosannenzadeh *et al.* do not provide greater detail on how these synergies should be achieved. Calvillo *et al.* elaborate that synergies may be achieved through urban master plans, for instance for districts, that take into consideration the future design of the urban environment and have a holistic view on energy-related activities in the specific urban area. Unfortunately, this solely concerns the design and planning of new districts or cities and not the upgrade of existing ones.

The only ones focusing on the interdependency among the intervention areas and identifying specific synergies are Lund *et al.*. Although they identify a variety of synergies, this paper focuses on synergies reducing the need for energy storage, as they are seen to be a representative example of benefits from a more holistic view on the energy system. When increasing the share of RES in an energy system, the need for electricity storage rises, due to the intermittency of RES and the physical requirements that supply and demand in the power grid must be balanced at all times. This leads to a reduced efficiency through energy losses and thus high electricity costs. Alternatively, storing electricity in batteries today is also highly expensive. A more integrated view of the energy system can increase its flexibility and thus reduce the need for energy storage and save costs [9].

If electricity is used for heating purposes, excess energy from RES in times of high production and low demand can be stored in the form of heat for buildings. Furthermore, electricity is needed in the process of hydrogenation. Hydrogen can then either be used to power vehicles or be further transformed to electrofuels. In both cases, the stored energy is not intended to be converted back to electricity but to be consumed in the respective sector. This ensures that the large capacity in renewable energy infrastructure, needed for times of high demand is also used effectively in times of low demand. Although requirements for electricity storage cannot be fully eliminated, a more holistic approach towards integrating RES can significantly reduce the need for electricity storage [9].

D. Stakeholders of SEC

Calvillo *et al.* and Mosannenzadeh *et al.* state, that key stakeholders should be taken into consideration when establishing a SEC concept. Whereas Calvillo *et al.* do not specify who these relevant stakeholders are, Mosannenzadeh *et al.* identify four groups of stakeholders. First, *decision-makers* can be both individuals and organizations, that have the authority to define the future course of action. Second, *service providers* offer "energy related or energy management services to others for charge" [3]. Third, *target groups* are individuals who consume these services. And fourth, *lateral effective stakeholders*, such as media, opinion leaders, or certain associations, are impacting other stakeholders, despite not being directly affected by SEC concepts. how to address or manage these groups.

III. Towards a unified smart energy city model

The *unified smart energy city model (USECM)*, as proposed by this work and shown in *Figure 2*, aims at illustrating the process of SEC conceptualization from a holistic perspective. The model is intended to provide a conceptual structure for cities' analysis and planning of SEC initiatives by combining and extending the findings of the three models compared in the previous section. At its core, the model identifies two stages, *"identify goals"* and *"strategize targeted action"*. As SEC concepts deal with energy issues in the context of smart cities, the *goals* of SEC initiatives naturally revolve around the topics of reducing cities' environmental impact and improving citizens' quality of life, both with regards to energy transformation. The stage of *strategizing targeted action* includes the planning of the technical solutions within the intervention areas as well as the analysis of synergies identified by the three models compared in the previous section. The *USECM* argues that the process of SEC conceptualization is propelled by so-called *driving forces*, that have a significant impact on cities' future energy system. Understanding these driving forces provides a more holistic understanding of the whole SEC transformation. On the other hand, there are barriers, which might restrain the planning and implementation of SEC initiatives, so-called *"disrupting forces"*. Above all, any SEC strategy must be *tailored to the city-specific* context, which includes, but is not limited to, considering stakeholders as outlined in the previous section. This points to the fact that no single standard solution can be applied to every city.

Thus, the *USECM* extends existing models mainly by adding *driving forces*, *disrupting forces*, and by accounting for the necessity of *city-specific tailoring*. The subequent sections will be dedicated to exploring these dimensions.

A. Driving forces

The process of SEC strategy conceptualization is influenced by three major trends. Firstly, RES are expected to dominate energy generation by 2035 [14]. This creates the challenge of integrating the intermittent RES into the electricity grid, which is stressed by all three models in section II. According to the three models compared in this work, this challenge can be addressed both on the supply-side through energy storage and through demand-side management.

Secondly, electricity demand worldwide will double until 2050, with its share in total energy generation increasing substantially [14]. This increase in electricity demand is mainly caused by the electrification of the transport and building sector. The electrification of the transport sector is in large parts attributable to what is referred to as "fuel shifting" in

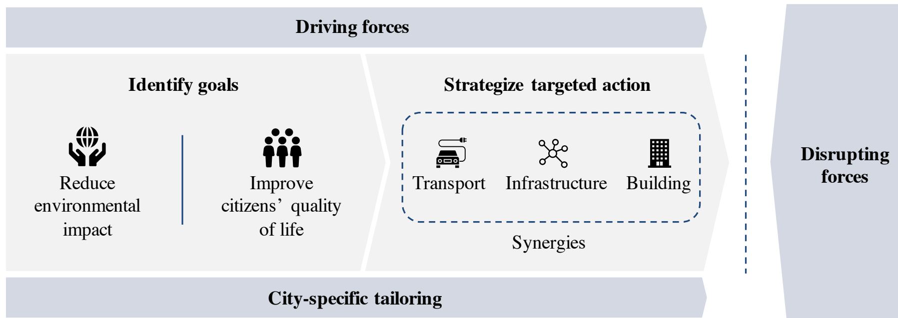

Fig. 2: Unified smart energy city model

the previous section (i.e. the shift towards less polluting fuels). In the course of this development electric vehicles (EVs) will see a large increase in sales once cost parity is reached in the first half of the next decade, with approximately 120 million vehicles on the road until 2030 [15]. This leads to challenges such as providing adequate charging infrastructure, load balancing, and generating the additional electricity demanded sustainably. The electrification of the buildings sector is driven by increasing demand for space cooling and appliances in non-OECD countries [14]. In many countries such as France, space heating is electrified, which provides the opportunity for heat energy storage.

Thirdly, sustainable technology development will transform the transport and building sector. As shown in all three models compared, a variety of technical solutions can be applied to make cities both more liveable and environmentally friendly. Current technological advancement is mainly driven by progress in artificial intelligence and sensor technology. In transport, besides the technological solutions described in section II-B2, fully autonomous vehicles have the potential to change mobility patterns, in promoting for instance mobility as a service solutions (MaaS) [16]. In the buildings sector, advances in energy management systems both at the utility and household level can lead to energy savings and reductions in energy cost, through tools such as demand-side management [17].

B. Disrupting forces

There are several disrupting forces regarding both the planning and the implementation of the SEC initiative. In the planning process, a lack of support for the project is a major concern. For instance, frequent obstacles are insufficient financing or long approval procedures [18]. Apart from this, a critical issue is the involvement of stakeholders. The variety of stakeholders involved, on the one hand, must be sufficient, so that they can contribute their expertise and support the project later on. On the other hand, the number of stakeholders involved, should not be too high in order to avoid complexity [19]. Additionally, stakeholders need to have sufficient expertise in the field and authority to make decisions. Other disruptive forces concern the results of the SEC planning. For instance, the objectives of the initiative might be too narrow without taking into account people's needs, for example by only focusing on reducing CO_2-emission while neglecting citizens' quality of life. On the other hand, however, the planning approach should not be too deterministic and allow for a multitude of different solutions. For example, technology-choice should not be predetermined in order to leave room for innovation. Additionally, goals should be achievable from a time and scope perspective. Goal conflicts between the goals of the SEC initiative and the partners can become problematic. Businesses need to be able to create a business case for their involvement in the initiative. This can turn out to be difficult, as initiatives often require a significant up-front investment, such as providing the charging infrastructure for EVs, but the return on such investment is uncertain due to the low number of current users of EVs. Conversely, the number of EV-users might not increase, unless a certain threshold of charging infrastructure is built. The issue is amplified by the fact that many investments have long time horizons (e.g. time required to build charging infrastructure) and are therefore prone to the risk that alternative solutions come up in the meantime, such as more efficient zero-emission powertrains.

C. City-specific tailoring

Shelton *et al.* and Kitchin *et al.* criticize the "wholesale importation of universal ideals into existing cities" [20] and "one-size fits all narratives" [21] in current literature. Therefore, SEC concepts need to consider the specific socioeconomic, locational and institutional conditions and challenges of the city and adapt solutions accordingly [20]–[22]. Therefore this notion is explicitly included into the USECM. Also, accounting for the needs identified by the stakeholder analysis leads to city-specific solutions [19]. Another question that might need to be addressed is which stakeholders are actually responsible for different aspects of the SEC. The SEC literature seems to be dominated by the assumption, that cities actively intervene to achieve their smart city vision. However, it is questionable to which degree cities' intervention is desirable and appropriate, which certainly also depends on the institutional context of the city. Cugurullo makes a related point in stating that the smart city literature creates the impression of cities having a unified smart city vision, while actual evidence on smart cities points to a fragmented implementation of the concept [23].

D. USECM Implementation Approach

In order to address all issues raised by the presented approach a thorough analysis of local options with regards to hard and soft interventions is recommended that also includes an analysis of driving and disrupting forces. However, this might be a complex task for city administrations not well acquainted with smart city concepts. Help can be provided by a standardized methodology as for instance offered by the EU smart cities guidance package [24].

IV. Conclusion

SEC is seen as a potential solution for the current urban challenges of increasing energy demand and climate change. The concept aims at reducing cities' environmental impact, using technology, particularly ICT, while ensuring the quality of life of citizens. This work compares three SEC models regarding their central characteristics and their SEC concept. It is shown that all models regard infrastructure, buildings, and transport as important areas of intervention. Within these domains, all models point to a variety of technological solutions, which consume energy from more sustainable sources, reduce total energy consumption, and generate energy more sustainably. For instance, all models point to the need for a smart grid, vehicle and fuel shifting, for more energy-efficient buildings, and electricity from RES. Additionally, the models are compared regarding their information on SEC stakeholders. However, the analysed models all provide partial views only. Therefore, USECM was developed combining and extending the findings of the three models. It adds the dimensions of *driving forces*, *disrupting forces*, and *city-specific tailoring*, and thus provides cities with a holistic model on the development of the SEC initiatives. In order to deal with the challenges identified in the USECM it is suggested to use process guidelines.

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