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Abstract

Transforming urbanized areas quickly and efficiently to make them less polluting and more resilient to global changes (including global warming) requires an integrative and holistic planning approach. This should be based on the concept presented in this article, of Smart Renewable Energy System (SRES), from the municipality to the district and building levels. Several methodological aspects are examined here to help understand the issues involved in energy-climate planning, qualify and validate the data and models used to address them, and choose coherent structures and technologies based on informed democratic social acceptance. The comparison of urban planning methods between two major cities (Strasbourg, France; Aarhus, Denmark) and the SRES simulations applied to a dense territory (Haut-Rhin) presented here are discussed with a view to implementing comprehensive, integrated methodological tools (scalable database, multi-parameter hourly simulations of intersectoral SRES coupling) for urban energy-climate planning.

Keywords
(separated by '-')

energy - climate - planning - renewable - SRES - methodology



Integration of a Smart Renewable Energy System in Sustainable and Resilient Urban Energy-Climate Planning

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Abstract. Transforming urbanized areas quickly and efficiently to make them less polluting and more resilient to global changes (including global warming) requires an integrative and holistic planning approach. This should be based on the concept presented in this article, of Smart Renewable Energy System (SRES), from the municipality to the district and building levels. Several methodological aspects are examined here to help understand the issues involved in energy-climate planning, qualify and validate the data and models used to address them, and choose coherent structures and technologies based on informed democratic social acceptance. The comparison of urban planning methods between two major cities (Strasbourg, France; Aarhus, Denmark) and the SRES simulations applied to a dense territory (Haut-Rhin) presented here are discussed with a view to implementing comprehensive, integrated methodological tools (scalable database, multi-parameter hourly simulations of intersectoral SRES coupling) for urban energy-climate planning.

Keywords: energy · climate · planning · renewable · SRES · methodology

1 Introduction

European initiatives such as Green Cities [1], Smart Cities [2], Concito [3] and the Green Solutions Awards [4] seek to integrate a more holistic vision into urban planning by bringing together major European cities to share their experience [5]. The most recent research in the field of low-energy, efficient and resilient urban planning [6–8] reflects the need for multi- and interdisciplinary expertise to address this challenge appropriately, at the scale of the building, the district, the entire city and even the surrounding rural area. It appears that energy is both the determining factor in urban fragility and resilience, and the vector for structural transformation towards sustainable, livable and resilient urbanism [9].

The Smart Renewable Energy System (SRES) concept described here derives from the Smart Energy System (SES) concept developed by the University of Aalborg, Denmark [10]. It expands this, i) by integrating all energy, climatic, geographical, architectural, urban planning and socio-economic structures in a coherent, holistic way; ii)

by directing urban development towards minimizing energy requirements (particularly in buildings), external dependencies, and emissions of pollutants and greenhouse gases (GHGs) in particular; iii) by valorizing all its renewable energy (RE) potential to supply all local needs.

The possibilities for the progressive implementation of dense urban and departmental SRESs are analyzed and modeled in this article. Methodological tools (complete scalable databases; numerical models and simulations) are presented and compared according to criteria that allow assessing their completeness and transparency. The methodology is being tested to compare French and Danish municipalities of similar size, and to assess the sensitivity of energy-climate transition trajectories for SRES at the scale of a dense French department (Haut-Rhin), as a preparatory step for a new urban planning approach to SRES at higher spatial resolution.

2 The SRES Concept

The architecture of a SRES (in French: SERI, *Système Énergétique Renouvelable Intelligent*) is based on the integrated design of the entire system of generation, conversion, transmission, distribution, storage and consumption of the various energy sources and carriers, with a cross-sectoral approach to optimize renewable energy flows to cover all useful end uses with the minimum of energy losses and excess/deficits that are not critical to stability of energy networks [11]. It also considers the economic and environmental aspects of pollution, greenhouse gas emissions, water use, societal needs, and imports and exports of energy and material resources.

2.1 Architecture of a SRES

The SRES is based on the systemic coupling of all local energy networks (heating, cooling, electricity, gas), multi-energy storage systems over multiple temporal and spatial scales, mobility (essentially electric mobility, as gas mobility is polluting and efficient enough), fresh and rainwater networks, recovery networks (urban wastewater, livestock effluent, municipal waste, materials). Figure 1 shows its general architecture.

The holistic structure of an urban SRES, implemented in the simulations presented in Sect. 3.2, avoids the need for conventional back-up thermal power plants (Fig. 2), greatly reduces the storage capacities of each energy carrier taken separately, and makes it possible to eliminate fossil GHG emissions very quickly (in addition to structural, systemic and behavioral energy sufficiency), by:

- integration of *local renewable energy production* (thermal, electrical, biofuels) that complements each other and covers the energy needs of the urban system, and even beyond [12],
- widespread use of *low-temperature 4G and 5G district heating and cooling* (DHC), connected to renewable and waste heat sources, thermal storage facilities and electricity grids using cogeneration (CHP, combined heat and power) units, high-efficiency industrial heat pumps (HP), heat-fridge pumps and absorption heat pumps. Current research [13–15] shows that 4G and 5G district heating and cooling are powerful cross-sector integrators for the economics and sustainability of SRESs,

- deployment of local *CHP units* using biomass, biogas and renewable gases obtained by hydrogasification of biomass waste, hydrothermal gasification (HTG) of urban and livestock effluents, and pyro-gasification of solid recovered fuels (SRF) and waste wood,
- daily to seasonal *thermal storage* for heating and domestic hot water [16],
- hourly-to-weekly *electricity storage* in powerful battery stations (sodium-ion, etc.) connected together to wind and photovoltaic (PV) farms and power grids (virtual power transmission lines, primary frequency regulation service) [17]; PV + wind generation for self-consumption in buildings in B2G (*building-to-grid*) mode, or in energy communities to participate in the energy flexibility of buildings [18]; road or river charging stations,

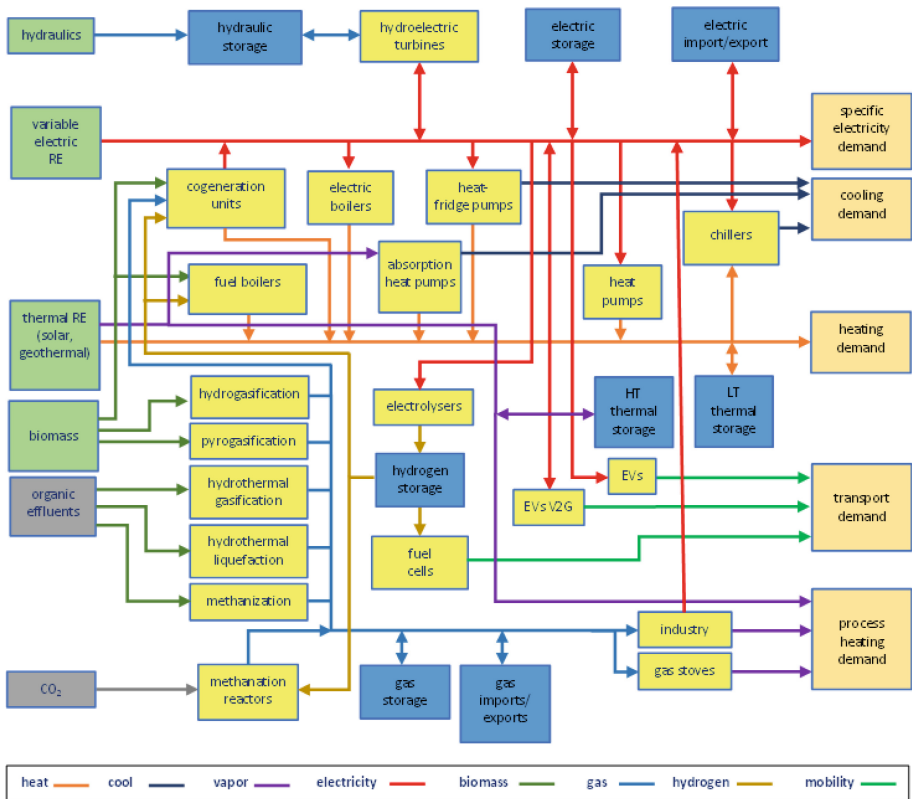


Fig. 1. General architecture of a SRES.

- hourly to daily *electricity storage* provided by electric vehicles (EVs) connected to local electricity grids in V2G (*vehicle-to-grid*) mode [19]. Each EV can thus store at least 10–20 kWh/vehicle at 7–11 kW, i.e. permanently available power of several tens of GW and electrical energy of several tens of GWh (for comparison, the total power of French Pumped Storage Hydropower stations (PSH) is 5 GW). In addition, the integration of EVs into residential, commercial and industrial buildings in

V2B (*vehicle-to-building*) mode makes it possible to boost buildings' PV production, reduce their overall demand and more effectively lower their GHG emissions [20],

- annual storage of *biomethane*, *e-fuels* for CHP units and chemical processes. Hydrogen, inefficient for transport and heating [21], is produced and stored for industry by cracking biomethane with carbon black recovery [22] and/or produced by electrolysis, for example for the methanation of CO₂ from methanizers. However, its high global warming potential (GWP₂₀ 40.1 ± 24.1 ; GWP₁₀₀ 12.8 ± 5.2 [23]) may compromise its supposed advantage in decarbonizing high-emission systems. Thus, in the SRES below (Fig. 2), replacing EVs with HVs (hydrogen-powered vehicles) is impossible (no solution of the equations), unless renewable electricity production significantly increases to a larger share of total power (at least 75%); consumption of biomass, pure water and thermal waste would then rise dramatically.

2.2 Efficiency of a Local or Urban SRES

Figure 2 compares a simple conventional energy system (supplied by classical power plants, fuel boilers and internal combustion engine vehicles), and several simple SRES based on electrical RE and biomass primary sources, CHP units, HPs, EVs (or HVs) with possible additional RE heat sources and RE fuel boilers. The *overall energy efficiency* η (i.e. end-use energy to primary energy ratio) rises from 47.4% to 90.1% when the conventional system is transformed into a simple SRES (with EVs), and primary fuel consumption (fossil vs. biomass & renewable waste) falls by 73%. The system's waste heat losses into the environment are reduced by 90%. Injecting 30% renewable heat and 5% biomass boilers into the SRES further increases overall efficiency (90.2%) and induces a significant reduction in biomass consumption and RE electricity supply (at a constant 60% of the total electricity supply). Conversely, hydrogenation in the transport sector is proving counter-productive (explosion of power consumption and waste heat).

3 Planning Methodology of Urban SRES

The intrinsic complexity of the local or urban SRES, which is essentially decentralized, horizontal and adapted to the fine granularity of the territory and its multiple interconnected components, contrasts with the top-down, hierarchical verticality of the classic centralized energy system that supplies cities through national electricity and gas grids.

The challenge of planning a SRES by an urban community to eliminate pollution and GHG emissions and to counteract the effects of global warming is all the greater because it involves a close symbiosis between urban planning and the energy-climate planning of the SRES, which in turn closely affects the thermal behavior of each building and district [24]. All socio-economic players need to be involved with an equitable sharing of the tasks and benefits of the transition for real social support [25]. The research on local energy planning methodology presented in this article focuses on its first two complementary components: i) the *construction of reliable, comprehensive Energy-Climate DataBases* (ECDBs) with easy access; ii) the *simulation of SRES at the local scale*. These serve as a validation test for their application (in progress) to the planning of refined energy-climate transitions at the urban scale (not presented here).

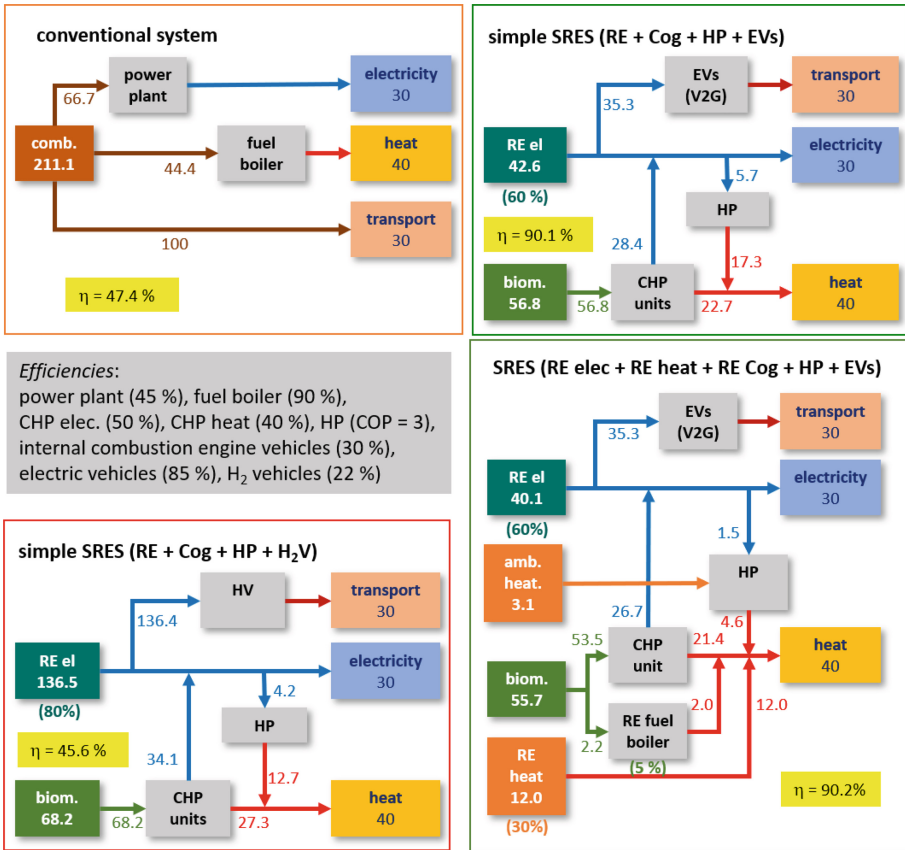


Fig. 2. Energy efficiency of simplified SRES vs Classical system (any energy unit).

3.1 Quality of Urban Energy-Climate Databases

As part of the COMET-PLANET project funded by the CNRS Energy Unit [26], a study was carried out to qualify and compare the accessibility to citizens/actors of their local ECDBs. Cities of similar size were compared: Aarhus City in Denmark and the Eurometropolis of Strasbourg (EMS) in France. Direct on-line accessibility was analyzed based on the 115 groups of input data (efficiencies, demands, productions; hourly distributions of demands, outdoor temperatures, insolation, winds; etc.) required for SRES simulations with the EnergyPLAN model [27] from Aalborg University, used in this work. This comparative study shows that ECDBs are neither fully open nor complete for performing fine-grained SRES planning in both cases, and that the availability rate (from 0 to 1) of ECDBs in the main data groups shown in the graph (Fig. 3) is much higher for Aarhus than for EMS.

Table 1 shows the proportion of accessible data by category. While 46.1% of the data is accessible to Danish citizens, only 17.4% is accessible to citizens of Strasbourg.

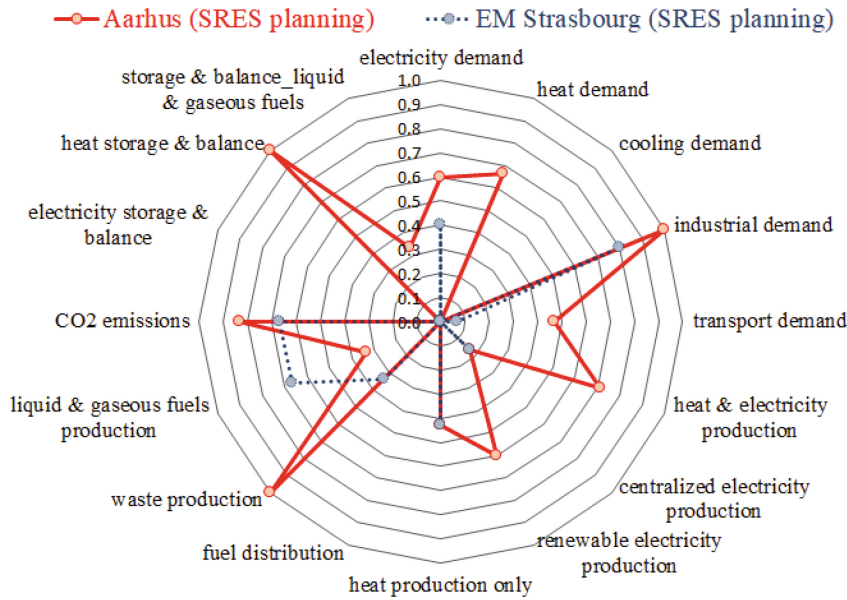


Fig. 3. Availability of energy data of Aarhus and Strasbourg for SRES planning [26].

Since the Concito project [3], Danish municipalities have been making their data freely available, and a considerable effort has been made to complete it.

Data on storage are still incomplete in Aarhus, despite the extensive use of thermal and electrical storage in Denmark, and incomplete in the EMS. However, certain necessary data (confidential or not) can be obtained on request from various public organizations, which requires a considerable amount of time but reduces the gap between French and Danish data availability. Thus, to initiate SRES simulations at the scale of the Haut-Rhin department (Grand Est region, France), 41% of the data were collected, the rest having been constructed based on statistical or physical assumptions (hourly demand and production data for certain energy carriers). Collecting the data necessary for relevant modeling of energy-climate transitions is therefore an essential issue for accurate, versatile, open and informed local planning.

Table 1. ECDB accessibility to citizens for SRES planning in Aarhus and Strasbourg [26].

European cities	Aarhus	Eurometropolis of Strasbourg
Number of compared data	115	115
Entire ECDB	46.1%	17.4%
Production data	48.9%	28.9%
Demand data	60.4%	14.6%
Storage data	25.0%	0.0%

3.2 Methodological Tools for Urban Energy-Climate Planning

Within the framework of the ESTEES project, financed by OHM Fessenheim [28], the EnergyPLAN modeling tool was used to simulate the current Haut-Rhin energy system and an SRES-type planning. This research freeware, widely used and validated throughout the world, ensures accurate hourly modeling of the operation of the most complex energy systems, with elaborate technical (no market constraints) or economic (market framework) optimization strategies [29]. All the current and emerging energy supply, storage, conversion, transport and distribution technologies are implemented and can be activated, parameterized and connected together within networks, whether coupled or not, regulated or not; end-use energy demand, energy supply and storage capacities, renewable energy potentials, consumption and meteorological hourly distributions, technical and environmental characteristics, energy balancing and storage, costs, taxes are provided as inputs by the user, and hourly distribution of energy consumption, production and exchange, economical costs and incomes, GHG emissions are computed as outputs.

After validating the model of the Haut-Rhin energy system with 2018 data, the separate or coupled influence of different equipment and structures on the reduction of GHG emissions and electricity exchange was studied for constant demand, as a first phase of future urban SRES simulations. For example, Fig. 4 shows the effect on electricity exchanges of electrifying 50% of road transport according to three types of electric charging modes (direct charge; Smart charge modulated according to variations in the system's electricity consumption and production; 50% Smart charge + 50% V2G). While vehicle electrification immediately increases electricity exchanges due to vehicle charging, Smart Charge and V2G technologies can reduce them by 30 to 40% by increasing the share of variable electric RE (50% wind, 50% PV) above 60%, more effectively than without electrification of the road fleet, while reducing total CO₂ emissions by 17%. Full electrification of the transport sector would cut total direct CO₂ emissions by 34% and energy consumption by around 80%, while keeping demand constant in terms of kilometers traveled.

Figure 5 illustrates the very significant impact of flexibility rules and simultaneous balancing of electricity and heat networks on the system's external electricity exchanges as the share of variable electric RE in the electricity mix increases. The basic SRES structure tested is as follows: 50% of individual heating systems connected to heat networks, electric heating replaced by heat pumps; changes in heat networks: solar thermal 30%, industrial heat recovery 25%, CHP 25% with 2/3 biomass and 1/3 biogas; road transport: 50% electric; PSH 55 MW, 590 MWh; thermal storage 200 GWh/yr. With only heat balancing regulation, where heat pumps seek to use only critical surpluses and V2G mode is limited to balancing them (*SRES 1 scenario*), the drop in electrical exchanges increases from 18% to 62% by increasing the share of variable electric RE from 0 to 60%, but then decreases if the share of variable electric RE continues to increase, due to these limited regulations.

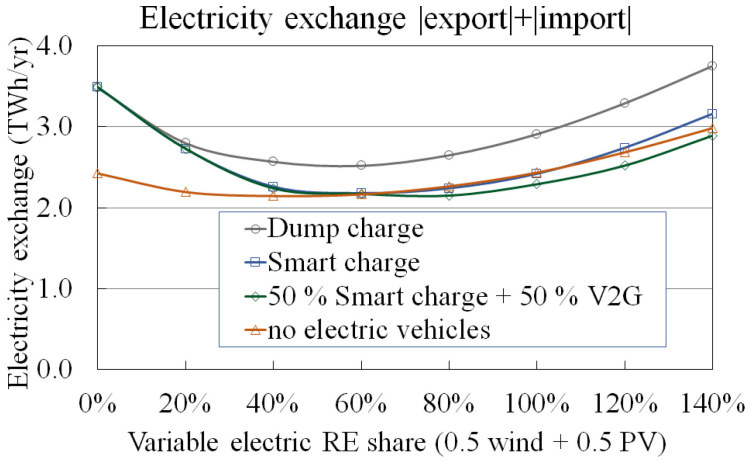


Fig. 4. Impact of electric vehicles on electricity exchange of Haut-Rhin according to the share of variable electric RE (50% wind, 50% PV) in 2018 [28].

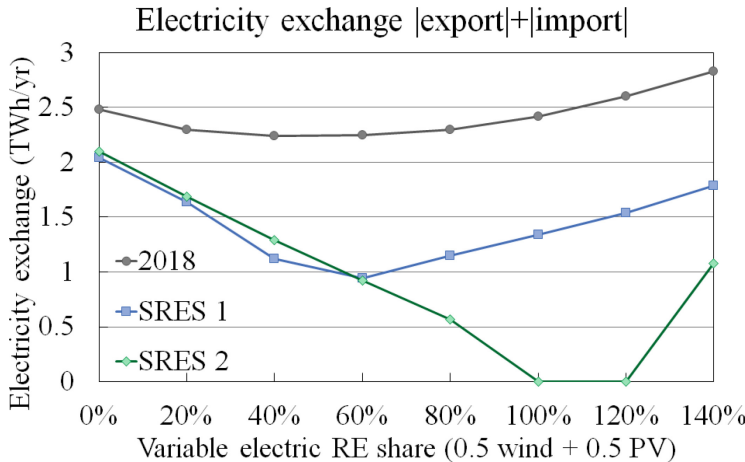


Fig. 5. Impact of SRES regulation on electricity exchange of Haut-Rhin according to the share of variable electric RE (50% wind, 50% PV) in 2018 [28].

By imposing the simultaneous balancing of heat and electricity demand, where the heat pumps use electricity exports and the V2G mode participates in the balancing of electricity exports and imports (*SRES 2 scenario*), the drop in electricity exchanges goes from 15% to 63%, but continues to grow up to 100% by further increasing the share of variable electric RE, thanks to the high complementary share of hydroelectricity in this area and the contribution of the PSH. Therefore, electrical storage in vehicle batteries in V2G mode, in the PSH and in future fixed batteries plays an essential local stabilizing role for electricity grid by minimizing external electric exchanges.

Assessing the impact of each separate implementation of SRES technologies in the initial system (structure 2018) also provides useful lessons for the design of the future SRES to be planned at the local level. Figures 6 and 7 compare, for example, the reduction in electricity imports and CO₂ emissions (without changing fuels) achieved by: i) replacing all direct electric heating with efficient heat pumps (*Scenario S1 HP*); ii) connecting half of individual heating to heat networks, either without modifying them (*Scenario S2 DH*), or supplying them via CHP with simultaneous balancing of heat and electricity networks (*Scenario S3 DH-CHP*). This results in electricity savings of 54% of the heating demand (and 6% of total electricity consumption) in S1 HP, leading to a 15% reduction in electricity imports. This reduction rises to 50% in the S3 RC-CHP scenario, confirming the high potential for electricity import savings provided by regulated coupling {heat network, CHP}. By contrast, the impact of the three scenarios on CO₂ emissions seems limited (−2% to −7% overall, including −8% to −14% for the heating sector alone) for three reasons related to the limited working assumptions used for this test: compared to 2018, heat demand and fuels (overwhelmingly natural gas and fuel oil) are left unchanged; GHG emissions from transport therefore still very much dominate; the industrial sector remains unchanged.

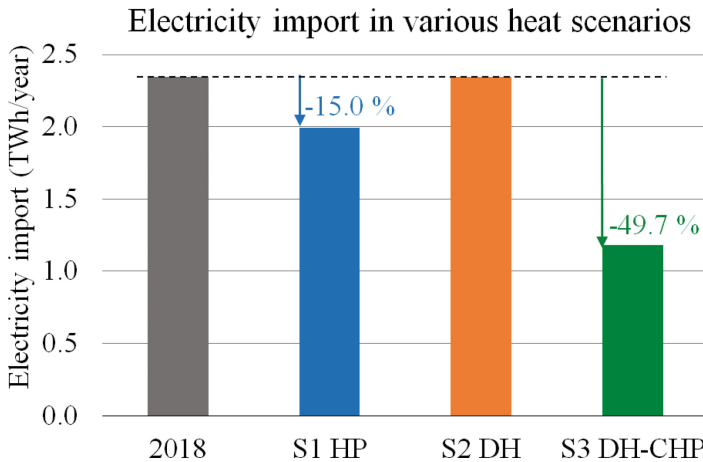


Fig. 6. Separate impact of heating scenarios on electricity imports of Haut-Rhin [28].

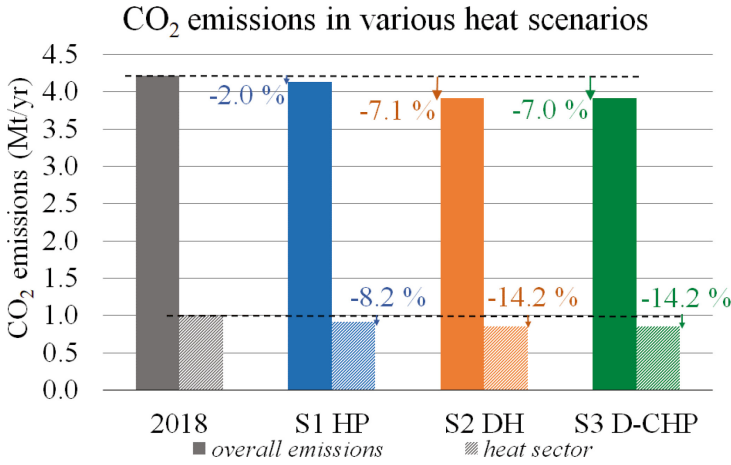


Fig. 7. Separate impact of heating scenarios on CO₂ emissions of Haut-Rhin [28].

On this basis, a new urban energy-climate planning tool is being developed [30]. It must integrate all geographical data and urban characteristics (buildings, traffic, uses) to create a scalable (updated monthly and annually to guarantee monitoring of the results of municipal decisions and to validate simulations) and parameterizable (structure and nature of buildings, SRES structure, individual and collective behaviors) ECDB as input for multi-criteria simulation of scenarios and predictions.

4 Conclusion

The sustainable structural transformation of cities and densely populated regions to meet climate, ecological and economic challenges requires the development of relevant planning tools that are easily accessible to local socio-economic stakeholders, so that energy-climate transitions can be explored in a reliable, efficient and socially acceptable way at the local, particularly urban, scale. The aim of the research presented here is to test the implementation of such a methodological tool, adapted to the local scale of densely populated areas.

The initial phase of building an open, comprehensive and scalable energy-climate database has shown that accessing the data needed to simulate complex, high-performance local energy systems is much more difficult in France than in Denmark, when comparing the cities of Strasbourg and Aarhus. It requires a lot of effort and time, even for teams of researchers. The first challenge is therefore to make this database as transparent as possible for those involved in local energy-climate planning. The next phase, the modeling of the structures of local energy systems and their operation, allowed the testing of the EnergyPLAN simulation tool, which has been used and proven worldwide for more than twenty years. The local energy system of the Haut-Rhin region in the reference year 2018 was modeled and simulated to validate the EnergyPLAN outputs.

Various separate and then coupled transformations were then programmed based on the SRES (smart renewable energy system) concept to test their impact on efficiency,

energy dependencies, development of local renewable energy potential and greenhouse gas emissions.

The results of these simulations showed that the close, smart coupling of the various energy networks, storage facilities and mobility systems makes it possible to integrate local renewable energies very effectively and on a large scale, and to optimize the SRES structure in such a way that external electricity exchanges are minimized and greenhouse gas emissions are significantly reduced.

Based on these results, the current phase of research work is focused on the development of a planning tool (database, ergonomic program) capable of simulating the urban system down to the district and building scale, integrating the urban climate and its evolution under the effect of global warming.

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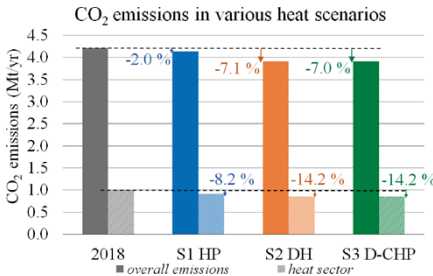
Chapter 46

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Page no	Fig/Photo	Thumbnail	Alt-text Description
3	Fig1		The image is a complex flow chart illustrating a process with multiple interconnected steps. It includes various colored boxes representing different stages or components, connected by arrows indicating the flow of information or actions. The colors and arrows are coded to represent different categories or types of relationships, as indicated by a legend at the bottom. The chart is structured to show how different elements interact within a system, with some boxes leading to multiple steps.
5	Fig2		The image is a panel figure consisting of four flow charts comparing different energy systems. Each chart illustrates the flow of energy through various components such as power plants, heat boilers, and transport systems. Arrows indicate the direction of energy flow, with percentages and numerical values representing energy efficiency and distribution. The systems include a conventional system and three variations of SRFS (Simple Renewable Fuel Systems) with different configurations. Key components are color-coded, and efficiency metrics are provided for each system.
6	Fig3		Radar chart comparing various energy and environmental metrics between Aarhus and EM Strasbourg under SRES planning. Metrics include electricity demand, heat demand, cooling demand, industrial demand, transport demand, heat & electricity production, centralized electricity production, renewable electricity production, heat production only, fuel distribution, waste production, liquid & gaseous fuels production, CO2 emissions, electricity storage & balance, heat storage & balance, and storage & balance liquid & gaseous fuels.

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			industrial demand, transport demand, and CO2 emissions. The chart uses two lines: red for Aarhus and blue for EM Strasbourg, illustrating differences in each category.
8	Fig4	Electricity exchange export + import Electricity exchange (TWh/yr) Variable electric RE share (0.5 wind + 0.5 PV) Legend: Dump charge, Smart charge, 50 % Smart charge + 50 % V2G, no electric vehicles	Chart showing electricity exchange (TWh/yr) versus variable electric renewable energy (RE) share (0.5 wind + 0.5 PV). The x-axis represents the variable electric RE share from 0% to 140%, and the y-axis represents electricity exchange from 1.0 to 4.0 TWh/yr. Four lines represent different scenarios: "Dump charge," "Smart charge," "50% Smart charge + 50% V2G," and "No electric vehicles." The chart illustrates how electricity exchange varies with different charging strategies and RE shares.
8	Fig5	Electricity exchange export + import Electricity exchange (TWh/yr) Variable electric RE share (0.5 wind - 0.5 PV) Legend: 2018, SRES 1, SRES 2	Line chart titled "Electricity exchange export/import" showing electricity exchange (TWh/yr) on the y-axis and variable electric RE share (0.5 wind - 0.5 PV) on the x-axis. Three lines represent different scenarios: 2018, SRES 1, and SRES 2. The 2018 line is relatively stable, SRES 1 shows a gradual increase, and SRES 2 decreases sharply before rising. The chart illustrates changes in electricity exchange with varying renewable energy shares.
9	Fig6	Electricity import in various heat scenarios Electricity import (TWh/year) Legend: 2018, S1 HP, S2 DH, S3 DH-CHP Annotations: -15.0 % (S1 HP), -49.7 % (S3 DH-CHP)	Bar chart titled "Electricity import in various heat scenarios" showing electricity import in TWh/year for four scenarios: 2018, S1 HP, S2 DH, and S3 DH-CHP. The 2018 bar is the highest, followed by S2 DH. S1 HP shows a 15.0% reduction, and S3 DH-CHP shows a 49.7% reduction.

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			S1 HP shows a 15.0% decrease, and S3 DH-CHP shows a 49.7% decrease compared to 2018.																									
10	Fig7	 CO₂ emissions in various heat scenarios The bar chart displays CO₂ emissions in Mt/yr on the y-axis (0.0 to 4.5) for four categories on the x-axis: 2018, S1 HP, S2 DH, and S3 D-CHP. For each category, there are two bars: a dark bar for 'overall emissions' and a light bar for 'heat sector'. Percentage reductions are indicated above each bar. <table><tr><th>Scenario</th><th>Overall Emissions (Mt/yr)</th><th>Heat Sector Emissions (Mt/yr)</th><th>Overall Reduction (%)</th><th>Heat Sector Reduction (%)</th></tr><tr><td>2018</td><td>4.2</td><td>1.0</td><td>-</td><td>-</td></tr><tr><td>S1 HP</td><td>4.0</td><td>0.8</td><td>-2.0%</td><td>-8.2%</td></tr><tr><td>S2 DH</td><td>3.9</td><td>0.7</td><td>-7.1%</td><td>-14.2%</td></tr><tr><td>S3 D-CHP</td><td>3.9</td><td>0.6</td><td>-7.0%</td><td>-14.2%</td></tr></table>	Scenario	Overall Emissions (Mt/yr)	Heat Sector Emissions (Mt/yr)	Overall Reduction (%)	Heat Sector Reduction (%)	2018	4.2	1.0	-	-	S1 HP	4.0	0.8	-2.0%	-8.2%	S2 DH	3.9	0.7	-7.1%	-14.2%	S3 D-CHP	3.9	0.6	-7.0%	-14.2%	Bar chart titled "CO emissions in various heat scenarios" showing emissions in megatonnes per year (Mt/yr) for 2018 and three scenarios: S1 HP, S2 DH, and S3 D-CHP. Each scenario has two bars: overall emissions and heat sector emissions. Percentage reductions are noted above each bar, with overall emissions decreasing by 2.0% to 14.2% and heat sector emissions decreasing by 8.2% to 14.2% across scenarios.
Scenario	Overall Emissions (Mt/yr)	Heat Sector Emissions (Mt/yr)	Overall Reduction (%)	Heat Sector Reduction (%)																								
2018	4.2	1.0	-	-																								
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