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System Dynamics Modeling for the Transition Trom Traditional Historic Urban Block to a Positive Energy Block

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ABSTRACT

In the light of the ambitious climate goals, the energy efficiency scope is gradually shifting from an individual building to a broader range – urban block, neighborhood, district, and city. Smart cities and communities show a significant potential of reaching energy efficiency goals. This study presents the results of a newly developed demand-supply energy flow model. The model simulates the energy demand and supply dynamics of a traditional building block in the historical center of Riga, the capital of Latvia. The authors analyzed 12 different scenarios applying four factors – energy efficiency, renewable energy technologies, waste heat recovery, and electricity storage in electric vehicles.

Keywords: positive energy block, electric vehicles, intelligent energy systems, renewable energy, waste heat

1. INTRODUCTION

The buildings and construction sector used 36% of final energy and created 39% of CO_2 emissions in 2018 [1]. 75% of the existing building stock in the European Union is found to be inefficient. 50% was built before energy performance standards were developed in the 1970ies, and 85-95% of buildings will still be in exploitation in 2050 [2]–[4]. With an energy renovation rate of 1% and below the 3% target set by the Energy Efficiency Directive [4], [5], the energy efficiency targets have been widened, focusing on the energy efficiency level of new buildings and building renovation. The latest amendments of the European Union Energy Performance of Buildings Directive call for decarbonization of existing building stock by reducing energy consumption via deep renovation of existing buildings and carbon-free energy supply [6].

In the context of positive energy blocks, scientific articles explore issues such as the scenarios of district heating extension [7] and decarbonization of heating systems using electrification [8]–[10] and bioenergy technologies [11], solar district heating [12], simulation tools of building stock decarbonization [13]–[15], economic and environmental trade-offs [16], and carbon pricing [17]. Particular urgency is given to the balancing of energy supply and demand with coupling buildings and electric vehicles [18].

Another scope is the building renovation itself. A sustainable building renovation approach is introduced, focusing not only on energy consumption reduction but incorporating three crucial facets in renovation design – environmental, economic, and social – and promoting life cycle thinking [18]. Searching for optimal renovation scenarios, the difference between environmentally and financially optimal renovation scenarios is found based on life cycle assessment [19]. But [20] have found that changing only the energy system is more beneficial than performing complete renovation of the building. These authors highlight the need for new approaches in building renovations.

This paper describes a newly developed computer simulation model of hourly demand and supply of energy flows in one block in the historical center of Riga. The model is based on the system dynamics modeling approach. It allows exploring scenarios to achieve a positive energy benchmark using variations of four variables: (i) energy efficiency measures, (ii) on-site renewable energy sources, (iii) waste heat recovery from large energy consumers, and (iv) renewable electricity storage in electric vehicles.

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2. MATERIALS AND METHODS

2.1 Case study description

Urban block in the historical center of Riga was chosen for the case study, located between Krisjana Barona, Perses, Marijas, and Dzirnavu streets. The selected urban block is rich in its variety. It comprises 25 buildings from different building periods with a mixed function (including coffee shops, bakeries, a grocery store, offices, and residential premises). The buildings differ in the architectural value and the used construction materials (wood, masonry, and prefabricated lightweight panels of the soviet era). The height of the buildings varies from two to six floors. The block area is 21,2 thousand square meters, and the treated floor area is 53 thousand square meters.

2.2 System dynamics model

System dynamics is a powerful computational tool to model complex and dynamic processes. The theory of system dynamics is based on studying the dynamic time-dependent behavior of a system and the structure underlying the behavior. By analyzing the structure of a system, interlinkages of the separate components of the system driving the processes can be better understood, which, in turn, allows targeting the interference to improve the overall performance more accurately, precisely, and efficiently.

The basic structure of the system dynamics model is given in Fig.1. The model is based on the following modules:

- Heating energy demand;

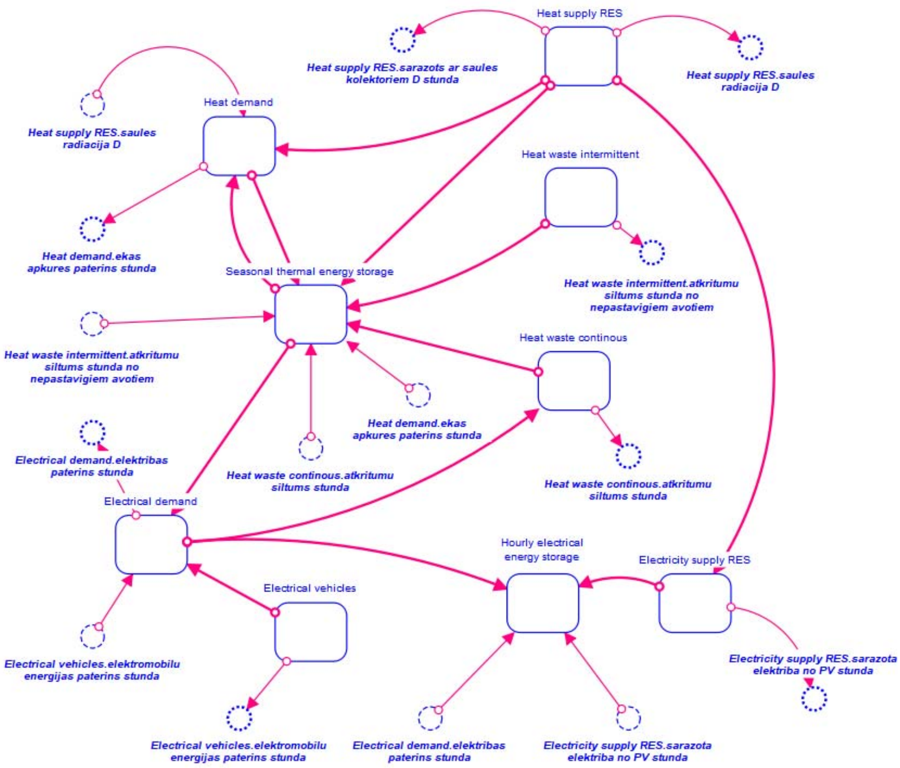

Figure 1. Major elements of the system dynamics model

Data on heat energy consumption is publicly available and was collected for each building individually. Data on electricity consumption is not publicly available; therefore, the electricity consumption was aggregated for the whole block and divided into small, average, and big consumers.

- Electricity demand;
- Heating provided by the on-site renewable energy sources;
- Electricity supplied by the on-site renewable energy sources;
- Seasonal thermal energy storage;
- Storage of on-site generated electricity;

- Waste heat, and;
- Electric vehicles.

The demand-supply energy flow model is created using the Stella® Architect software. The design of the model is based on the input of identified sources and targets of energy flows.

The vehicle-to-grid technology and its variations (vehicle-to-home and vehicle-to-building) offer possibilities to improve vehicle utilization efficiency. In their study, Borge-Diez [21] et al. found that energy charged in electric cars during the night and later delivered in a building can lower annual electricity demand by 49%. Such an approach decreases energy peaks, gives CO2 savings, and reduces energy costs. Further on, results can be even improved in case renewable energy sources are used for vehicle charging. For example, Barisa et al. found that a typical Latvian household using an electric vehicle charged with solar PV during low electricity demand hours, in the best case, can save up 87% of CO2 emissions compared to the baseline scenario with electricity consumption from the grid and a conventional car running on diesel [22]. As pointed out by Peng et al., with increasing numbers of electric cars on the roads, electric vehicles play an important role in grid frequency regulation [23].

3. THEORY/CALCULATION

3.1. Scenarios for reaching positive energy block benchmark

Two scenarios are considered: (a) Scenario "Energy efficiency first" and (b) Scenario "Cultural heritage first". The scenario "Energy efficiency first" foresees deep renovation, which means that all building facades except decorative facades of architectural monuments are insulated using conventional techniques, including an insulated roof, high-performance windows, and a ventilation system with heat recovery. In scenario "Cultural heritage first" partial renovation is proposed meaning that only those facades permitted by authorities (facades of buildings that are not listed, and courtyard facades of all buildings) are insulated using conventional techniques (insulated roof, medium performance windows (concerning the original appearance), and natural air exchange).

The goal is to observe the annual balance of total energy consumption. In each of the scenarios, factor values are set before the simulation run. Factors considered are: (i) energy efficiency level, (ii) renewable energy sources, (iii) waste heat recovery, and (iv) electricity storage/recovery in electric vehicles. The experiment aims to evaluate the potential to reach a positive energy benchmark for heating and electricity consumption.

Factor "Energy efficiency level" considers thermal properties of buildings. The basic level corresponds to the existing situation.

Factor "Renewable energy sources" is defined in on/off mode, and the skyline of rooftops is defined as the preservable landscape of the historical center of Riga. Therefore, two alternatives are considered – with or without on-site energy generation using solar technologies – hybrid PVT technology for heat and electricity generation and BiPV panels for electricity generation.

Factor "Waste heat recovery" is defined in on/off mode to illustrate the potential and share of waste heat recovery in overall energy balance.

Factor "Electric vehicles" is defined in on/off mode to illustrate the potential of coupling renewable energy generation and electricity consumption through the vehicle-to-building concept. This allows reducing peak demand and increasing the overall energy efficiency of the block.

A matrix of possible scenarios for reducing total heating energy consumption is created (see in the results Table 1). In combinations of 3 variables, 12 scenarios are considered.

4. RESULTS

The research presented in the paper focuses on the in-depth simulation of energy flows within an urban block benefiting from mixed-use of the urban block, exploring different scenarios of reducing energy consumption and using renewable energy sources.

4.1 Baseline energy consumption

The baseline scenario illustrates the existing situation and current energy consumption of the case study block with total heating energy consumption of 4,6 GWh per annum and electricity consumption of 5,4 GWh per annum. The thermal properties of buildings correspond to the existing situation; no renewable energy sources or waste heat recovery technologies are used in the baseline scenario.

4.2 Heat energy demand scenarios

The resulting total heating consumption varies in scenarios starting from 0,2 GWh (8th scenario), achieving specific energy consumption of 4 kWh/m^{2}a.

Scenarios considering stringent rules of preservation of cultural heritage perform considerably higher than energy efficiency first scenarios. Scenarios exploring on-site energy generation illustrate the depletion of the need for external energy sources provided by renewable energy and seasonal energy storage. For the 8th and 6th scenarios, on-site renewable energy generation can almost entirely cover heating energy demand. Other scenarios need more tangible support from external sources. On-site thermal energy production can be boosted using solar collectors instead of PVT technology.

Table 1. Matrix of scenarios for the experiment. Heating consumption

	Scenarios											
Factors	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Energy efficiency	0	0	0	0	1	1	1	1	2	2	2	2
RES	0	1	0	1	0	1	0	1	0	1	0	1
Waste heat recovery	0	0	1	1	0	0	1	1	0	0	1	1
Energy consumption (GWh)	**4,6**	**3,1**	**4,2**	**2,7**	**2,0**	**0,5**	**1,7**	**0,2**	**2,9**	**1,4**	**2,5**	**1,0**

Figure 2 depicts a visual representation of accumulated heat consumption in described scenarios (one year 8640 hours). Valley in graphs over summer months illustrates the RES-generated heat.

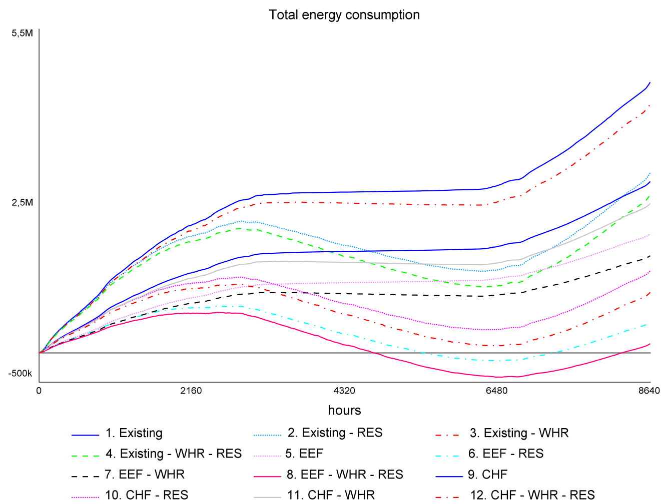

Figure 2. Scenarios for annual accumulated heat consumption

4.3 Electricity demand scenarios

It can be seen in Figure 3 that with the maximum share of PVT technology on the roof, electricity generation from renewable sources can cover only a small part of the overall electricity demand.

The primary reason is the high electricity consumption of the data center, which is part of the case study building block.

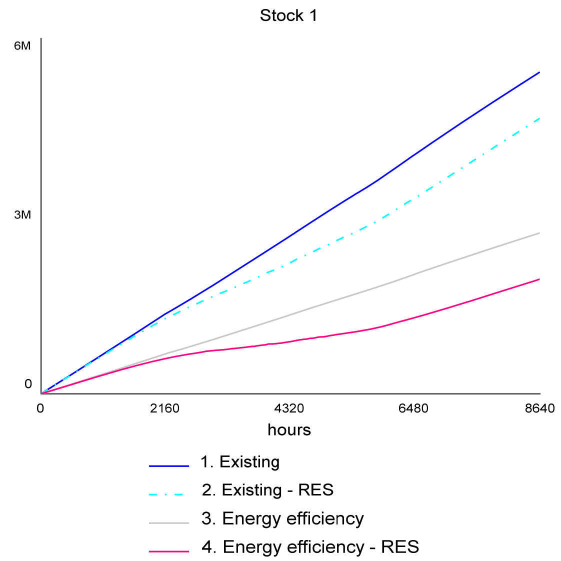

Figure 3. Scenarios for yearly electricity demand

5. DISCUSSION

From the proposed scenarios, it can be concluded that reaching a positive energy balance might call for adjustments in cultural heritage preservation techniques. Based on findings in this research, discussion with the experts of urban historical heritage can be introduced. But from the other hand, this study shows that innovative techniques for both building energy efficiency techniques and urban on-site energy generation technologies other than solar are needed to prevent seasonal storage heat losses and make the overall generation and storage system more effective.

In the proposed building block, conventional energy efficiency solutions are considered. To continue reducing heating energy demand, innovative materials could be used, such as vacuum or aerogel insulation, vacuum glazing, and energy-storing composite phase change materials.

In the following stages of the study, the impact of the smart energy system with low and very low heat supply temperatures on overall energy balance will be explored (defined in the sub-model “thermal energy storage”). Low energy systems make waste heat recovery more effective, and it allows to recover a wider range of waste heat sources, thus lowering the overall energy demand. In addition, policies for accelerating the use of renewable sources for both energy generation and waste heat recovery will be explored.

The heating and domestic hot water preparation for the particular building block is currently provided by individual natural gas boilers or district heating.

Most of the heat (around 75%) is generated in natural gas cogeneration plants for the district heating system in Riga, but biomass boilers and cogeneration provide the rest of the necessary thermal energy. Analysed scenarios do not include the district heating system's heat supply`s decarbonisation as a possible technological solution because the focus is attributed to the on-site energy generation scenarios, and district heating can not currently be a carbon-neutral heat supply option. However, further studies should also evaluate the impacts from covering the heat demand by highly efficient and renewable district heating systems providing the thermal needs in periods when there is no waste heat, solar energy, or surplus RES power available. It could be a cost-effective solution due to the developed heat generation and transmission infrastructure of district heating systems.

From the district heat supplier perspective, the development of positive energy blocks that do not need to purchase heat from the external supplier might cause a negative impact on the decrease of heat sales and increase of fixed heat generation costs. However, the district heating supplier can introduce innovative business models and manage energy systems in positive building blocks/districts by using existing infrastructure, qualified employees, and the existing experience in the field. Such cooperation could be further investigated mainly from an economic perspective. Proposed scenarios preferred heat production over electricity. Another option would be to preferred electricity generation over heat generation and seek the right balance of heat and electricity generation and interaction with grids.

6. CONCLUSIONS

Ambitious global European climate goals call for ambitious local actions. In the study presented in this paper, the transformation from a traditional urban block to a positive energy block is explored based on a case study. Novell approach is proposed with the help of an in-depth system dynamics model for hourly supply-demand energy flow simulation.

In the simulation experiment with four significant factors – energy efficiency level, renewable energy technologies, waste heat recovery, and electricity storage in electric vehicles – twelve scenarios for heating and 4 scenarios for electricity are developed, and the impact of each factor is evaluated. Looking at thermal energy demand, a positive energy block benchmark can be almost achieved only by a combination of deep renovation, extensive on-site thermal energy generation, and storage and waste heat recovery.

Prioritizing the thermal energy generation sets back the coverage of electricity demand. Using rooftops only for PVT technologies does not allow generating electricity at maximum capacity.

In further studies optimization of energy flows will be explored, maximizing the yield of renewable energy and the recovery of waste heat through exploring different temperature gradients and increasing the impact of electric vehicles.

Created system dynamic model can be a valuable instrument evaluating the possibilities for the transition from traditional to low or positive energy blocks/districts locally as well as worldwide.

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