Coupling system dynamics model and multi-criteria analysis for a sustainability assessment of a district heating system's development

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Abstract:

The study provides the hybrid model that couples system dynamics (SD) modelling and multi-criteria analysis. The SD model allows obtaining energy, economic, environmental indicators of a DH company and evaluating its dynamics in a time horizon until 2050. Considered decarbonization scenarios include the transition of the DH system towards a 4th generation DH (4GDH) system adhering to 4 strategies: the DH system uses at least (a) 50% RES; (b) 50 % waste heat, (c) 75 % cogenerated heat or (d) 50 % of combined aforementioned energy and heat. In addition, the development scenarios include various energy efficiency improvement measures on the consumer side and in the heating networks. The sustainability of each scenario was assessed with multi-criteria analysis methods - TOPSIS. The hybrid model provides a ranking of the selected transition pathways according to their sustainability score and benchmarks results of developed scenarios against a carbon neutral DH system. This model serves as a guidance to DH system developers and decision makers. The case of Riga is presented in the study.

Keywords:

4th generation district heating, Decarbonisation, District heating system, Multi-criteria Decision Analysis, sustainability assessment, TOPSIS

1. Introduction

The district heating sector is responsible for a large share of greenhouse gas emissions. The environmental impact along with economic and technical limitations is increasingly looked as a key factor in decision making in development of DH systems [1]. These different parameters impact the current operation of these systems and will influence them in the future because of new legislation, market trends and changing public outlook.

Dynamic energy system models are used as a decision support tool that can characterize existing and future DH systems because they are designed to simulate the behaviour of energy systems over time, considering the interactions between heat production, distribution and utilization [2]. Different development scenarios therefore can be modelled to find the technological mix fit for a sustainable DH system. Decarbonization, transition to renewable energy sources can be set as an optimizable goal for the system in year 2050 together with the expected economic considerations.

This modelling approach produces a set of possible development scenarios that each have a unique combination and degree of developed technologies. The assessment of these scenarios is essential for decision-making process and different methodologies exist for this purpose. Maigret et al. modelled the development of a carbon intensive industry and compared the possible development scenarios by their Pareto fronts [3]. Finke and Bertsch developed a method for multi-objective optimisation of energy systems and a framework for finding Pareto-optimal solutions and trade-offs between objectives [4]. While these methods can provide insights into the energy systems' technological limits and possible development scenarios, they still require a final judgment of the decision-maker. Yuan et al. coupled smart energy system simulation with multi-objective optimization tool MOPSO and multi-criteria analysis (MCA) method TOPSIS for an optimal heating strategy selection moving towards 100% renewable energy use [5]. The use of MCA methods can alleviate the burden of decision-makers as those can consider different viewpoints and conflicting objectives. That makes them ideal for DH system assessment where often clashing economic, technical, environmental and social aspects play a significant role.

MCA methods are used in the field of renewable energy policy planning include AHP, TOPSIS, WSM, ELECTRE, PROMETHEE and VIKOR [6]. In a previous study it was assessed that TOPSIS method is a

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suitable MCA method for sustainability analysis of DH systems due to its relative simplicity and similar results to other methods [7].

The aim of the study is therefore to evaluate the performance of waste heat (WH), high-efficiency combined heat and power (CHP) and RES technology in the DH system by moving towards carbon neutrality in various development scenarios. Based on an algorithm that combines the SD model with the TOPSIS method, the economic, environmental and energy parameters of the DH system development scenarios were evaluated for creating decarbonization strategy of a city DH system.

2. Methods

The algorithm of the study is presented in Figure 1. A system dynamics model of a DH system is taken as a base for further optimization and development planning.

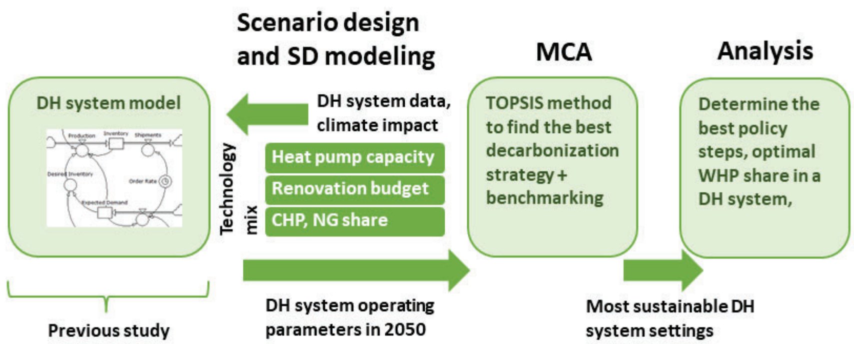

Figure 1. Algorithm of the study

Technological, climate and policy scenarios are designed based on literature review. Simulations with these scenarios and optimizable technological parameters are performed. The next step is MCA where the DH system operating parameters are assessed by the TOPSIS method to find the most sustainable technology mix within each scenario. The last step is analysis of MCA results and policy and development proposals.

2.1. DH model description for case study of DH system

In a previous study, a s SD model corresponding to the urban DH system was developed [2] and improved [1].The SD model includes all stages of DH - heat production, transmission and consumption. The model is based on the installed capacity of various technologies. Energy sources include fossil fuels (natural gas) and renewable energy sources, such as wood chips, as well as potentially developed technologies - heat recovery from treated wastewater, industrial processes, solar collectors. The DH technology block consists of eight different technologies. Heat consumption tends to decrease because of improved energy efficiency of buildings - its demand therefore can decrease by renovating buildings while also increasing due to building of new ones that correspond to the nearly zero energy standard. In addition, the possible impact of global warming on the thermal energy demand of buildings and the resulting changes in the installed capacity of DH systems with or without renovation of existing apartment buildings are evaluated to move to a sustainable 4GDH system in the long term. Table 1 shows the priority technologies in four developed scenarios clusters.

Table 1. Selection of priority technologies in various DH system development scenarios.*

Technologies	RES-NG scenarios	RES scenarios (50% renewable energy)	CHP scenarios (75% CHP& CHP priority)	WH scenarios (50% WH& WH priority)
CHP biomass	✓	✓	✓	
CHP NG	✓		✓	
HOB biomass	✓	✓		
HOB NG	✓			
Solar collectors		✓		
Large scale heat pumps		✓		✓
Heat exchangers & heat pumps		✓		✓
Wastewater heat pumps		✓		✓

* ✓ - priority technologies

The Directive on energy efficiency (2018) promotes development of technologies that allow achieving the highest cumulative end-use energy savings and lowest primary energy consumption [8]. Three scenario clusters were selected for the study considering the definition of an efficient district heating and cooling system set by the Directive 2012/27/EU: one ensures 50% of RES by using biomass as the energy source (RES); second, where 75% of heat is produced by CHPs (CHP); third that provides the use of WH in DH system. Fourth scenario cluster was considered where the DH company continued to produce part of the heat by NG (RES/NG).

2.2. Assumption and constrains of selected scenarios

The DH system of Riga city was chosen as a case study area. The initial installed capacity of the produced heat and assumptions of each development scenario is provided in Table 2.

Table 2. Current heat supply and assumption of capacity to be installed.

Scenarios	Technologies, MW							
	Boiler NG	Boiler biomass	CHP by NG	CHP by biomass	Solar collectors	Large scale HP	Industrial waste heat HP	Wastewater absorption HP (AHP)
Existing installed capacity	300*	68	47	22	0	0	18	0
RES-NG	No limit	250	No limit	No limit	19	20	14/0**	4
RES	Ban on new installations from 2025 [9]	No limit	No limit	No limit	19	20	14/0**	4
CHP	Ban on new installations from 2025 [9]	CHP priority	No limit	No limit	19	20	14/0**	4
WH	Ban on new installations from 2025 [9]	No limit	No limit	No limit	19	30	14/14**	8

*capacity of HOB by NG excluding reserve; **potential of recovered WH in DH company/ potential of recovered WH from industry

The capacity of solar collectors, large scale HP and WH shown in Table 2 are based on the technological limitations that exist in the case study area. It was assumed that solar collectors could only be installed on land belonging to the DH company (i.e. next to an existing heat source). Thus, the installed number of collectors was limited to 1,700 (approx. 21,000 m2), which corresponds to 19 MW (640 h per year). NG boilers are planned to be replaced by a large-scale HP in one of the existing heat sources, which is located on the riverbank. The use of industrial WH is currently related to the operation of condensing economizers. In all development scenarios, it is planned to expand the integration of industrial WH into DH system. The use of heat recovery from treated wastewater in Riga is limited due to the heat demands of the adjacent heating zone. It is possible to use a maximum heat capacity of 8 MW, which is much lower than the total heat potential of the treated wastewater. More details about investment and fixed O&M costs applied in the SD model can be find in previous article by Ziemele&Dace [1].

For all four scenario-clusters we applied one scenario without impact of global warming and three global warming scenarios, which include different level of representative concentration pathways (RCP) – RCP2.6 (low), RCP4.5 (medium) and RCP8.5 (high) (see Table 3). According to the selected climate change scenarios the outdoor temperature during the heating season is estimated to increase from the current +1.1 °C to 3.0, 3.4 and 4.0 °C in scenarios RCP2.6, RCP4.5 and RCP8.5, respectively. Additionally, the impact of building renovation on heat demand was evaluated. There are considered three level of renovation. The budget for building reconstruction in the selected DH area was 5.8 million EUR per year for first level, which roughly corresponds to the current financing. The depth of renovation was adopted according to national legislation, i.e. 60 kWh/m2 for heating existing apartment buildings (corresponding to class B) and 40 kWh/m^2 for heating new buildings (corresponding to class A) [10]. In addition, a scenario in which the energy efficiency policy will be implemented with acceleration and the available funding will be quadrupled is being considered.

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Table 3. Description of scenarios

Nr.	Scenarios	Conditions		
		Renovation of multi-apartment buildings	Global warming	Investment
1.	RES/0/RCP0	-	-	0
2.	RES/0/RCP2.6	-	✓	0
3.	RES/0/RCP4.5	-	✓	0
4.	RES/0/RCP8.5	-	✓	0
5.	RES-NG/1/RCP0	✓	-	1
6.	RES-NG/1/RCP2.6	✓	✓	1
7.	RES-NG/1/RCP4.5	✓	✓	1
8.	RES-NG/1/RCP8.5	✓	✓	1
9.	RES-NG/2/RCP0	✓	-	2
10.	RES-NG/2/RCP2.6	✓	✓	2
11.	RES-NG/2/RCP4.5	✓	✓	2
12.	RES-NG/2/RCP8.5	✓	✓	2
13.	RES/1/RCP0	✓	-	1
14.	RES/1/RCP2.6	✓	✓	1
15.	RES/1/RCP4.5	✓	✓	1
16.	RES/1/RCP8.5	✓	✓	1
17.	RES/2/RCP0	✓	-	2
18.	RES/2/RCP2.6	✓	✓	2
19.	RES/2/RCP4.5	✓	✓	2
20.	RES/2/RCP8.5	✓	✓	2
21.	CHP/1/RCP0	✓	-	1
22.	CHP/1/RCP2.6	✓	✓	1
23.	CHP/1/RCP 4.5	✓	✓	1
24.	CHP/1/RCP 8.5	✓	✓	1
25.	CHP/2/RCP0	✓	-	2
26.	CHP/2/RCP2.6	✓	✓	2
27.	CHP/2/RCP 4.5	✓	✓	2
28.	CHP/2/RCP 8.5	✓	✓	2
29.	WH/1/RCP0	✓	-	1
30.	WH/1/RCP2.6	✓	✓	1
31.	WH/1/RCP 4.5	✓	✓	1
32.	WH/1/RCP 8.5	✓	✓	1
33.	WH/2/RCP0	✓	-	2
34.	WH/2/RCP2.6	✓	✓	2
35.	WH/2/RCP 4.5	✓	✓	2
36.	WH/2/RCP 8.5	✓	✓	2

As a result, 36 DH's system development scenario simulation in the SD model allows obtaining input parameters to create an initial matrix for multi-criteria analysis.

2.3. Coupling system dynamics (SD) modelling and multi-criteria analysis (MCA) for DH sustainability assessment

In the framework of this study, energy, environmental and economic parameters were chosen, which fully describe the DH system transition towards decarbonization and allow to identify the most sustainable paths for the transition towards 4GDH considering various conflicting goals. Table 4 summarizes the eight identified criteria that used in the research.

Table 4. Selected criteria of multi-criteria analysis.

Type of criterion	Name of criterion	Criterion designation, unit	Criterion designation in MCA
Energy	Primary energy factor	PEF	X1
	Specific heat consumption for heating in buildings	E_{buil}, kWh/m^2 per year	X2
Environment	Avoided CO_2 emissions from DH system	SA_{CO2}, t CO_2 per year	X3
	Radiation forcing	Rad	X4

Type of criterion	Name of criterion	Criterion designation, unit	Criterion designation in MCA
	Share of renewable energy sources	Sh_{res}, %	X5
	Share of recovered heat from waste heat	Sh_{rec}, %	X6
Economy	Avoided CO_2 emissions costs	AC_{CO2}, EUR/ t CO_2	X7
	Heat tariff	T_{tot}, EUR/MWh	X8

The PEF was calculated in accordance with the ISO 5200-1:2007 [11] using the primary resource factors given in Table 2:

$$PEF = (\sum_z F_z \cdot f_{nren,j} + \sum_z F_z \cdot f_{ren,z})/Q_{con} \tag{1}$$

where F_z is the energy source (fuel, electricity) consumption in the DH system, MWh per year; $f_{nren,z}$ is the primary resource factor of non-renewable energy of ***z****th* sources; $f_{ren,z}$ is the primary resource factor of renewable energy of zth resources. The study uses the primary resource factors according to ISO 52000-1:2017 [11].

The calculation of CO2 emissions was done according to national legislation [12] that based on Emission factors from the IPCC methodology [13] and is part of the SD model. The avoided CO2 emissions (SA_{CO2}, %) are calculated as follows:

$$SA_{CO2} = A_{CO2_{init}} - A_{CO2_{fin}} \tag{2}$$

$$A_{CO2} = \sum_z F_z \cdot e_z \tag{3}$$

where $A_{CO2_{init}}$ is the initial amount of CO_2 emissions, t_{CO2}/yr; $A_{CO2_{fin}}$ is the amount of CO_2 emissions in end of period, t_{CO2}/yr; $\cdot e_z$ is the CO_2 emission factor for z^{th} resources.

Heat tariff in each scenario (*T*, EUR/MWh) is calculated using the following equation:

$$T = \sum_z T_{prod,z} \cdot \varphi_z + T_{tr} + T_s \tag{4}$$

where $T_{prod,z}$ – production tariff for *j* technology, EUR/MWh; φ_z – the share of z technology; T_{tr} – transmission tariff, EUR/MWh; T_s – sales tariff, EUR/MWh.

Investment and O&M costs for the technologies used in this study were assumed according to data reported in previous studies by the authors. [1]. For instance, investments for constructing wood chips CHP are 3000/2500 kEUR/MW_e for 2020/2050 years, but for wood chips boiler - 350/300 kEUR/MW_{th} for 2020/2050 years [14].

The values of these criteria for each scenario were used to create a decision matrix (Equation (Eq.5) and were normalized according to the linear 'Max' method (Eq.6 and 7).

$$\begin{array}{c c} & \begin{array}{cccccccc} X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_{11} \\ \vdots \\ A_{36} \end{array} & \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} & x_{17} & x_{18} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} & x_{26} & x_{27} & x_{28} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{111} & x_{112} & x_{113} & x_{114} & x_{115} & x_{116} & x_{117} & x_{118} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{361} & x_{362} & x_{363} & x_{364} & x_{365} & x_{366} & x_{367} & x_{368} \end{bmatrix} \end{array} \tag{5}$$

$$r_{ij} = \frac{maxX_{ij} - X_{ij}}{maxX_{ij} - minX_{ij}} \tag{6}$$

$$r_{ij} = \frac{X_{ij} - minx_{ij}}{maxX_{ij} - minX_{ij}} \tag{7}$$

where r_{ij} – normalized value of criterion x_{ij}; $maxX_{ij}$ – maximal value of the criterion; $minX_{ij}$ – minimal value of the criterion; X_{ij} – criterion value; I – number of alternatives; j – number of criteria.

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The set of weights was calculated taking into account the dispersion of the input data and using the entropy method [15]:

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \; i = 1, \dots, m; \quad j = 1, \dots, n \tag{8}$$

$$E_j = -\frac{\left(\sum_{i=1}^{m} p_{ij} \ln(p_{ij})\right)}{\ln(m)} \quad j = 1, \dots, n \tag{9}$$

$$w_j = \frac{1 - E_j}{\sum_{i=1}^{n}(1 - E_j)} \quad j = 1, \dots, n \tag{10}$$

where r_{ij} – normalized value of criterion x_{ij}; E_j – information Entropy method; w_j – Entropy method weight.

The scenario ranking was done by the TOPSIS method. It is a MCA method that finds the ranks scenarios by calculating their closeness to an imaginary positive ideal scenario. It is done by weighting the input matrix (Eq.11), finding the positive and negative ideal scenarios (Eq.12 and 13) and the closeness of each scenario to the ideal scenario (Eq.14).

$$v_{ij} = w_j r_{ij} \tag{11}$$

where r_{ij} - normalized value of criterion x_{ij}, w_j – weight of criterion j, v_{ij}- the weighted normalized value of criterion x_{ij}.

$$S_i^+ = [\sum_{j=1}^{n} (v_{ij} - v_j^+)\,]^{1/2} \tag{12}$$

$$S_i^- = [\sum_{j=1}^{n} (v_{ij} - v_j^-)\,]^{1/2} \tag{13}$$

(S_i^+) – positive ideal scenario, (S_i^-) – negative ideal scenario, v_{ij} – weighted normalized value of alternative i with respect to criterion j; v_j^+ – maximal normalized value with respect to criterion j; v_j^- – minimal normalized value with respect to criterion j.

$$C_i^* = \frac{S_i^+}{S_i^+ + S_i^-} \tag{14}$$

where C_i^* – closeness to the ideal scenario.

2.4. Analysis

The results of the MCA can be expressed as a ranking of the technology combinations from best to worst for each of the climate scenarios. At first, the effect of different weights is evaluated. The best method for weight determination is then chosen. The most sustainable technology mixes for each of the climate scenarios are compared by determining trade-offs between the economic, technical and environmental parameters. The further choice of the development strategy of the DH company is made based on the policy makers' opinion of preference regarding the design of the DH company and its development strategy and based on balancing the components of the energy trilemma: economic feasibility, environmental sustainability, and security of energy supply.

3. Results and discussion

3.1. Results of MCA

The multi-criteria analysis includes 36 different scenarios for the development of the DH system, which differ in the amount of renovation of buildings, the mix and share of heat energy production technologies and outdoor air temperature during the heating season due to climate change (see assumption in table 2 and 3). The initial matrix of criteria of the multi-criteria analysis presented in Table 5.

Table 5. Multi-criteria analysis decision matrix.

Scenarios	Parameters							
	X1	X2	X3	X4	X5	X6	X7	X8
Weight	12.6%	14.1%	14.0%	12.1%	12.7%	7.8%	14.5%	12.2%
Optimal value	min	min	max	min	max	max	min	min
RES/0/RCP0	1.150	96.4	102 664	0.00	89.12	3.59	92.81	73.97

Scenarios	Parameters							
	X1	X2	X3	X4	X5	X6	X7	X8
RES/0/RCP2.6*	**1.145**	**83.2**	**106 709**	**2.60**	**88.60**	**3.76**	**77.76**	**73.82**
RES/0/RCP4.5	1.143	79.2	107 937	4.50	88.44	3.82	73.53	73.77
RES/0/RCP8.5	1.140	72.0	110 169	8.50	88.12	3.92	66.22	73.69
RES-NG/1/RCP0	1.146	93.1	77 517	0.00	73.03	3.61	114.71	79.06
RES-NG/1/RCP2.6	**1.142**	**81.0**	**83 663**	**2.60**	**72.73**	**3.78**	**99.05**	**79.10**
RES-NG/1/RCP4.5	1.141	77.4	85 515	4.50	72.64	3.83	94.66	79.11
RES-NG/1/RCP8.5	1.138	70.8	88 858	8.50	72.46	3.93	87.12	79.13
RES-NG/2/RCP0	1.143	83.3	82 371	0.00	72.80	3.74	102.26	79.09
RES-NG/2/RCP2.6	**1.140**	**74.6**	**86 826**	**2.60**	**72.55**	**3.88**	**91.51**	**79.12**
RES-NG/2/RCP4.5	1.138	72.0	88 167	4.50	72.47	3.93	88.44	79.13
RES-NG/2/RCP8.5	1.136	67.3	90 579	8.50	72.32	4.01	83.12	79.15
RES/1/RCP0	1.149	93.1	103 628	0.00	89.00	3.63	89.05	68.30
RES/1/RCP2.6	**1.144**	**81.0**	**107 330**	**2.60**	**88.50**	**3.79**	**75.45**	**67.91**
RES/1/RCP4.5	1.142	77.4	108 453	4.50	88.34	3.85	71.59	67.78
RES/1/RCP8.5	1.139	70.8	110 491	8.50	88.04	3.94	64.93	67.55
RES/2/RCP0	1.145	83.3	106 563	0.00	88.62	3.75	78.30	68.00
RES/2/RCP2.6	**1.141**	**74.6**	**109 222**	**2.60**	**88.19**	**3.90**	**68.70**	**67.66**
RES/2/RCP4.5	1.140	72.0	110 027	4.50	88.05	3.94	65.94	67.55
RES/2/RCP8.5	1.137	67.3	111 482	8.50	87.80	4.02	61.13	67.36
CHP/1/RCP0	1.160	93.1	102 832	0.00	88.66	3.54	104.67	70.56
CHP/1/RCP2.6	**1.154**	**81.0**	**109 744**	**2.60**	**90.24**	**3.74**	**84.20**	**68.56**
CHP/1/RCP 4.5	1.152	77.4	111 758	4.50	90.72	3.81	78.78	67.93
CHP/1/RCP 8.5	1.148	70.8	115 303	8.50	91.62	3.92	69.80	66.79
CHP/2/RCP0	1.155	83.3	108 377	0.00	89.94	3.69	88.18	68.97
CHP/2/RCP2.6	**1.150**	**74.6**	**113 323**	**2.60**	**91.17**	**3.87**	**74.66**	**67.35**
CHP/2/RCP 4.5	1.148	72.0	114 773	4.50	91.55	3.92	70.97	66.85
CHP/2/RCP 8.5	1.146	67.3	117 336	8.50	92.24	4.02	64.73	65.94
WH/1/RCP0	1.110	93.1	122 879	0.00	100.00	6.84	89.83	60.32
WH/1/RCP2.6	**1.103**	**81.0**	**125 800**	**2.60**	**100.00**	**7.13**	**77.23**	**60.32**
WH/1/RCP 4.5	1.101	77.4	126 675	4.50	100.00	7.23	73.63	60.32
WH/1/RCP 8.5	1.097	70.8	128 246	8.50	100.00	7.40	67.39	60.32
WH/2/RCP0	1.105	83.3	125 180	0.00	100.00	7.06	79.93	59.78
WH/2/RCP2.6	**1.099**	**74.6**	**127 311**	**2.60**	**100.00**	**7.32**	**71.02**	**59.16**
WH/2/RCP 4.5	1.098	72.0	127 949	4.50	100.00	7.40	68.45	58.96
WH/2/RCP 8.5	1.094	67.3	129 093	8.50	100.00	7.54	63.95	58.60

*scenarios with global warming RCP2.6 marked in bold

To achieve the highest degree of decarbonization, each criterion ought to be either minimized or maximized (table 5 – optimal value), thus creating a multi-objective optimization task.
Considering that the common trends of clusters of different global warming scenarios (RCP2.6, RCP4.5 and RCP8.5) are similar, scenarios with the level of representative concentration pathways RCP2.6 are analysed below. The sustainability of a DH system is determined by the optimal values of eight criteria, which tend towards the maximum (avoided CO_2 emissions from DH system, share of renewable energy sources, share of recovered heat from waste heat) or minimum values (primary energy factor, specific heat consumption for heating in buildings, radiation forcing, avoided CO2 emissions costs, heat tariff). The table 5 shows that more optimal criteria values are provided by the scenarios in which the waste heat is integrated into the DH system. Determining the sustainability of other scenarios is not straightforward, because, for example, scenario CHP/1/RCP2.6 compared to scenario RES/1/RCP2.6 achieves the biggest share of RES and most avoided CO2 emissions, but the heat tariff and avoided CO2 emissions costs are higher. The TOPSIS multi-criteria analysis method was used for sustainability evaluation of different scenarios the TOPSIS method was used.

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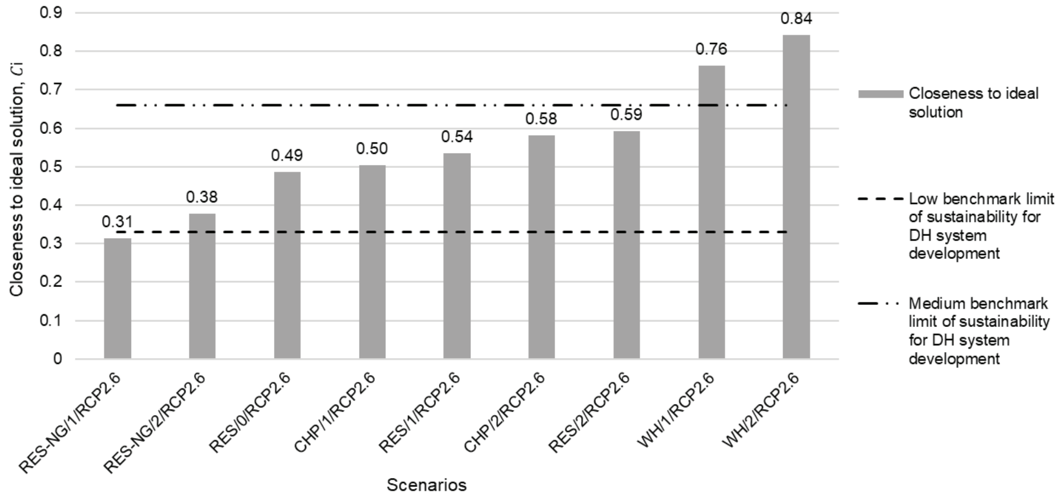

Figure 2. Results of sustainability assessment of DH development scenarios.

Figure 2 depicts the results of the multi-criteria analysis, which shows the ranking of all scenarios from the least sustainable to the most sustainable by expressing the closeness to the most ideal (sustainable) scenario.

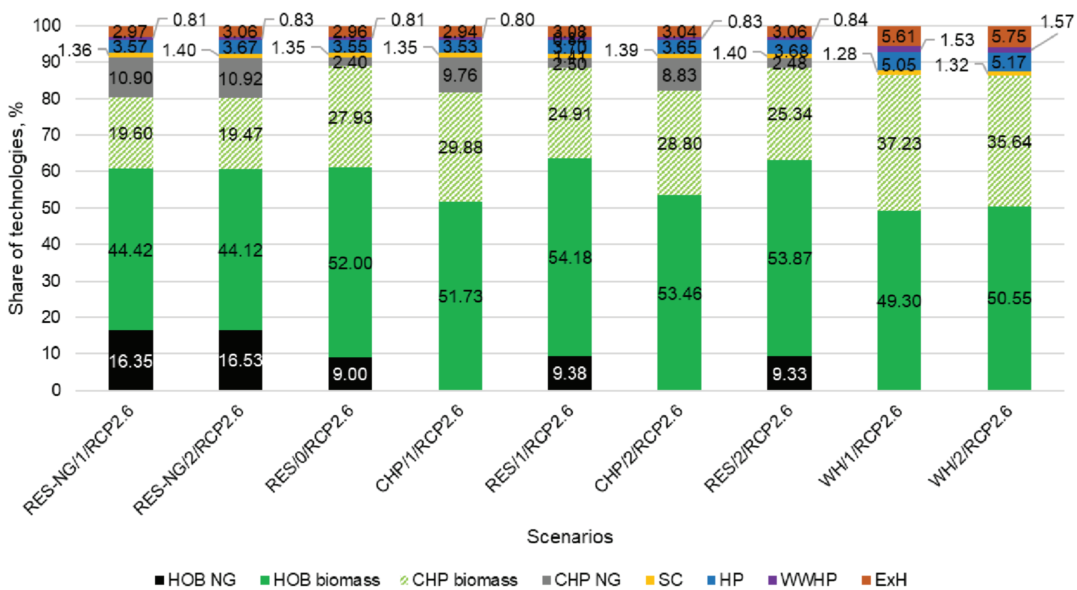

Figure 3. Share of technologies in different development scenarios in 2050.

The graph also includes low and average benchmark limits of sustainability for DH system development. The decarbonized scenarios, which characterize the sustainability vision, are defined by the penetration of several sustainable technologies in the DH system. Therefore, one of the main criteria determining the placement of the DH system's development scenario in the limits of the low, medium, or high level of sustainability is the mix of technologies used in heat energy production.

Figure 3 depicts share of technologies in all researched development scenarios. The scenarios in which the DH company continues to use natural gas in boilers and cogeneration plants show less sustainable results of performance. For example, scenarios RES-NG/1/RCP2.6 and RES-NG/2/RCP2.6 show the lowest sustainability level of the DH system performance (closeness to ideal solution - 0.31 and 0.38 for scenario RES-NG/1/RCP2.6 and RES-NG/2/RCP2.6, respectively), because in these scenarios the share of natural gas technologies is the highest and achieve approximately 27%. As described above, the highest level of sustainability is shown by scenarios (WH/1/RCP2.6 and WH/2/RCP2.6) that use RES for heat production, but also envisage the integration of waste heat into the DH system. Parameters of the closeness to ideal solution are 0.76 and 0.84 for these scenarios respectively. Six scenarios are within medium sustainability. Competing among these scenarios are scenarios that envisage CHP technology as a priority (CHP/1/RCP2.6 and

CHP/2/RCP2.6) and scenarios in which the RES is used in biomass chips (RES/1/RCP2.6 and RES/2/RCP2.6). Even though the CHP/1/RCP2.6 and CHP/2/RCP2.6 scenarios have higher avoided CO_2 emissions (109,744 tCO_2/year and 113,323 tCO_2/year) compared to RES/1/RCP2.6 and RES/2/RCP2.6 scenarios (107,330 tCO_2/year and 109,222 tCO_2/year), the latter generally show the best sustainability (closeness to ideal solution - 0.54 and 0,59 opposite 0.5 and 0.58), because the heat tariff and the cost of avoided CO_2 emissions are the lowest in them. Higher costs in scenarios that prioritize CHP technology are determined by the relative cost of these technologies compared to boilers (see chapter 2.3).

3.2. Results of decarbonization assessment of DH development

The choice of heat production technologies and related fuels determines the amount of CO2 emissions that will be emitted and the costs of these technologies. As a result, the costs of avoided emissions are calculated, which are then compared with CO_2 emission quotas.

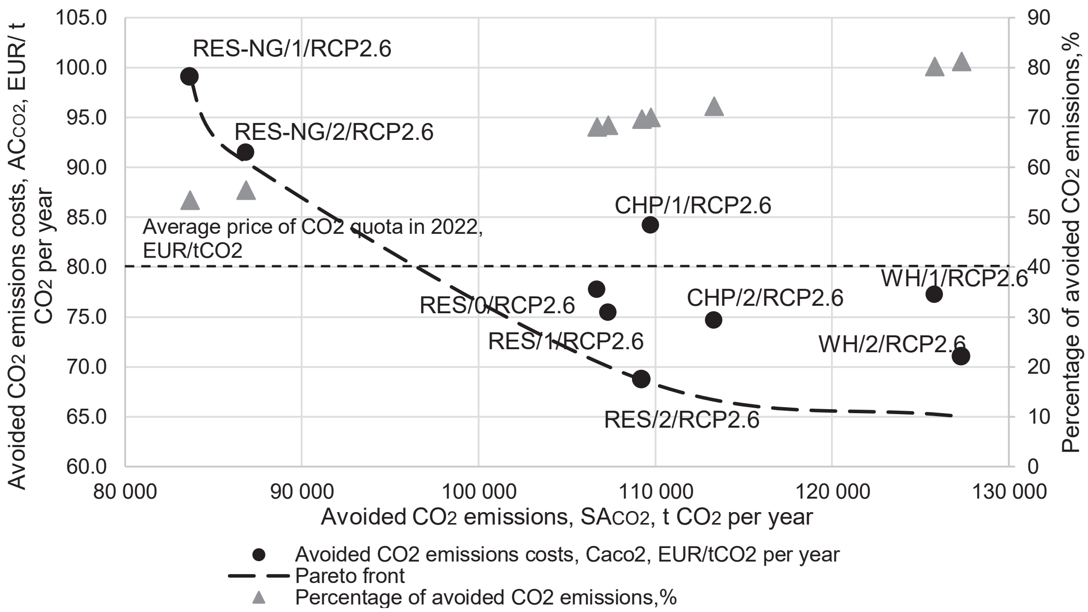

Figure 4. The corelation between the avoided CO_2 emissions costs and the amount of avoided CO_2 emissions.

Figure 4 shows the corelation between the avoided CO_2 emissions costs (economy criteria) and the amount of avoided CO_2 emissions (environmental criteria) and is based on one-objective optimization, where the economic objective function includes both the amount of avoided emissions and also indirectly used heat production technologies, that are strongly connected with the energy parameters of heat production. As a result, we can conclude that acquired dependence characterizes both environmental and economy criteria and indirectly also energy. A Pareto front limits the potentially possible solutions of DH development scenarios, in which we will be able to achieve the maximum amount of avoided CO_2 emissions by lowest their cost. Despite the fact that both scenarios including waste heat integration into the DH system have the highest closeness to the ideal solution, they ensure the highest amount of avoided CO_2 emissions (125,800 tCO_2/year and 127,311 tCO2/year for scenarios WH/1/RCP2.6 and WH/2/RCP2.6 respectively). The costs of avoided CO_2 emissions are not the lowest because the implementation of scenarios with waste heat need installation of heat pump technologies with relatively higher investment comparison to biomass boilers. Nevertheless, both scenarios (WH/1/RCP2.6 and WH/2/RCP2.6) allow to achieve the highest CO_2 emissions reduction and, as a result, a higher level of DH system decarbonization – 80.3% and 81.2%. The lowest costs of avoided CO2 emissions are in scenarios RES/1/RCP2.6 and RES/2/RCP2.6. These are 75.45 and 68.70 EUR/tCO_2 per year in scenarios respectively. The DH system decarbonization level in these scenarios is lower and achieve just 68.5 and 69.7 for these scenarios. The indicators of the worst-case scenarios coincide with the results of the multi-criteria analysis and provide only 53.4% and 55.4% reduction of CO_2 emissions (RES-NG/1/RCP2.6 and RES-NG/2/RCP2.6). The price level of quotas of CO_2 emissions in 2022 was 80.6 EUR/tCO_2 [16]. This price could be an additional argument for decision makers by choosing the implementation of a specific scenario.

4. Conclusions

The paper presents an evaluation of the DH systems' transition towards carbon neutrality by the implementation of WH and by using AHP, high-efficiency CHP and RES technology in various development scenarios. Based on an algorithm that combines the SD model with the TOPSIS method, the economic,

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environmental and energy criteria were considered, and development scenarios were evaluated to find the best decarbonization strategy for the DH system of Riga.

The application of MCA allows to determine the closeness of each specific DH system development scenario to the ideal solution considering eight energy (Primary energy factor, specific heat consumption for heating), environmental (avoided CO_2 emissions from DH system, radiation forcing, share of renewable energy sources, share of recovered heat from waste heat), and economy (avoided CO2 emissions costs and heat tariff) parameters. The result of the multi-criteria analysis is a list of scenarios sorted in one of three sustainability classes: high, medium, or low.

The highest level of sustainability is shown by scenarios WH/1/RCP2.6 and WH/2/RCP2.6 that use 100% RES for heat production including approximately 7% of waste heat integration into the DH system. Parameters of the closeness to ideal solution are 0.76 and 0.84 for these scenarios respectively. These scenarios allow to achieve the highest CO_2 emission reduction by 80.3% and 81.2% (WH/1/RCP2.6 and WH/2/RCP2.6 respectively).

The correlation between the avoided CO_2 emissions costs and the amount of avoided CO_2 emissions is presented and provides one-objective optimization. A Pareto front depicts the potentially possible solutions of the DH development scenarios, in which the maximum amount of avoided CO_2 emissions can be achieved with the lowest cost. The lowest costs of avoided CO_2 emissions can be achieved in scenarios RES/1/RCP2.6 and RES/2/RCP2.6, there are 75.45 and 68.70 EUR/tCO_2 per year, for abovementioned scenarios respectively.

The hybrid model provided in this paper couples SD modelling and multi-criteria analysis and allows, on the one hand, the ranking of the selected transition scenarios according to their sustainability score and, on the other hand, to benchmark the results of developed scenarios against a carbon neutral DH system. In the future, decision makers can evaluate strengths and weaknesses in each case of specific scenarios.

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References

[1] Ziemele J., Dace E., An analytical framework for assessing the integration of the waste heat into a district heating system: Case of the city of Riga. Energy 2022;10.1016/J.ENERGY.2022.124285.

[2] Ziemele J., Gravelsins A., Blumberga A., Vigants G., Blumberga D., System dynamics model analysis of pathway to 4th generation district heating in Latvia. Energy 2016;10.1016/J.ENERGY.2015.11.073.

[3] J. de Maigret *et al.*, A multi-objective optimization approach in defining the decarbonization strategy of a refinery. Smart Energy 2022;10.1016/J.SEGY.2022.100076.

[4] Finke J., Bertsch V., Implementing a highly adaptable method for the multi-objective optimisation of energy systems. Appl Energy 2023;10.1016/J.APENERGY.2022.120521.

[5] Yuan M., Thellufsen J. Z., Sorknæs P., Lund H., Liang Y., District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps. Energy Convers Manag 2021;10.1016/J.ENCONMAN.2021.114527.

[6] Bohra S. S., Anvari-Moghaddam A., A comprehensive review on applications of multicriteria decision-making methods in power and energy systems. Int J Energy Res 2022;10.1002/ER.7517.

[7] Daugavietis J. E., Soloha R., Dace E., Ziemele J., A Comparison of Multi-Criteria Decision Analysis Methods for Sustainability Assessment of District Heating Systems. Energies 2022;10.3390/EN15072411.

[8] DIRECTIVE (EU) 2018/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 11 December 2018 - amending Directive 2012/27/ EU on energy efficiency.

[9] International Energy Agency 2021, Net zero by 2050: a roadmap for the global energy sector - A special report by the International Energy Agency. 2021.

[10] Regulations on the Latvian building code LBN 003-19 'Building climatology'. Available at:<https://likumi.lv/ta/id/309453-noteikumi-par-latvijas-buvnormativu-lbn-003-19-buvklimatologija> [accessed 13.03.2023].

[11] International Organization for Standardization, ISO 52000-1:2017. Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures' , 2017.

[12] Regulations of the Cabinet of Ministers No. 222., Building energy efficiency calculation methods and building energy certification rules. Available at: <https://likumi.lv/ta/id/322436-eku-energoefektivitates-aprekina-metodes-un-eku-energosertifikacijas-noteikumi> [accessed 13.03.2023]

[13] IPCC Updates Methodology for Greenhouse Gas Inventories. 2019. Available at: https://www.ipcc.ch/2019/05/13/ipcc-2019-refinement/ [accessed 13.03.2023].

[14] Danish Energy Agency, Technology Data for Generation of Electricity and District Heating. Available at:<*https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and*.> [accessed 13.03.2023].

[15] Zardari N. H., Ahmed K., Shirazi S. M., Yusop bin Z., Weighting Methods and their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management. SpringerBriefs in Water Science and Technology. Springer Cham. 2014. p. 166.

[16] European Union Emission Trading System (EU-ETS) carbon pricing in 2022. Available at:<https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/#:~:text=EU%2DETS%20futures%20pricing%20in%20the%20European%20Union%202022&text=The%20price%20of%20emissions%20allowances> [accessed 13.03.2023].

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