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Integrated planning of electricity, gas and heat supply to municipality

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Abstract: This paper presents the results of a case study to investigate different alternatives for the energy supply to a municipality on the western coast of Norway. The following alternatives for energy supply are modelled and analysed: i) a district heating system with three different heat centrals, ii) a natural gas distribution system and iii) a low temperature distribution system. The case study is performed with the optimization model "eTransport" developed for the planning of local energy systems where several alternative energy carriers and technologies are considered simultaneously. The model minimizes the total energy system cost of meeting the demands of electricity, heating, cooling and gas within a geographical area over a given planning horizon. The model uses a detailed network representation of infrastructures to consider investments in distributed central stations, components, cables and pipelines. The object function includes investments, operating and environmental costs.

Keywords

Local energy planning
Investments
Cooling network
Heat pump
Low temperature distribution

Integrirano planiranje opskrbe električnom energijom, plinom i toplinskom energijom u općini *

Izvornoznanstveni rad

Sažetak: Ovaj članak prezentira rezultate analize slučaja koja istražuje razne alternative za opskrbu energije jedne općine na zapadnoj obali Norveške. Sljedeće alternative za opskrbu energije su modelirane i analizirane: i) Područno grijanje s tri različite toplane ii) Distribucijski sustav za prirodni plin iii) Niskotemperaturni distribucijski sustav. Analiza slučaja je napravljena pomoću optimizacijskog modela „eTransport“ razvijenog za planiranje lokalnih energetskih sustava s primjenom raznih nosioca energije i tehnologija. Model minimizira cijenu sustava koji zadovoljava potrebu za električnom i toplinskom energijom, hlađenjem i plinom u nekom geografskom području za vrijeme planiranja. Model koristi detaljnu reprezentaciju mrežne infrastrukture da uzme u obzir investiciju u toplane, komponente, troškove okoliša i operativne troškove.

Ključne riječi

Lokalno energetsko planiranje
Investicije
Mreža hlađenja
Dizalica topline
Niskotemperaturna distribucija

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1. Introduction

In the increasing drive for a sustainable society and more renewable energy, new technologies and advanced solutions for distributed energy systems are emerging, removing the previous distinction of centralised supply options and distributed passive loads. These new technologies yield better possibilities to design sustainable energy systems for the future, but also introduce more complex energy systems to design, operate and maintain. Different types of micro-cogeneration, heat pumps and fuel cells create mutual influence and dependency between different infrastructures. While public planners need to be able to give a fair and neutral evaluation of alternative projects across the traditional energy supply systems of electricity, heating (or cooling) and gas, strategic planners in energy companies need to consider complementarities and competition between the different energy infrastructures within their supply area.

A number of models for the optimization of local energy systems have been developed over the last decade(s) [1]. Some are focusing on the optimization of electricity and heat supply from cogeneration units ([2],[3]), while others apply a more generalized optimization of multiple energy carriers, incorporating electricity, gas, heat and hydrogen on the supply side as well as electricity, heating and cooling on the demand side ([4]-[7]). Both the German model *DEECO* (Dynamic Energy Emission and Cost Optimization) ([8]-[10]) and the Danish model *EnergyPLAN* ([11],[12]) are developed to optimise the rational use of energy and the utilization of renewable energy in local energy systems on an hourly basis. None of these approaches, however, consider the issue of expansion/investment planning of multiple infrastructures.

Nomenclature/ Nomenklatura

Parameters/ Parametri

A_{fkt} - Constraint coefficients for component k in timestep t/ Koeficijent ograničenja za komponentu k i vremenskom trenutku t

b_{ft} - Restrictions on resources/capacities in timestep t/ Ograničenja na resurse/ kapacitete u vremenskom trenutku t

c_d^{inv} - Investment cost for investment d [Euro]/ Investicijski troškovi za investiciju d [Euro]

COP - Coefficient of performance/ Faktor hlađenja

δ - Annual discount factor/ Godišnja diskontna stopa; $\delta = 1/(1+r)$

ε_C - Carnot power factor/ Faktor snage Carnotovog procesa [-]

ε_s^{Cl} - Power factor for cooling supply s/ Faktor snage izvora hlađenja s [-]

λ_d - Lifetime of investment alternative d/ Životni vijek investicijske alternative d [years]

L_{lt}^{Cl} - Cooling load at load node l in timestep t/ Rashladno opterećenje za opterećenje l u vremenskom trenutku t [MWh/h]

η_c - Carnot-efficiency-factor/ Stupanj efikasnosti Karnotovog procesa

η_l^{Cl} - Connection loss factor for cooling load l/ Faktor gubitka priključka za rashladno opterećenje l

η_p^{Ch} - Connection loss factor for Chiller p/ Faktor gubitka priključka za hladnjak p

Π_{start} - The first year in the first timestep in the planning horizon/ Prva godina prvog vremenskog koraka za period planiranja

Π_{end} - The first year in the final timestep in the planning horizon/ Prva godina zadnjeg vremenskog koraka za period planiranja

Π_{step} - The number of years in each timestep in the planning horizon/ Broj godina u svakom vremenskom periodu za period planiranja

Pen^{Cl} - Cooling deficit penalty/ Penali za manjak hlađenja [Euro/MWh]

r - Interest rate/ Kamatna stopa [pu]

S_s^{CSup} - Source Type (ambient air or water) in cooling supply s/ Vrsta izvora (zrak ili voda) za hlađenje s

T_0 - Evaporating temperature in K/ Temperatura isparavanja u K

T_K - Condensation temperature in K/ Temperatura kondenzacije u K

$Tair_s^{CSup}$ - Air Temperature in cooling supply s/ Temperatura zraka izvora hlađenja s [^{o}C]

$Twater_s^{CSup}$ - Water Temperature in cooling supply s/ Temperatura vode izvora hlađenja s [^{o}C]

$Treq_s^{CSup}$ - Required Temperature in cooling supply s/ Potrebna temperature izvora hlađenja [^{o}C]

$\Delta T\max_s^{CSup}$ - Max Air Temperature Difference/ Maksimalna razlika temperature zraka [K]

w_ζ - Weight factor for length of segments/ Težinski faktor dužine segmenata [days]

Variables/ Varijable

c_{kt} - Operating cost of component k in timestep t/ Troškovi vođenja komponente k u vremenskom trenutku t

C^p - Operating cost for different technologies/ Troškovi vođenja različitih tehnologija [Euro]; $p \in Technologies$

$C_{s\pi\varsigma}^{ope}$ - Operating cost in a given state s, period π and time segment ζ/ Troškovi vođenja u određenom stanju s, periodu πi vremenskom segmentu ζ [Euro]

$c_{s\pi}^{ope}$ - Annual operating costs for state s in period π/ Godišnji troškovi vođenja za stanje s u periodu π [Euro]

C_π^* - Minimum net present value for period π through ($\Pi_{end} + \Pi_{step}$)/ Minimalna neto sadašnja vrijednost za period π kroz ($\Pi_{end} + \Pi_{step}$) [Euro]

D_{lt}^{Cl} - Cooling deficit in cooling demand in timestep t/ Nedostatak hlađenja u vremenskom trenutku t [MWh/h]

Φ - Rest value of investments/ Vrijednost ostatka investicije [Euro]

$I_{d\pi}$ - Binary variable that identifies investments. $I_{d\pi}$ = 1 if the investment $d \in D$ has been carried out in period π, and $I_{d\pi}$ = 0 otherwise./ Binarna vrijednost koja identificira investicije. $I_{d\pi}$ = 1 ako je investicija d ϵ D provedena u periodu π a inače $I_{d\pi}$ = 0.

$I_{d\pi}^{scrap}$ - Binary variable that identifies scrapping of equipment. $I_{d\pi}^{scrap}$ = 1 if the equipment from project $d \in D$ has been scrapped in period π, and 0 otherwise./ Binarna varijabla koja identificira otpisivanje opreme, $I_{d\pi}^{scrap}$ = 1 ako je oprema projekta $d \in D$ bila otpisana u period π, 0 inače

π - Identifier for investment periods given as first year in each period/ Identifikator investicijskog perioda danog kao prva godina u svakom periodu

P_{st}^{El} - Electric energy input to cooling supply s or Chiller p/ Električna energija za rad hladnjaka p [MWh/h]

P_{ijt}^{Ld} - Load_flow$_{ijt}$: Energy flow from network node i to load node j in timestep t/ Energetski tok iz mrežnog čvora i u čvor opterećenja j u vremenskom trenutku t [MWh/h]

P_{ijt}^{Loc} - Local_flow$_{ijt}$: Energy flow from supply node i to load node j in timestep t/ energetski tok iz opskrbnog čvora i u čvor opterećenja j u vremenskom trenutku t [MWh/h]

P_{ijt}^{N2N} - Net2net_flow$_{ijt}$:Energy flow between network nodes i to j in timestep t/Energetski tok od mrežnog čvora i do mrežnog čvora j u vremenskom trenutku t [MWh/h]

P_{sit}^{Sup} - Supply_flow$_{ijt}$: Energy flow from supply node i to network node j in timestep t/ Energetski tok od opskrbnog čvora i do mrežnog čvora j u vremenskom trenutku t [MWh/h]

Q_0 - Evaporation Heat (cooling power)/ Toplina isparavanja (rashladna snaga) [MWh/h]

Q_K - Condenser Heat/ Toplina kondenzacije [MWh/h]

S_π - State identifier/ Identifikator stanja; $S_\pi \in States$

t - Index for timesteps (e.g. hours) within operational model/ Indeks vremenskog koraka (npr. sati) u operacijskom modelu, $t \in Time\_steps$

τ - Index for years within an investment period/ Indeks godina u investicijskom periodu, $\tau \in \{1, \ldots, \Pi_{step}\}$

U_{st}^{Cl} - Use of cooling energy at supply point s in timestep t/ Korištenje energije za hlađenje u točki opskrbe s u vremenskom trenutku t [MWh/h]

U_{pt}^{Ch} - Supply of cooling energy from Chiller p in timestep t/ Opskrba sa energijom za hlađenje iz hladnjaka p u vremenskom trenutku t [MWh/h]

U_{pt}^{Heat} - Supply of excess heat from Chiller p in timestep t/ Opskrba viškom topline iz hladnjaka p u vremenskom trenutku t [MWh/h]

W - Input work (Carnot cycle)/ Ulazni rad (Carnotov ciklus) [MWh/h]

W_{el} - Compressor work/ Rad kompresora [MWh/h]

ΔS - Entropy difference/ Razlika entropija [J/K]

x_{kt} - Decision variable for component k in timestep t/ Varijabla odluke za komponentu k u vremenskom trenutku t

ζ - Index for load segments within a year/ Indeks za segment opterećenja u godini

Sets/Setovi

Cold_loads - Set of cooling loads/ Set rashladnih opterećenja

D - Set of investment alternatives/ Set investicijskih alternativa

Emissions - Set of (predefined) emission types; Emissions = [CO_2, CO, NO_x, SO_x]/ Set (unaprijed određenih) vrsta emisija; Emisije = [CO_2, CO, NO_x, SO_x]

Load_points	- Set of load and market nodes/Set čvorova opterećenja i tržišnih opterećenja
Net2load	- Set to define connections between network nodes and load nodes/ Set koji definira spojeve među mrežnim čvorovima i čvorovima opterećenja
Net2net	- Set to define connections between two different networks/ Set koji definira spojeve između dvije različite mreže
Network_nodes	- Set of network nodes/ Set mrežnih čvorova
Periods	- Set of investment periods/ Set investicijskih perioda
States	- Set of system states (alternative system designs)/ Set stanja sustava (alternativnih oblika sustava)
Segments	- Set of load levels within a year/ Set razina opterećenja u godini
Supply2load	- Set to define direct connections between supply nodes and load nodes/ Set koji definira izravne veze između čvorova opskrbe i čvorova opterećenja
Supply2net	- Set to define connections between supply nodes and network nodes/ Set koji definira veze između čvorova opskrbe i mrežnih čvorova
Cold_supplies	- Set of supply points for cooling/ Set točaka opskrbe za hlađenje
Technologies	- Set of technology modules contributing to the object function; Technologies = [Cold_supplies, Cold_loads, Chiller, ...]/ Set tehnoloških modula koji doprinose funkciji objekta; Tehnologije = [Cold_supplies, Cold_loads, Chiller, ...]
Time_steps	- Set of hours in the operating model, typically [1, ..., 24]/ Set sati u operativnom modelu, uobičajeno [1,…,24]

Optimal expansion planning in general energy systems is traditionally performed with large scale optimisation tools for regional or global system studies like MARKAL/TIMES, EFOM, MESSAGE and similar models ([13]-[16]). In such large scale tools the energy system is typically represented with an aggregated type of modelling with energy balances per energy carrier, and with resources deployed on one side and end use extracted on the other side. Various technologies are modelled with emissions and energy losses.

A much higher level of detail is required for expansion planning of local energy supply systems with multiple energy supply options. Various conversion technologies and infrastructure alternatives within the geographical area of concern have to be optimized together to quantify the complementarities and differences between possible combinations of solutions. Geography, topology and timing are all key elements in local energy planning. It is not only a question of which energy resources and which amounts to use, but also *where* in the geographical system the investments take place.

2. The eTransport Model

The optimization model "eTransport" is developed for expansion planning in local energy systems where several alternative energy carriers and technologies are considered simultaneously ([17]-[19]). The model uses a detailed network representation of technologies and infrastructure to enable identification of single components, cables and pipelines while calculating the optimal hourly operation of a given energy system. Then an optimal expansion plan for the energy infrastructure is calculated over a planning horizon of several decades. The approach is not limited to continuous energy transport like lines, cables and pipelines, but can also include discrete transport by sea, road or rail.

2.1 Model overview

eTransport is separated into an *operational model* (energy system model) and an *investment model*, as illustrated in Figure 1 [17]. In the operational model there are sub-models for each energy carrier and for conversion components. The planning horizon is relatively short (1-3 days) with a typical time-step of one hour. The operational model finds the cost-minimising hourly operation for a given infrastructure and for given energy loads. Annual operating costs for different energy system designs are calculated by solving the operational model for different seasons (e.g. peak load, low load, intermediate etc.), different investment periods (e.g. 2-5 year intervals) and relevant system designs. Annual operating and environmental costs for all different periods and energy system designs are then used by the investment model to find the investment plan that minimises the present value of all costs over the planning horizon.

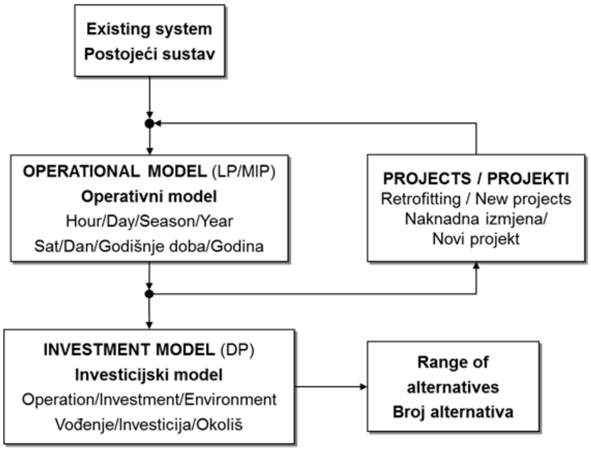

Figure 1. Combination of operation and investment optimization in eTransport

Slika 1. Kombinacija optimizacije vođenja i investicije u eTransportu

The sub-models for different components are connected by general energy flow variables that identify the flow between energy sources, network components for transport, conversion and storage, and energy sinks like loads and markets. The connections between these are case-specific as defined by the user. The modules are added together to form a single linear optimisation problem where the objective function is the sum of the contributions from the different modules, and the restrictions of the problem include all the restrictions defined in each of the modules. This is formulated as a general minimization problem:

$$C^{ope} = \min \sum_t \sum_k c_{kt} x_{kt} \qquad (1)$$

subject to

$$\sum_k A_{fkt} x_{kt} \le b_{ft}\ ,\ f \in [1,\dots,m]\ , \forall\ t$$

$$\sum_k A_{fkt} x_{kt} = b_{ft}\ ,\ f \in [m+1,\dots,n]\ , \forall\ t$$

The minimum operational cost of Eq. (1) is aggregated over different seasons (Segments) to give a minimum annual cost for each alternative system design (state), see also Section 2.3. Emissions are calculated from a subset of components that are emitting CO_2, NOx, CO and SOx (typically power plants/CHP, boilers, road/ship transport etc.). Further environmental consequences can be implemented. Emissions are accounted for as separate results, and when emission penalties are introduced by the user (e.g. a CO_2 tax) the resulting costs are included in the object function and thus added to other operating costs.

The task for the *investment model* is then to find the optimal set of investments during the period of analysis, based on the investment costs for different projects and the annual operating costs for different periods and states. The user defines a set of investment alternatives where each alternative consists of one or more physical components with predefined connections to the rest of the energy system. The same component can be included in several competing investment alternatives, thus making the alternatives mutually exclusive. Such alternatives are identified by the model in the search for the best expansion plan, but the user can further restrict the solution both with respect to timing and combination of alternatives. The optimal investment plan is found as the plan that minimises the discounted present value of all costs in the planning period, i.e. operating costs plus investment costs minus the rest value of investments. The investment algorithm is briefly outlined in Section 2.3, while a more detailed documentation can be found in [18].

The combined operational and investment analysis enables a very flexible time resolution as illustrated in Figure 2. The user specifies the hourly profiles of prices and loads for one or more *Days*, which are aggregated into one or more seasonal *Segments* (e.g. winter, summer, spring and autumn). The sum of the Segments equals one *Year*, which is the basis for the results from the operational analysis. Yearly values of costs and emissions are input into the investment analysis, where one or more years define an *Investment period* (where the model is allowed to make investments). The sum of all investment periods, which do not have to be of equal length, is the *Planning horizon* of the case. In principle all energy sources can be implemented in the model: Primary fuels (coal, gas, oil, biomass etc.), renewable energy sources (wind, hydro, solar, wave etc.) and secondary energy supply (electricity, heat etc.).

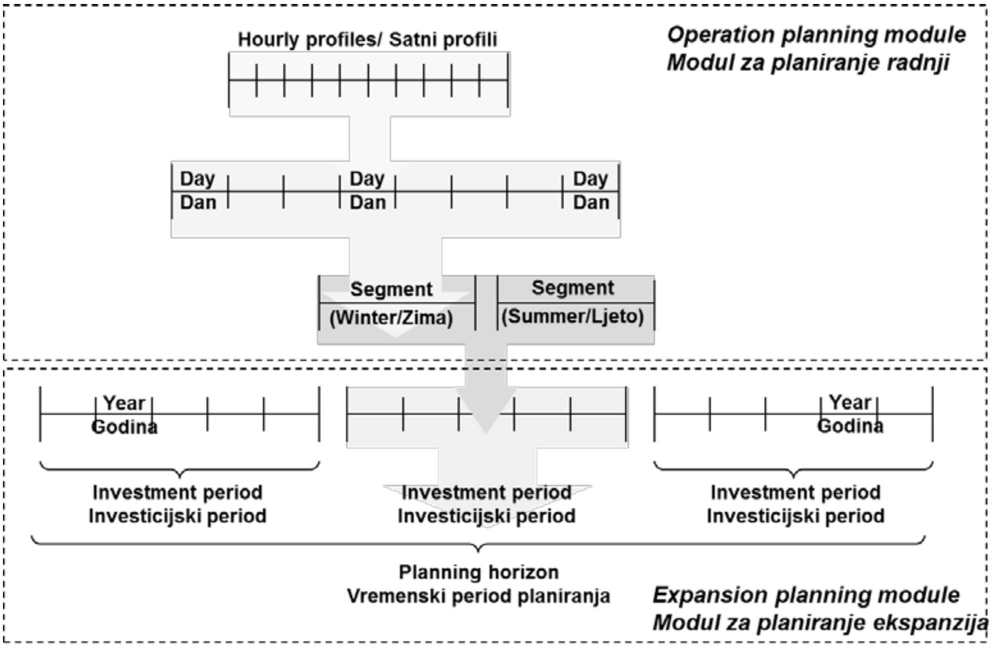

Figure 2. Time resolution in eTransport
Slika 2. Vremenska rezolucija u eTransportu

Sources are implemented either as an hourly energy profile (e.g. in the case of hydro or solar energy), a price profile (e.g. electricity market prices) or a combination of energy and price profiles. However, since the lowest time resolution of the model is one hour, intra-hour fluctuations of e.g. wind and wave energy cannot be represented.

The operational model uses a combination of linear programming (LP) and mixed integer programming (MIP) to optimize the hourly operation of each possible energy system design. The investment model then uses dynamic programming (DP) to find the optimal investment plan over the planning horizon. A prototype version with stochastic DP to handle uncertainty in future parameters like fuel prices and demand levels is also available. The operational model is implemented in the AMPL programming language with CPLEX as the solver, while the investment model is implemented in C++. A modular design ensures that new technology modules developed for the operational model are automatically embedded in the investment model. A full-graphical Windows interface is developed for the model in MS Visio. All data for a given case are stored in a database.

2.2 Recent model improvements

Due to the modular design of eTransport, a number of improvements have been implemented over the last years for very different technologies. In particular, the model has been used for optimization of the infrastructure for CO_2 capture and storage where mass flow was included in the network structure [20]; a mixed integer module for biomass supply chains is developed to handle time dependent drying processes [21]; and a new module for cooling networks is developed [22]. In the context of this paper, some examples of the latter have been included to illustrate the modelling structure.

The cooling network module developed in a Master thesis in cooperation with the Clausthal University of Technology in Germany currently has six new technology models [22]:

Cooling Demand:	Industrial cooling or air conditioning
Cooling Supply:	Source for natural cooling (cold water or ambient air) for a cooling network or single loads
Compression Chiller:	Simplified model of a one-level refrigeration machine
Heat Sink:	Condenser with heat recovery option
Cooling Network:	District or local cooling network
Cool Heat Supply:	Link between cooling network and heat pump

Figure 3 shows the symbolic cooling technology models implemented in eTransport. The cooling network models can be combined in different ways and allow for modeling for both district cooling purposes and local cooling applications. Both industrial cooling down to low temperatures and air conditioning can be modeled.

Most of the models contain special formulations and restrictions to be able to account for the special properties of the different applications.

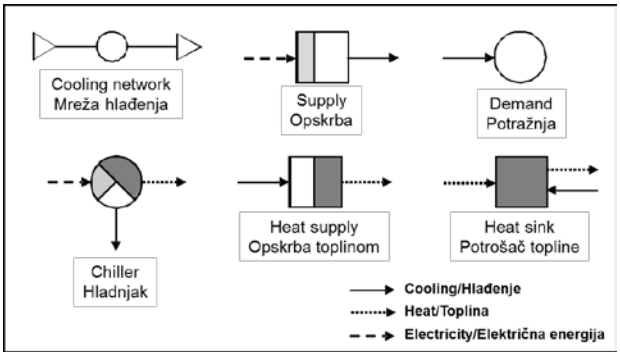

Figure 3. Cooling models in eTransport – symbolic pictures
Slika 3. Modeli hlađenja u eTransportu – simbolički prikaz

Supply of cooling and heating are often combined with each other. With the heat recovery option in the condenser (*Heat Sink* model) and the possibility of connecting heat pumps to the cooling network, a link to the existing heating models in eTransport has been created.

In the following section, the main mathematical formulations for the *Cooling Demand*, the *Cooling Supply* and the *Chiller* model are given as samples of the Cooling module.

2.2.1 Cooling Demand

Demand for cooling energy can be supplied by a *Cooling Network* or locally from the *Cooling Supply* or the *Chiller*. The model includes variables for cooling demand and possible cooling deficit. The energy balance in load point *l* is given by:

$$\eta_l^{Cl}\cdot\left(\sum_{i:(i,l)\in Net2load} P_{ilt}^{Ld} + \sum_{s:(s,l)\in Supply2load} P_{slt}^{Loc}\right) = L_{lt}^{Cl} - D_{lt}^{Cl} \qquad (2)$$

$$\forall\, l \in Cold\_loads, t \in Time\_steps$$

The operating cost for the *Cooling Demand* consists of a possible penalty for cooling deficit:

$$C^{Cold\_loads} = \sum_{t\in Time\_steps}\left(Pen^{Cl}\cdot \sum_{l\in Cold\_loads} D_{lt}^{Cl}\right) \qquad (3)$$

The load deficit penalty of the Cooling Demand depends on the parameter *Load Type*. It can be chosen between “Industry” (high penalty) or “Air Conditioning Buildings” (moderate penalty). Depending on the technology type, such energy balances and operating costs for each component in the system are added together in Eq. (1).

2.2.2 Cooling Supply

The sub-model for the supply of cooling energy to the defined energy system will typically be the supply of either ambient air or water for natural cooling purposes. Whether air or water is supplied as a cooling medium is determined by the parameter S_s^{CSup}. The cooling agent temperatures $Tair_s^{CSup}$ and $Twater_s^{CSup}$ are parameters in the model, but can be chosen freely. $Treq_s^{CSup}$ is the temperature required to ensure sufficient cold supply to the cold load connected. Default values are given dependent on the choice of S_s^{CSup}. If “Ambient Air” is chosen as a source, the parameter $\Delta T\max_s^{CSup}$ is considered in the calculation. This parameter describes the difference between the temperature required by the load and the ambient air temperature. $\Delta T\max_s^{CSup}$ limits the output of the cooling supply model. If

$$Tair_s^{CSup} > Treq_s^{CSup} + \Delta T\max_s^{CSup} \qquad (4)$$

$$\forall\, s \in Cold\_supplies ,$$

the temperature difference is not sufficient to supply cooling to the cooling load connected. In this case no cooling energy can be produced and the output of the cooling supply model is set to zero.

Air Conditioning often requires auxiliary equipment such as e.g. pumps and fans to transport the cooling medium indoors. These units are often driven electrically, and the electric power required for this purpose is dependent on the cooling energy delivered. A linear dependency between the electricity consumption for auxiliary equipment and the cooling energy output is assumed.

The useful cooling energy U_{st}^{Cl} taken from a given supply point can either be fed to network nodes or used by a load connected directly to the supply. Note that since the cooling supply takes electricity as input, the input and output nodes belong to the set of *Network_nodes*. The cooling energy output node thus belongs to the set *Net2load* if the cooling energy is delivered directly to a load node, and to *Net2net* if the supply is connected to a cooling network. The energy balance for cooling supply points is:

$$U_{st}^{Cl} = \sum_{i:(s,i)\in Net2net} P_{sit}^{N2N} + \sum_{l:(s,l)\in Net2load} P_{slt}^{Ld} \qquad (5)$$

$$\forall s \in Cold\_supplies, t \in Time\_steps$$

Similarly, the electricity needed by the cooling supply can either be supplied by an electricity source directly connected to the cooling supply (belongs to the set *Supply2net*) or from an electricity network (*Net2net*):

$$P_{st}^{El} = \varepsilon_s^{Cl} \cdot U_{st}^{Cl} = \sum_{i:(i,s)\in Supply2net} P_{ist}^{Sup} + \sum_{n:(n,s)\in Net2net} P_{nst}^{N2N} \qquad (6)$$

$$\forall s \in Cold\_supply,\, t \in Time\_steps$$

There are no operating costs associated with the *Cooling Supply* model itself since the cost for the required electricity P_{st}^{El} is accounted for in the electricity supply model.

2.2.3 Compression Chiller

The Compression Chiller is a model of a one-level refrigeration machine producing cooling energy in a cooling agent circuit by using electricity. It is the most detailed model in the cooling network module. To allow for proper work of the chiller model, the heat output point (condenser heat) always has to be connected to the *Heat sink* model. Both the input and the output nodes of the chiller belong to the set *Network_nodes*.

The theoretical cycle used to describe the refrigeration process is the Carnot-cycle. In the ideal Carnot-cycle, the input heat plus the used work equals the output heat since no losses appear. Thus, the Carnot-power-factor can be determined by the temperature difference between evaporator and condenser:

$$\varepsilon_C = \frac{Q_0}{W} = \frac{T_0 \cdot \Delta S}{\left(T_K - T_0\right)\cdot \Delta S} = \frac{T_0}{T_K - T_0} \quad . \qquad (7)$$

Detailed calculation of a vapor compression cycle with all changeable variables as described in [23] is too detailed for a linear eTransport technology module. Therefore, the compression cycle is not applied in the model and the modeling of the compression chiller is based on energy flow and the temperature level in evaporator and condenser.

One known input variable is the cooling energy Q_0 which has to be delivered to cover the demand of the connected cooling load. The condenser heat is equal to the cooling energy output (evaporation heat) plus compressor work:

$$Q_K = Q_0 + W_{el} \qquad (8)$$

The COP (Coefficient of Performance) determines the performance of a refrigeration machine. It is the ratio of cooling power (evaporation heat) and compressor work. Compared to the ideal Carnot-cycle several loss elements appear in a real refrigeration machine which are summed up by the Carnot-efficiency-factor η_c. By multiplying the Carnot-power-factor ε_c with the Carnot-efficiency-factor η_c the COP for a real refrigeration process can be determined by the following equation:

$$\varepsilon_C \cdot \eta_C = COP = \frac{Q_0}{W_{el}} \qquad (9)$$

The flow equations for delivered cooling energy U_{pt}^{Ch}, electricity consumption P_{pt}^{El} and condenser heat U_{pt}^{Heat} for the Chiller are given in Equations (10a)-(10c), respectively:

$$U_{pt}^{Ch} = \sum_{n:(p,n)\in Net2net} P_{pnt}^{N2N} + \sum_{l:(p,l)\in Net2load} P_{plt}^{Ld}\,, \qquad (10a)$$

$$P_{pt}^{El} = \frac{1}{COP_p}\cdot U_{pt}^{Ch} = \eta_p^{Ch}\cdot\left(\sum_{n:(n,p)\in Net2net} P_{npt}^{N2N} + \sum_{s:(s,p)\in Supply2net} P_{spt}^{Sup}\right), \qquad (10b)$$

$$U_{pt}^{Heat} = U_{pt}^{Ch} + P_{pt}^{El} = \sum_{n:(p,n)\in Net2net} P_{pnt}^{N2N} + \sum_{l:(p,l)\in Net2load} P_{plt}^{Ld}\,. \qquad (10c)$$

$$\forall p \in Chillers,\, t \in Time\_steps$$

With the cooling energy output required and the evaporating and condensation temperatures known, the COP can be calculated and thus the electric power needed to run the compressor. Default values for the Carnot efficiency factor η_c dependent on system size are given in the model based on [24].

The temperature levels in the evaporator and the condenser are defined by the user. The input parameters are the evaporator outlet temperature (supply temperature to load) and the condenser inlet temperature. For both temperatures four different default alternatives considering different load and condenser types are given in the model:

Evaporator outlet temperature;

- Industry Supply (-18 °C)
- Building Supply (Air System) (15 °C)
- Building Supply (Water System) (10 °C)
- Cooling Network Supply (low temperature network) (7 °C).

Condenser inlet temperature;

- Ambient Air (= Outdoor Temperature)
- Indoor Air (20 °C)
- Water; once through (river or lake) (10 °C)
- Water; recirculating (water circuit e.g. in combination with a cooling tower) (20 °C).

Both in the evaporator and the condenser a temperature difference is required to enable heat transfer. The default value is 5 K but can be modified by the user. With the temperature differences, the evaporator outlet and the condenser inlet temperature defined by the user the evaporating and condensation temperatures are calculated and the operating conditions for the compression chiller are found. There are some more aspects implemented in the model restricting the evaporating and condensation temperatures (e.g. due to chiller construction, data sheet etc.). Further details are found in [22].

The compression chiller model is the only model in the cooling module which causes emissions due to the cooling agent in the refrigeration system. Emissions caused both by leakage and incomplete recycling of the cooling agent are considered. The two characteristic numbers for the calculation of emissions caused by the compression chiller applied in the model are the GWP (Global Warming Potential) and the TEWI (Total Equivalent Warming Impact). Default values for the GWP of different cooling agents and the mass of the cooling agent dependent on the rated capacity of the refrigerator (data sheet) are given in the model. If an emission penalty is defined in the chiller model for these emissions, the cost is added to the total operation cost.

2.3 Investment model

For each *State s* (layout of the system), investment *Period* π and seasonal *Segment* ζ, all technologies that contribute to operational costs (e.g. Eq. (3)) are added together, Eq. (11):

$$C^{ope}_{s\pi\varsigma} = \sum_{p\in\text{Technologies}} C^{p} \qquad (11)$$

$\forall\ s \in States,\ \pi \in Periods,\ \varsigma \in Segments$

This equation corresponds to the general formulation of Eq. (1) for each Segment. If more than one Segment is defined, the model will go to the next Segment and update load profiles etc. Then the operational model is solved again. When the operational model has been solved for all segments within the year, the annual operating costs are calculated as the sum of the daily operating costs multiplied by the weighing factor w_ζ for the number of days represented by the respective segments, Eq. (12):

$$c^{ope}_{s\pi} = \sum_{\varsigma\in Segments} C^{ope}_{s\pi\varsigma}\cdot w_{\varsigma} \qquad (12)$$

$\forall\ s \in States,\ \pi \in Periods$

A matrix of annual operational costs for all States and Periods is sent to the investment model. The investment model uses dynamic programming to find the investment plan that minimizes the present value of operation and investment costs minus the scrapping value of new investments over the planning horizon. The dynamic programming formulation of the investment model is given in equations (13) – (17) [18].

$$C^{*}_{\pi}\left(S_{\pi}\right) = \min\left\{\delta^{\pi-\Pi_{start}}\cdot\left(\sum_{\tau\in\left\{1,\ldots,\Pi_{step}\right\}}\delta^{\tau-1}\cdot c^{ope}_{s,\pi} + \sum_{d\in D} c^{inv}_{d}\cdot I_{d\pi}\right) - \delta^{\Pi_{end}+\Pi_{step}-\Pi_{start}}\cdot\Phi + C^{*}_{\pi+1}\left(S_{\pi+1}\right)\right\} \qquad (13)$$

$\forall\ \pi \in Periods$

where

$$S_{\pi+1} = S_{\pi} + \sum_{d\in D} 2^{ord(d)-1}\left(I_{d\pi} - I^{scrap}_{d\pi}\right) \qquad (14)$$

$$\Phi = \sum_{\pi\in\left[\Pi_{start},\Pi_{end}\right]}\sum_{d\in D} c^{inv}_{d}\cdot I_{d\pi}\cdot\max\left\{0;1-\frac{\Pi_{end}-\pi+\Pi_{step}}{\lambda_{d}}\right\} \qquad (15)$$

$$C^{*}_{\Pi_{end}+1} = 0 \qquad (16)$$

$$S_{\Pi_{start}} = 0 \qquad (17)$$

3. Municipal Case Study

The municipality of Flora is located on the western coast of Norway. About 8000 people live in and around the main town in the area defined by the system borders of this analysis. In addition to residential consumers, the area includes commercial and public buildings, industry, public schools, a sports arena, a hospital and an airport. It is expected that there will be a significant increase in the number of inhabitants and activities in the coming years, and the municipality is currently updating their plans for future energy, water and road infrastructures.

The Planning horizon of the analysis is 25 years (2010-2034), split into 5 investment periods of 5 years each. Investments are allowed at the start of each investment period. The Norwegian Ministry of Finance currently recommends a discount rate between 4% and 6% for public investments depending on risk. The discount rate for the Flora case is set to 5%.

To reflect the main seasonal variations in the coastal region of Flora, three hourly profiles for electricity and heat demand for different customer groups are established. These profiles are aggregated into three yearly segments (see also Figure 2): *Peak load* of 29 days, *Intermediate load* of 243 days and *Low load* of 92 days. The profiles are calculated from measured annual energy demand in the area, disaggregated with national load profiles for relevant customer groups [25].

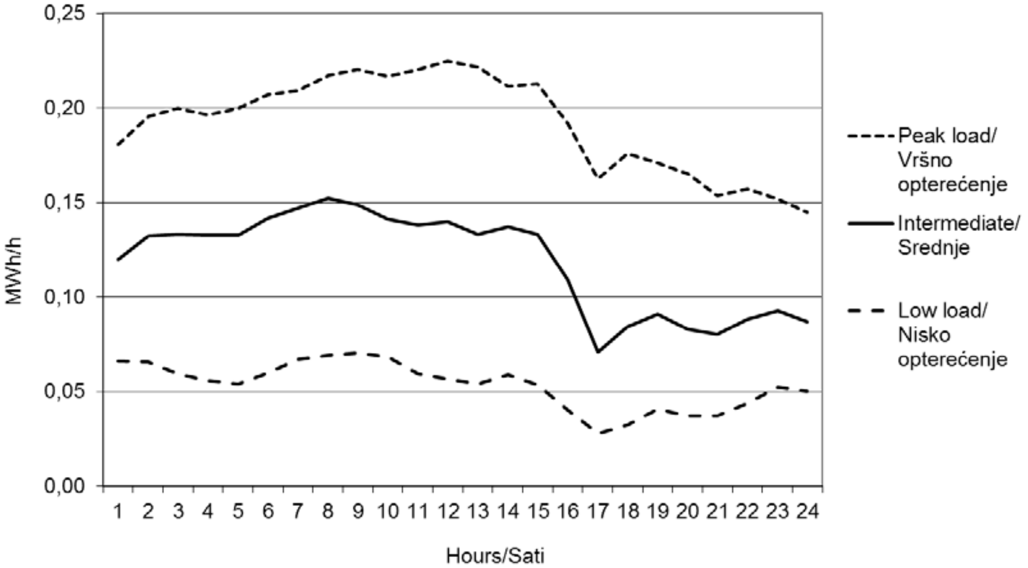

Figure 4. Example of residential heat demand profiles (150 detached houses)[1]
Slika 4. Primjeri profila potražnje za toplinskom energijom u kućanstvima (150 odvojenih kuća)[1]

As an example, Figure 4 shows the residential heat demand profiles for 150 new buildings planned as the first stage of a new suburb. The total area load is assumed to increase 6% per 5 years during the period of analysis.

Initially, also existing cooling demand in commercial and public buildings was supposed to be included in the analysis. However, this had to be omitted due to a lack of sufficient data for the demand.

3.2 Alternatives for energy supply

In this case study, six different supply alternatives are considered for the municipality of Flora:

0. No alternative heating systems beyond current electricity and oil boilers
1. District heating (DH) grid with gas fired cogeneration
2. District heating (DH) grid with gas fired boiler
3. District heating (DH) grid with biomass/pellets fired boiler
4. Distribution of natural gas
5. Distribution of low temperature heat from sea water

In addition, two specific cases are analysed where only one suburb is considered for heating based on either a centralised heat pump (HP) or a gas fired boiler. The design of the five main supply options is shown in more detail in Figure 5 while an overview picture of the complete case model is included in Appendix 1.

The heat centrals are designed with a separate 60% base load capacity and a 40% peak load with back up capacity for the base load only. Investment costs are based on national data and previous analyses in the area [26, 27]. Figure 6 shows how the investment costs for heat generation, distribution system and customer installations are split for the different alternatives. Note that in the cases of district heating, investments costs for the network are identical while the costs for the heat centrals differ. The low temperature distribution grid based on sea water heat is a special concept that is already in operation in a municipality not far from Flora. Sea water pumped from 50 m depth with an annual temperature range of 7-11 ^{o}C is exchanged with fresh water for distribution. Compared to the high temperature district heating systems, the technical solution of a low temperature network operating around 10 ^{o}C is very cheap, with only plastic pipes instead of insulated steel pipes. A disadvantage of this system is the need for heat pumps at each customer location to raise the temperature to supply the building's heat system. However, cooling can be obtained directly from the low temperature water with only a simple heat exchanger.

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[1] The new buildings are assumed to have an average size of 90 m^2 and to be built according to the national building standard of 2008 with a total annual energy demand of 125 kWh/m^2 (Energy class C).

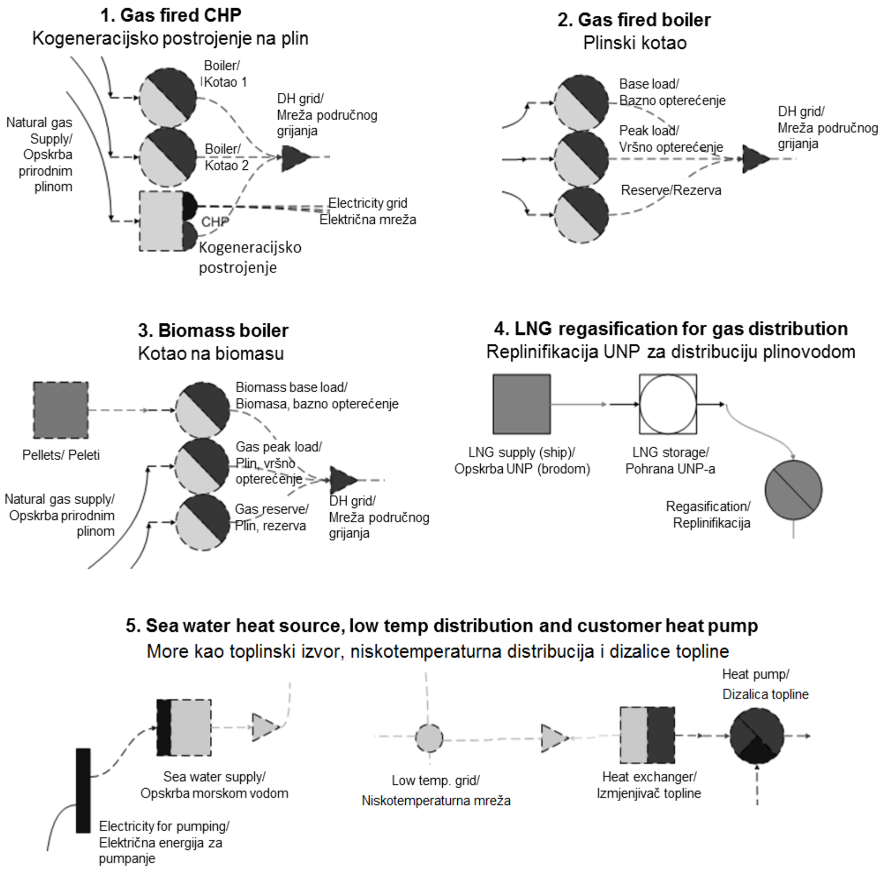
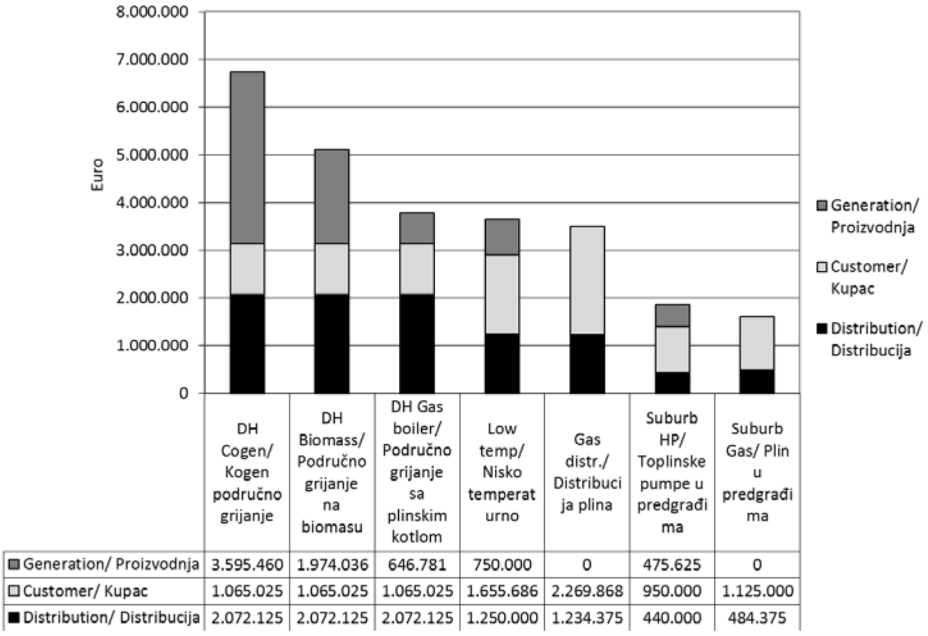


Figure 5. The five main energy supply options for Flora
Slika 5. Pet glavnih opcija za opskrbu Flore energijom



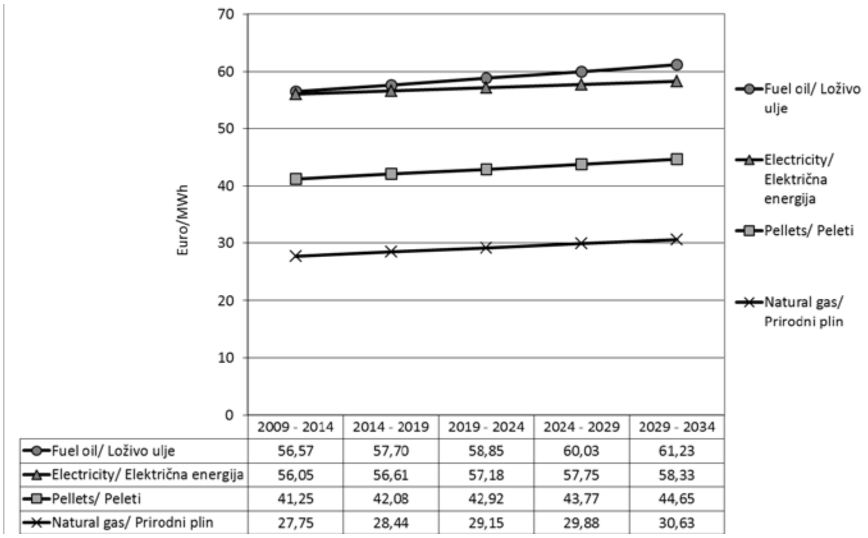
	DH Cogen/ Kogen područno grijanje	DH Biomass/ Područno grijanje na biomasu	DH Gas boiler/ Područno grijanje sa plinskim kotlom	Low temp/ Nisko temperaturno	Gas distr./ Distribucija plina	Suburb HP/ Toplinske pumpe u predgrađima	Suburb Gas/ Plin u predgrađima
▨ Generation/ Proizvodnja	3.595.460	1.974.036	646.781	750.000	0	475.625	0
☐ Customer/ Kupac	1.065.025	1.065.025	1.065.025	1.655.686	2.269.868	950.000	1.125.000
■ Distribution/ Distribucija	2.072.125	2.072.125	2.072.125	1.250.000	1.234.375	440.000	484.375

Figure 6. Investment costs for the different investment alternatives (Euro)
Slika 6. Investicijski troškovi različitih investicijskih alternativa (Euro)

The low temperature distribution grid based on sea water heat is a special concept that is already in operation in a municipality not far from Flora. Sea water pumped from 50 m depth with an annual temperature range of 7-11 ^{o}C is exchanged with fresh water for distribution. Compared to the high temperature district heating systems, the technical solution of a low temperature network operating around 10 ^{o}C is very cheap, with only plastic pipes instead of insulated steel pipes. A disadvantage of this system is the need for heat pumps at each customer location to raise the temperature to supply the building's heat system. However, cooling can be obtained directly from the low temperature water with only a simple heat exchanger.

3.3 Energy prices

The average energy prices as presented in Figure 7 are based on projections from existing national statistics [26], adjusted to local conditions in dialog with the regional energy company. The electricity price to end users consists of electricity spot price plus grid tariff. No taxes are included in the prices.



	2009 - 2014	2014 - 2019	2019 - 2024	2024 - 2029	2029 - 2034
Fuel oil/ Loživo ulje	56,57	57,70	58,85	60,03	61,23
Electricity/ Električna energija	56,05	56,61	57,18	57,75	58,33
Pellets/ Peleti	41,25	42,08	42,92	43,77	44,65
Natural gas/ Prirodni plin	27,75	28,44	29,15	29,88	30,63

Figure 7. Average end user energy prices (Euro/MWh)
Slika 7. Prosječne cijene energije za korisnike (Euro/MWh)

3.4 Main results

When eTransport is run with initial assumptions as described above, the resulting ranking of alternatives is given in Figure 8. The numbers in parenthesis in the legend indicate the year of investment. At first inspection, the difference between the alternatives seems very small but the resulting annuities are not the only factors that need to be considered before making an investment decision. The resulting annuities can be split into investment cost and operational cost per investment period.

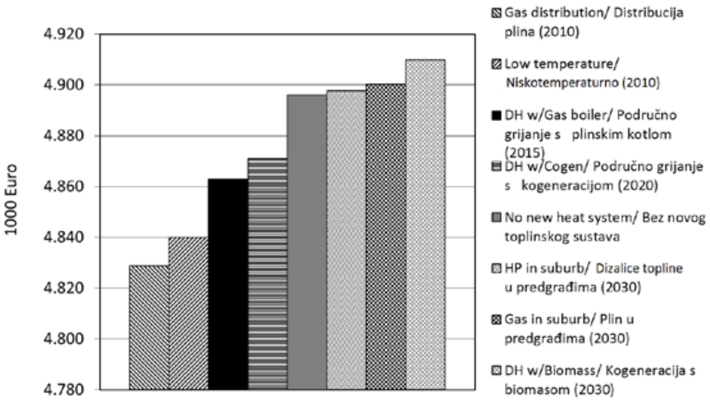


Figure 8. Ranking of investment alternatives (shown as annuities for the whole period)
Slika 8. Rangiranje investicijskih alternativa (za cijeli period)

Figure 9 shows the optimal investment timing of the alternatives. Only the gas distribution (#4) and the low temperature distribution (#5) alternatives are realised in the first investment period (2010). District heating with gas boiler (#2) is realised in the second period (2015) and district heating with cogeneration (#1) in the third period (2020), while the last three investments are realised in the final period.

When investments are delayed beyond the first period, this implies that the municipality will have to use the current energy supply of electricity and oil boilers for one or more periods before it is economically feasible to realise a new design. This is however not consistent with the municipality's intent to combine a new energy supply system with major updates of roads and water/sewage systems in the coming years. If all investments are forced in the first investment period, the price differences between them increase but the ranking order does not change. Thus, in principle, only gas distribution and low temperature distribution are feasible solutions for the area.

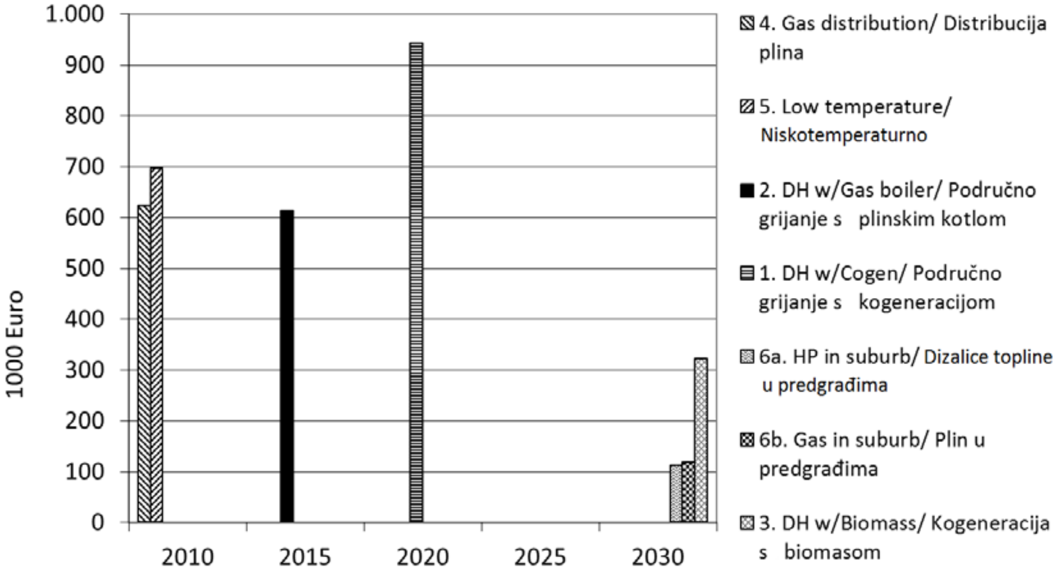


Figure 9. Distribution of investments (shown as annuities for each investment period)
Slika 9. Raspodjela investicija (prikazano za cijeli period)

Emissions of CO_2, NO_x, SO_2 and CO for each alternative and period are shown in Figure 10. All alternatives involving combustion of natural gas have higher emissions than the alternatives without gas. Since emission taxes are not included in this analysis, the different emissions do not influence the annuities of Figure 8 directly but it further emphasizes the advantage of the low temperature distribution solution. Note that direct emissions from existing oil boilers in the area are not included due to lack of data, so the emissions from the existing solution (#0) do not include these.

3.5 Operational results

Detailed operational profiles for all components in all seasons and for all system solutions can be inspected to help the decision maker to better evaluate the utilization of components and search for critical bottlenecks or undesirable operational situations that are not observable from the investment conclusions.

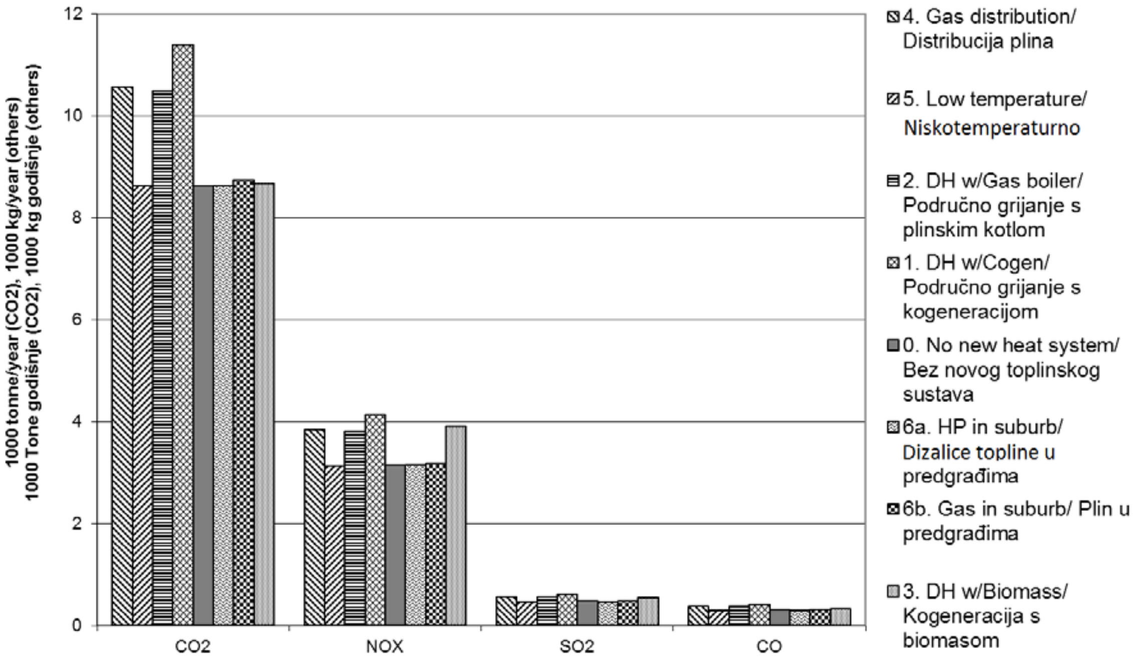


Figure 10. Annual emissions for each alternative and investment period
Slika 10. Godišnje emisije za svaku alternativu i investicijski period

Figures 11a and 11b show one example of how the heat load is covered for one selected customer, in this case the local hotel, during peak load and low load for the two most relevant alternatives. In the Low temperature alternative (Fig. 11a) the heat pump is not dimensioned to cover the maximum load so an oil boiler is needed during peak load hours. During low load, however, the heat pump is sufficient to cover all heat demand. In the Gas distribution alternative the gas boiler is dimensioned to additionally cover maximum load so that no supplementary energy source is needed during the peak load (Fig. 11b).

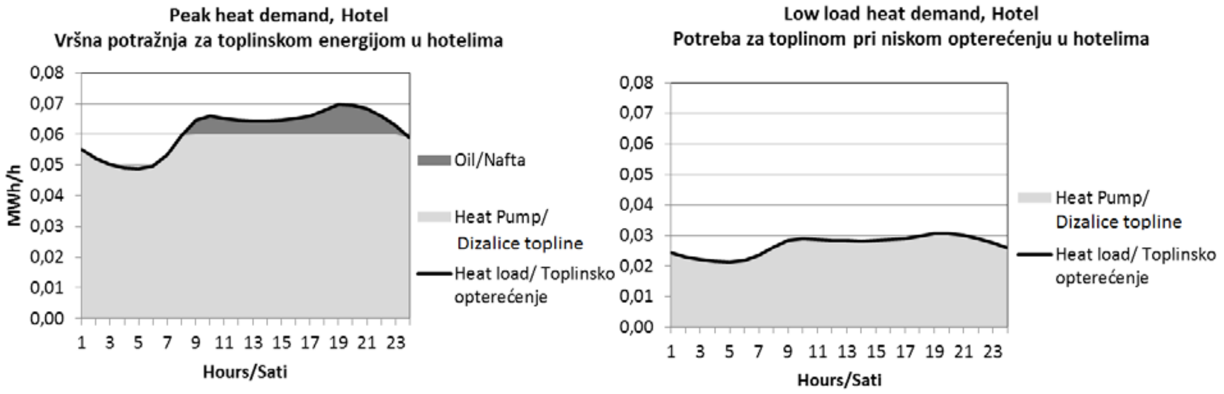


Figure 11a. Heat supply to hotel in peak and low load periods for Low temp. alternative.
Slika 11a. Opskrba hotela toplinskom energijom u vršnim i niskim periodima za alternativu s niskom temperaturom

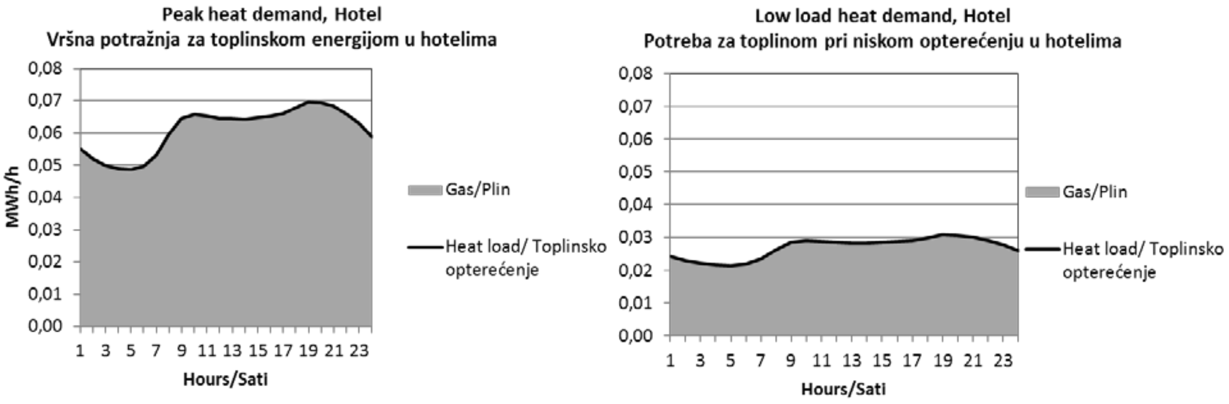


Figure 11b. Heat supply to hotel in peak and low load periods for Gas distribution alternative.
Slika 11b. Opskrba hotela toplinskom energijom u vršnim i niskim periodima za alternativu sa distribucijom plina

3.6 Sensitivity analysis

As part of the case study, four different sensitivity analyses were performed: i) Gas price increased to equal fuel oil price, ii) 25% reduced investment cost for district heating with gas boilers (alternative #2), iii) CO_2 emission tax added and iv) changes in electricity price. The main conclusions are summarized in the following sections.

3.5.1 Increased gas price

When the gas price is increased to equal the fuel oil price of Figure 6, the gas fired alternatives lose their competitive advantage, and the Low temperature alternative (#5) emerges as a clear winner. Referring to the initial ranking in Figures 8 and 9, the Low temperature alternative is not affected by the increase in gas price and remains in the first investment period, while all other alternatives are postponed to the final investment period.

3.5.2 Reduced investment cost for district heating with gas boilers

The district heating alternative with gas boilers (#2) has the lowest heat central investment of the three DH alternatives (network investments are assumed to be equal, see Fig. 6), and ranks as third in the initial investment analysis of Figure 8. A 25% reduction of (total) investment cost for this alternative is necessary to make it competitive with respect to gas distribution and it is moved up from the second to the first investment period. However, 25% is a larger reduction than can be expected by combining construction work with roads and water.

3.5.3 Addition of CO_2 tax

If emission taxes are added in the model, the cost of emissions will be included in the operational costs. This might influence the investment ranking. A CO_2 tax of 25.88 €/tonne CO_2 for fuel oil and 25.63 €/tonne CO_2 for natural gas (currently proposed by the Norwegian authorities) will reduce the profitability of all alternatives that involve use of fossil fuels. The alternative with gas distribution (#4) remains in the first investment period, but the Low temperature alternative now emerges as a clear winner.

3.5.4 Changes in electricity price

Electricity is a dominant energy source in the area, also when alternative heating systems are introduced. Thus, the total operational costs of all alternatives are quite sensitive to electricity price.

In the initial ranking, the average electricity price is 56.25 €/MWh over the period of analysis. If the average electricity price is reduced to 50 €/MWh and then to 47 €/MWh (while price profiles are kept unchanged), the investments are delayed, first to 2015 then to 2020. Low temperature distribution and gas distribution remain the two most profitable ones, though.

If average electricity price is increased to 65.60 €/MWh, district heating with cogeneration (#1) moves up as the best alternative, both due to low electricity demand and the ability to sell surplus electricity back to the grid.

4. Conclusion

This paper has presented the results of a case study to investigate different alternatives for the energy supply to a municipality on the western coast of Norway. The case study is performed with the optimization model eTransport which is developed for the planning of local energy systems with several alternative energy carriers.

The optimal investment ranking of Figure 8 shows small numerical differences between the alternatives, but further considerations give important insights to enable a clearer conclusion from the study. Only distribution of natural gas with local boilers and low temperature water distribution with local heat pumps are implemented in the first investment period. Since the municipality wants to combine the development of the new energy supply system with construction work on roads and water/sewage systems, these two alternatives are the only realistic ones. Sensitivity analyses influence the costs of the alternatives, but the ranking of them more or less remains the same. Furthermore, since it is very likely that a CO_2 tax will be imposed on all use of fossil fuels in the near future, the low temperature distribution alternative emerges as the preferred solution. Adding the possibility of the direct cooling of office buildings (which is not included in this analysis) gives further advantages for this alternative.

The regional energy company SFE has continued with more detailed technical studies of the Flora area, and finally applied to the Norwegian Water and Energy Administration for concession to establish a combined district heating and cooling system based on sea water heat, heat pumps and electricity boilers for peak load [28]. They received concession for such a system on the 4th of February, 2011 [29].

Acknowledgements

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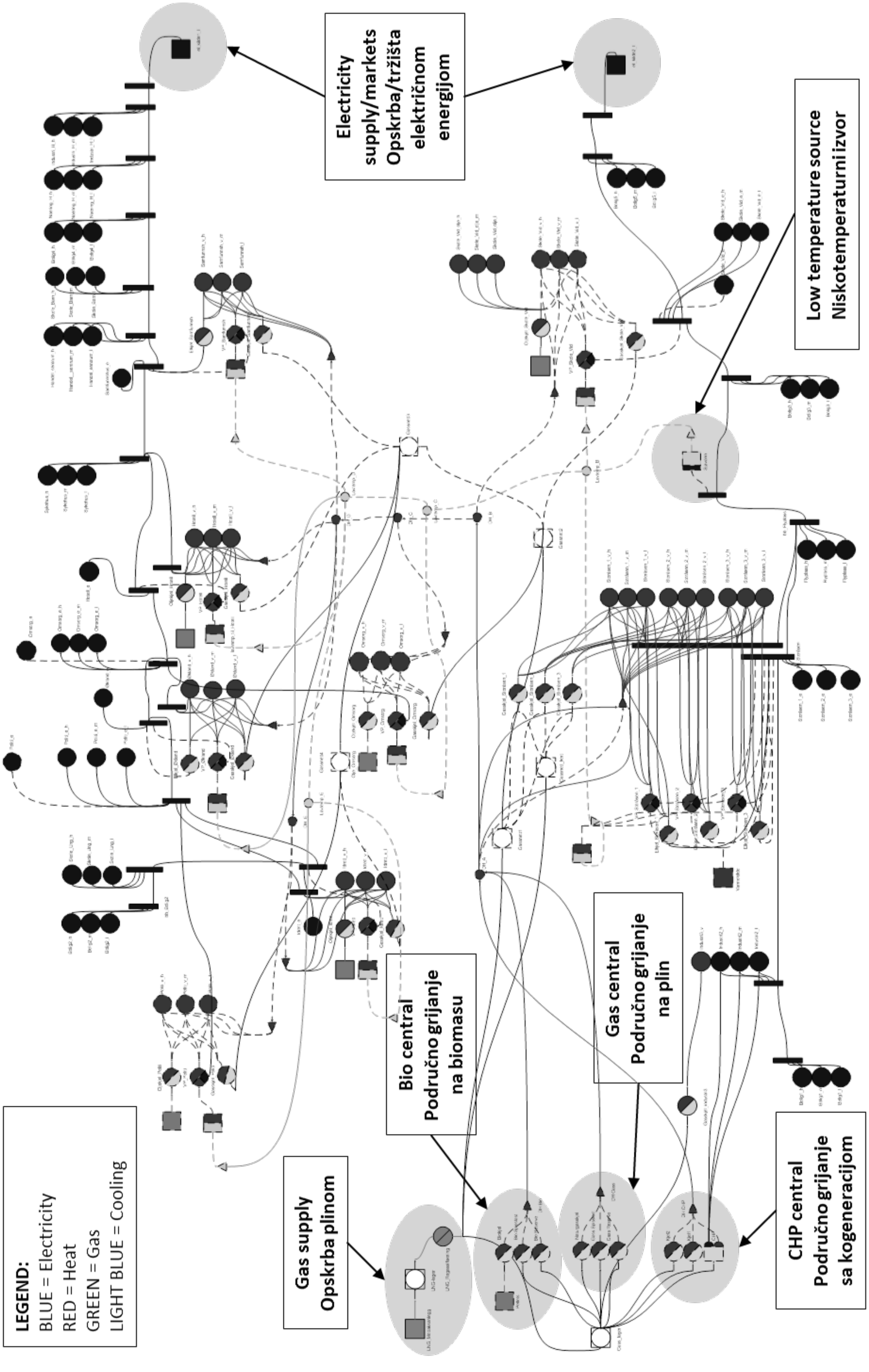
Appendix: The eTransport Model of Flora

The following figure shows the complete case model of Flora in eTransport. Squares are sources and black/dark grey circles are loads. Each physical load is split into three segments; Peak, Intermediate and Low load periods. Existing technologies at the start of the analysis are drawn with solid lines, while alternatives (to be optimized by the model) are dashed. The alternative energy sources are highlighted by grey shadows.


Electricity supply/markets
Opskrba/tržišta električnom energijom
Low temperature source
Niskotemperaturni izvor
Gas central
Područno grijanje na plin
Bio central
Područno grijanje na biomasu
CHP central
Područno grijanje sa kogeneracijom
Gas supply
Opskrba plinom
LEGEND:
BLUE = Electricity
RED = Heat
GREEN = Gas
LIGHT BLUE = Cooling