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CITYOPT – Holistic Simulation and Optimisation of Energy in Smart Cities – Vienna Study Case

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***Abstract* — 68% of the European Union population lives in urban areas, this proportion is growing as the urbanization trend continues, this presents us with an opportunity to reduce individual carbon footprint providing the city is designed in an efficient way. This energy demand currently represents 70% of the total. This highlights the importance of the development of more sustainable urban areas which are more energy and resource efficient, the use renewable energy sources, reduction of the carbon footprint, infrastructure development, engagement of the stakeholders and users, removing administrative and regulatory barriers and new business models.**

CITYOPT is a collaborative project supported by the European Commission through the Seventh Framework Programme (FP7) the main goal of which is to create a set of applications to optimize the energy system in different life cycle phases to support planning, design and operation of energy systems in urban districts. In particular, CITYOPT planning tool will support analysing, simulating, optimizing and communicating various city planning alternatives. This holistic approach will integrate, among others, energy dynamics of local grids, buildings and consumption behaviour and patterns, energy storages, and local energy production using renewables. In this paper, the CITYOPT planning tool and the methodology behind it for the test site of Vienna is presented. This study case is based on three office buildings which lie in close proximity to the Rail Tec Arsenal Fahrzeugversuchsanlage (RTA) Climatic wind tunnel. This facility is intensively used for aviation, road- and rail-vehicle testing. During these tests a huge amount of waste heat is rejected from the chillers. The objective of the Vienna study case is to utilize this waste heat with the existing thermal energy supply systems of the office buildings in an optimal way. Thermal energy storage is also considered to be linked to this network to maximize the use of the waste heat matching on this way heat production and demand. For this, several configurations of the district heating network will be modelled in APROS, a multifunctional dynamic simulation tool and linked to the CITYOPT tool which will optimize the design to determine the best solution in terms of energy, CO_2 emissions and economic efficiency. Additionally, due to the novelty and complexity of such system a new business model has been developed to outline its economic viability.

Keywords* — *Smart Cities, Energy Systems, Urban Planning support, Dynamic simulation, Decision support tools.

I. INTRODUCTION

68% of the European Union population lives in urban areas, this proportion is growing as the urbanization trend continues, raising the energy demand for private and public consumers and for economic activities with the subsequent increase in CO_2 emissions. This energy demand currently represents 70% of the total [1]. Furthermore, urban areas have high levels of air pollution, primarily from the burning of fossil fuels in energy production and road transport, resulting in enormous economic and social costs [2], [3]. Additionally, energy security is also becoming increasingly important with declining European natural gas and oil reserves together with the current geo-strategy situation [4], [5]. This highlights the importance of the development of more sustainable urban areas which are more energy and resource efficient, the use renewable energy sources, reduction of the carbon footprint, infrastructure development, engagement of the stakeholders and users, removing administrative and regulatory barriers and new business models [6].

The main objective of the CITYOPT project is to create a set of applications and related guidelines that support planning, detailed design and operation of energy systems in urban districts. The expected results are applications that bring together information and guidelines for designing scenarios of energy systems and will show how to prioritize alternative energy solution scenarios based on social, economic and environmental criteria. These will be supported by analysis of people's attitudes, behaviours and mental models.

The concrete end result is the CITYOPT Tool, whose main function is to provide support for a decision maker by providing a platform with which diverse input information can be combined, a possibility to perform optimization based on the input information and mathematical models, ways to report the results and to compare different solutions in order to make an informed decision and way to receive load shedding solicitations and to see their effects

This paper is structured as follow. In section II the software design of the CITYOPT Application is presented. In section III the Viennese study case is presented and analysed. In section IV the business model about the Viennese study case is explained. Finally, in section V the main conclusions of this paper are presented.

II. Software Design

The CITYOPT Tool is divided into two software implementations: CITYOPT Planning and CITYOPT Operational. The first one will assist in the planning and design phases of the energy system whereas the latter is intended for use by dwellers in the operational phase of the energy system. In particular, for the Viennese study case the CITYOPT Planning application will be applied. The tools will consider appropriate service business models, privacy and trustworthiness and shall involve users throughout all phases of the project.

To give an overview of the CITYOPT Planning design, in the following the requested input information for the application, user groups, modelling and calculation methodology, optimisation methodology, graphical user interface, reporting methodology, over architecture and design constrains are presented.

A. Input information

The CITYOPT Planning tool will help users to combine and manage diverse input data gathered from various sources during a design process. As described in [7] the input information often is collected manually and fed in to Excel sheets etc. Such information can include the design target, its geographical location or time horizon of the operation.

Current tools usually do not provide the possibility to deal with information specifics such as when the information was obtained or its source. Also an estimate of its accuracy as a result of detailed analysis is usually missing. Furthermore, [7] indicates a need for migration of information from an earlier design phase to later stages. The CITYOPT Planning tool strives to answer these challenges by organizing all the information needed for the design or operational optimization into projects and scenarios. In addition to the input information described above, a project contains data, numerical models, scenarios (i.e. particular values of model parameters), optimization goals (optimization sets) and results (numerical data and reports). A project is an entity that the user can create, edit, reuse and distribute.

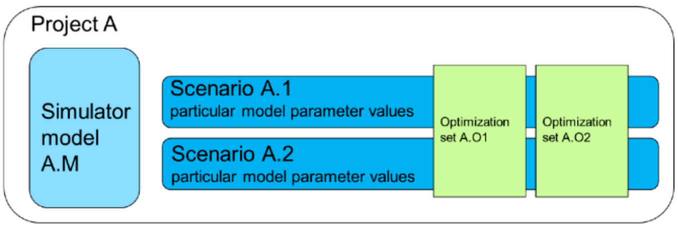

Fig. 1. Hierarchy of projects, models, scenarios and optimization sets

B. User Groups and Characteristics

A wide variety of stakeholders will access the software tools. These could be energy system operators, who are responsible for operation, maintenance and development of transmission systems or energy system designers, who are implementing energy systems, or a dweller who is able to participate in the electric market using web or apps.

Therefore a user/role concept is implemented, which grants permissions per user group. It allows accessibility to the suitable functionalities which cover different needs: An *Administrator* is allowed to create projects and have unlimited access to all data and functionality types including the configuration of the software, *Experts* are allowed to create projects, have unlimited access to operational data and functionalities, except for the configuration of the software and the definition of the user groups, A *Standard user* is allowed to work on projects without restrictions and *Guests* are only allowed to visualise and export a limited set of data.

C. Modelling

CITYOPT Planning is a generic solution able to interact with a wide range of energy simulation software. The types of models in the CITYOPT Planning context are numerical models because the energy systems, which are usually simulated, are large, complex and dynamic in nature making it difficult to obtain explicit equations to represent them. This will be achieved by organising the output data of simulations within the tool, making these models the major source of information. Therefore the CITYOPT Planning tool will not run the models by itself but will interact with them defining the parameters of the simulation, generating optimisation sets and scenarios and accepting the numerical results. This information can be used to build metrics which allow the analysis of the performance of an energy system under different conditions. In particular, CITYOPT planning tool will be tested with APROS simulation software. This simulation energy software allows to model complex urban energy system in a flexible way [8].

D. Optimization

In the CITYOPT Planning tool the optimization will focus on two aspects on the design and operation of the energy system.

CITYOPT Planning will use the current information of its database to identify the optimum solution of a specific optimization set. This implies that this database should be rich enough to identify the proper solution. Two different methods in the optimization procedure can be applied to identify the optimum solution:

1. Searching in the database: the current information of the database is used to identify the optimum solution.

2. Genetic algorithm (GA): This method is employed to find the optimum solution or in the multi-objective case a set of Pareto-optimal solutions. The data generated by the GA will be stored in the database for the search-based optimization.

E. Graphical User Interface (GUI)

CityOPT Planning is implemented as web application, their users are interacting via a web front end, which is viewable by any standard web browser. The planning tool offers functionalities to define projects, scenarios and optimisation sets and to initialise the simulation and optimization process. Since those processes are considered as long-term asynchronous threads, the GUI provides appropriate feedback about task status and error messages.

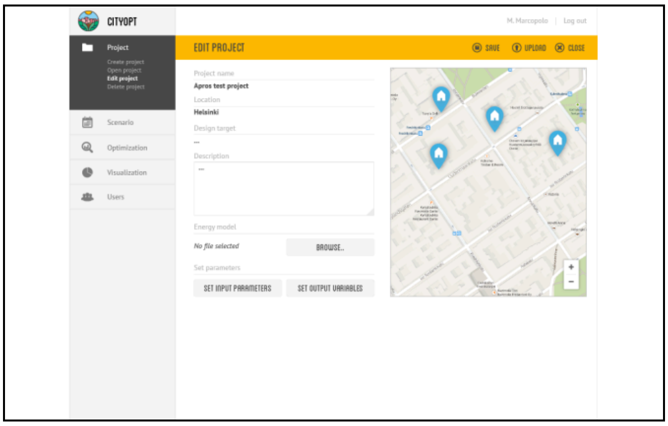

Fig. 2. Graphical user interface

F. Reporting

As CITYOPT Planning will generate a lot of data by using optimization an emphasis needs to be put on how to present such results to decision makers. The reporting inside the CITYOPT Planning will utilize standard visualization methods such as time series data, trends, pie charts and spider charts giving the possibility to compare a set of solutions of the same or different study cases. In addition to reporting the results, the CITYOPT Planning tool will provide ways to visualize the input information provided to it.

G. Overall architecture

Deployment view of the CITYOPT Planning architecture is presented below in Fig. 3

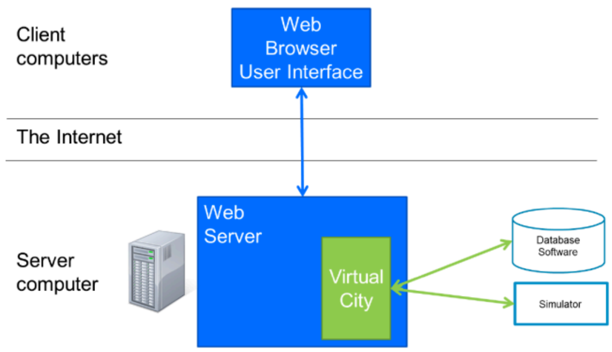

Fig. 3. Overview of the CITYOPT Planning architecture.

CityOPT Planning is deployed as web application on a web server. Users will apply the browser to connect to the web server, which is relaying the request to an application server... Apart from web and application server as server-side components a database is used to store all respective data. Furthermore an external simulator generates more data if needed.

From the conceptual structural viewpoint the CITYOPT Planning software will consist of different software packages:

Web package: The web package contains the components that control the request flow from the user to the application. The package can be understood as a Web Server that filters the requests and delegates them to the appropriate packages. It will also handle user authentication.

Business logic package: The business package contains the business logic of the web application, which handles the actions requested by the user, such as defining a project, generating a report, querying the database, etc.

Database access package. This package forms the needed queries to the database software, executes them and post-processes the results.

Simulator access: This package is responsible for starting the simulation software with appropriate simulator model and parameter instances as defined in the scenario at hand. Furthermore the component is responsible for processing the data (files) produced by the simulator.

Optimization package: This package will implement the optimization algorithm(s). In the first phase the optimization will be finite search database queries.

Presentation package: The presentation package contains the visualization components, which are based on dynamic JSP page generation combined with static content,

III. VIENNESE STUDY CASE

The Vienna study case is based on three office buildings located on the 21st district of Vienna named TECHbase, ENERGYbase and FUTUREbase. FUTUREbase is still under planning and therefore is not yet built. They lie in close proximity to the facilities of Rail Tec Arsenal GmbH (RTA). This facility specialises in the testing of vehicles at sub-zero temperatures using one of European largest climatic wind tunnels. During these tests a huge amount of waste heat is rejected from the chillers to the air.

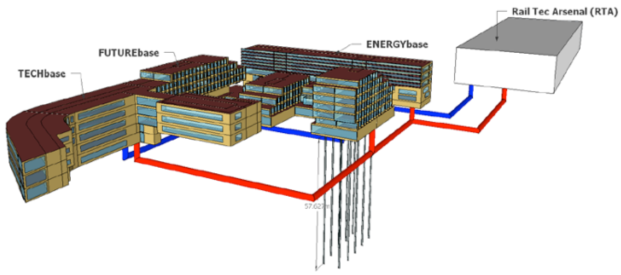

Fig. 4. Overview of the Viennese study case

In this section the different elements of the Viennese study case are presented. This includes the description of the energy network, building, RTA´s climatic wind tunnel, thermal energy storages and the current energy system, the optimization goals and stakeholder´s motivations.

A. Energy network

The relationship between the different components of the network for the Vienna study case is illustrated in Figure 12. Two ground source heat pumps and solar thermal panels provide heat to the ENERGYbase building. A gas boiler provides heat to the TECHbase building. The FUTUREbase building is planned to be a "plus energy" building. Like ENERGYbase it is designed to maximize the internal gains of occupants and equipment to almost eliminate heating demand. It will have a Solar Thermal array and potentially an additional ground source heat pump. It is envisioned that the whole system will be connected by a district heating network. In addition to the current system, two mid-term thermal storage tanks will allow the storage of excess energy from the solar thermal panels and from the RTA waste heat, to respond to the heat demand when necessary.

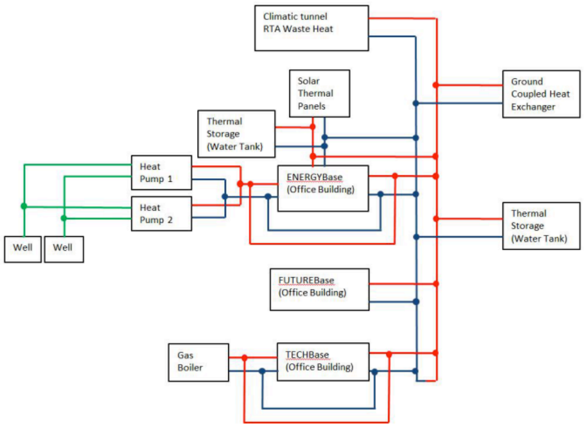

Fig. 5. District heating network

B. *Office Buildings*

TECHbase is a four storey building consisting of a lecture theatre, event area, office and seminar rooms, power plant, laboratories and a canteen. Its gross floor area is 9,236 m^2 and was built in 2005 and designed for around 310 occupants. The building also includes a basement which partially comprises a parking garage. The building is constructed with concrete-steel reinforced walls and ceilings with external Expanded Polystyrene (EPS) insulation and a light interior construction. Exterior sections that are exposed to greater humidity and the flat roof are insulated with Extruded Polystyrene (XPS). Double glazed windows, with a low emission coating, are used throughout and complied with the regional building regulations of the time. All windows in the office area can be opened manually. To assist with cooling flexible external blinds are mounted on the east, south and west facades and the north with jalousies.

Fig. 6. TECHbase office building

ENERGYbase was constructed in 2008 as a demonstration building intended to provide stimuli for cutting edge office and industrial building design. It is built following the passive house standards with heating and cooling supplied by 285 m^2 of solar thermal collectors, 400m^2 of Photovoltaic modules, ground water and internal gains from occupants and equipment. The building façade is designed to reduce solar heat gains in summer, maximize them in winter, whilst still allowing natural light all year round.

Fig. 7. ENERGYbase office building

Construction of *FUTUREbase* is anticipated to begin in 2016. It will have a floor area of approximately 12,000m^2 and is expected to take the ENERGYbase design to the next level and function as a "plus energy" building, meaning it should produce more energy than it consumes. It will be shaped in such a way that it has no impact on the PV and solar modules on ENERGYbase.

Fig. 8. Possible scenario for the FUTUREbase office building

C. *RTA's climatic wind tunnels*

RTA is a testing facility for large vehicles such as trains, helicopters and buses, in order to assess their ability to withstand extreme conditions. It is 100m long, has a temperature range of -45 to 60°C and a maximum wind speed of 300km/h. The air humidity can be regulated from 10 to 98% at temperatures above 10°C. Intense solar radiation can be simulated by a 47.5m lamp field with an intensity range of 250 to 1000W/m². A smaller lamp field is available for the front of the test object. In addition, snow, rain, and ice can be added to simulate specific weather conditions. The small climatic wind tunnel has similar functionality but on a shorter length of 33.8m. The lamp field is 30m and the maximum wind speed is 120km/h. Figure 16 shows a view of the RTA´s climatic wind tunnel

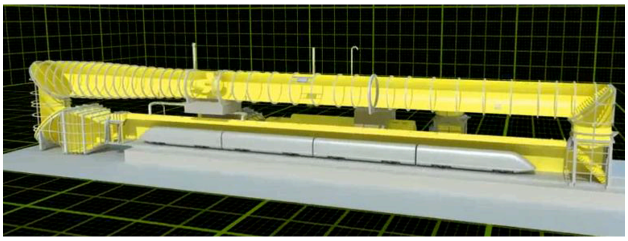

Fig. 9. RTA´s Climatic Wind Tunnel

The technical characteristics of the chiller system to cool down the temperature of the wind climatic tunnel are shown in following table

TABLE I. RTA´S CLIMATIC WIND TUNNEL

Technical characteristics	
Screw compressor	*3*
Capacity of the evaporative condensers	*1.3 MW*
Nominal power of the ventilators (at high rotational speed) of the evaporative condensers	*360 kW (8 ventilators each 45 kW)*

Three main possibilities could be applied to recover the waste heat:

- To recover the sensible heat from the compressors, currently rejected via the oil coolers, the collector tank and finally by the evaporative condensers

- To use directly the sensible heat from desuperheating of the hot gas (i.e. superheated vapour of the refrigerant from the outlet of the compressors) recover via desuperheater instead of current rejection via the evaporative condensers;

- To use directly the latent heat from condensation via a condenser instead of the current rejection via the evaporative condensers.

D. Thermal energy storage

Two possible storage solutions are envisaged for the Vienna pilot site, an over ground mid-term storage tank and/or an underground seasonal storage.

Mid-Term storage, depending on the experiments performance in the RTA´s climatic tunnel the temperature levels and total heat loads of the waste heat able to be supplied to thermal energy network will vary significantly. In addition to this, the periods of the facility when no experiments are taking place have to be considered. Therefore mid-term thermal storage is expected to be an important feature of the balancing system, making it a key component of the thermal energy network performance in the Vienna study case. Using the mid-term storage, the surplus heat could be stored for a few days to enable the network to balance heat generation with demand.

Utilization of the *Underground for heating, cooling and storage,* in addition to a mid-term storage, heat underneath the site of the soon to be constructed FUTUREbase is a posibility. An initial study was carried out analysing the geological and hydrogeological conditions at the site of the Vienna study case.

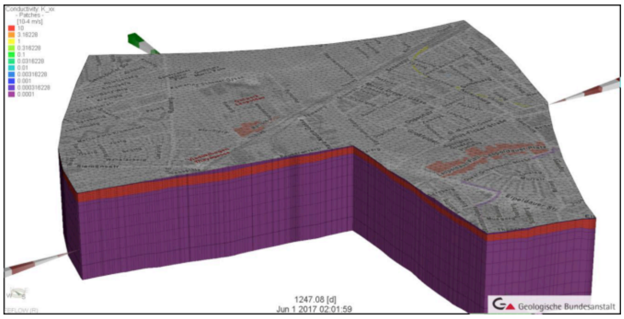

Fig. 10. Underground section for the heating and cooling storage

E. Current energy systems

The heating system of the ENERGYbase building consists of Thermal Activated Building Structure (TABS) in the ceilings of the four floors. This is supplied by water from two ground source heat pumps. As the system was designed for the worst case scenario it has two heat pumps but only one is currently in use. In winter groundwater is above the ambient temperature. It is extracted using a water pump and its temperature lifted by the heat pump up to around 45 ° C. The generated hot water is distributed on the one hand to the TABS and to the ventilation system to supply warm air to the building. The heat pumps can work in parallel with a heating capacity of 160 kW each.

Additionally solar heat is provided by 285 m² of flat-plate collectors (SONNENKRAFT SK500NECO). The collector system is integrated in the top segment of the south oriented façade at an angle of 32°. Its working fluid is a water-glycol mix (70% ater/propyleneglycol 30%). The solar heat system operates in ‘low flow mode’ which means the specific collector mass flow is only around 20 kg/sec. The solar heat is stored in a 15,000 litres tank which enables vertical temperature stratification and supports improved efficiency of the solar heat generation. Its primary function is to supply the desiccant cooling system used to supply cool air to ENERGYbase during the summer months. In addition to this it also supplements the heating demand of both the air treatment system and the concrete core activation system during winter.

TECHbase is currently run by two gas boilers installed in parallel which have a total capacity of 1 MW. They are connected via a hydraulic separator to the heating system which has a flow and a return temperature of 80 and 50 °C. To meet the actual demand, the boiler output can be reduced down to 10 %.

F. Optimization goals

Process description: The optimization process in the Vienna study case is based on the integration under a thermal energy network of the office buildings, current supply systems, energy storages together with the use of the waste heat from the RTA´s climatic wind tunnel.

Performance metrics: The performance metrics which should take into account are:

- Energy consumption (kWh)
- CO_2 emissions (tons)
- Investment costs (€)
- Running costs (€)

Running costs make reference to the operational and maintenance costs.

Degrees of freedom: The design optimization should define the best option according to the objective functions and constraints defined by the user. The objective function also will be able to combine all the listed metrics weighted properly by the user. There are two main goals; first, to optimise the design of the thermal energy network by a suitable design of the water tank which is used as thermal energy storage and the number of boreholes of the ground heat exchanger and secondly, the optimization of the operation of system taking into account the temperature levels and the mass flows. In this context, there are several types of constraints that should be considered among other to perform the optimization process: the maximum size of the water tank, the maximum area were the boreholes of the heat exchanger can be allocated, the maximum temperature of the ground which can be reached by the rejected heat, the minimum and maximum temperature levels of the warm water needed to cover the heat demand of the office buildings, economical constraint based on the investment and operational costs of the system, oscillations on the production of the waste heat from RTA´s climatic tunnel due to its use, influence of the weather conditions in the heat production from the solar thermal panels.

Scenarios: To produce usable information the optimizations are performed in different scenarios which comprise different options in terms of the design of the water tank, ground heat exchanger, the district heating networks together with operation of the system according to the variation on the defined constrains. These scenarios could include the best design of the district heating network: to maximize the rejected heat to the ground to maximize the energy efficiency of the chillers of the RTA´s climatic tunnel, to minimize the CO_2 emissions of the overall system according with the technical and economic constrains, to minimize the importation of the energy (gas and electricity) to the system, to minimize the energy bill of the of the office buildings, etc.

G. Stakeholders of the study case

In the Viennese study case several stakeholders has been involve in the discussion to take advance of the development of the district heating network. These stakeholders are facility managers, energy providers and the thermal grid operators.

Facilities managers are focused on using best business practices to improve the efficiency to deliver the necessary services in their buildings. One of the most important aspects of this service is to provide good thermal comfort conditions in the office areas, which is also one of the most costly. The possibility of using the waste heat from RTA´s climatic tunnel allows an opportunity to reduce these running costs making the renting of the offices to companies more attractive and competitive. Additionally, there is currently an excess of installed capacity (i.e. thermal solar panels, heat pumps and gas boilers) to supply heat locally in TECHbase and ENERGYbase which is expected to be high enough to cover the heat needs of FUTUREbase in the scenario where the waste heat production from RTA´s climatic tunnel ceases and there is no support from the thermal storage to cover the energy demand. This opens the possibility to avoid additional costs to install new equipment to make up for the lack of waste heat.

Energy providers, RTA's objective is to supply the rejected heat form the chiller from the climatic tunnel to the energy thermal network connected to the buildings. The possibility that the buildings could absorb the waste heat from the chillers of this facility is very interesting because it implies a reduction in the electrical cost of the chillers and at the same time an increase of the energy efficiency. Business models bounded for RTA should not only to emphasize this goal, also to maximize it.

The role of the *thermal grid operator* is to manage the security in the thermal networks, in real time and coordinate the supply of and demand, in accordance with standards in order to ensure quality and avoid interruptions of supply. The possibility to have a thermal grid operator, independent of the main actors in the Vienna study case, which allows optimise the grid coordinating the different supply technologies, the thermal storages and the waste heat from the RTA´s climatic tunnel to cover thermal demand of the building could be explored in the different business models.

IV. BUSINESS MODELS

The pressure to reduce emissions in Europe will result in a large change in the energy market. New technologies and new actors will enter the arena. A change in the energy market will also lead to a change in the business models used by energy companies. New actors can use improved business models for promoting their services and companies that are already established on the market must develop their models in order to maintain their market position. In this context, due to the novelty and complexity of the energy system under the Viennese study case a new business model has to be developed.

The business models developed are based on Osterwalder's business model canvas [9]. The purpose of the business model canvas is, on the one hand, to provide a framework for laying out the stakeholders, activities and resources needed to produce a value proposition and, on the other hand, to present the customer relationships and channels needed to deliver the value proposition to the customer segments. Also included are the cost structure and revenue streams.

A centralised structure is considered the most suitable because of the small number of potential participants in the local heat market and the absence of suitable software solutions for the market operation. A New Energy Service Company (NEW ESCO) has to be established, which is taking over the different responsibilities and is managing the purchase, the distribution and the sales of the heat. The existing ownership structure of the buildings, the heat production units (gas boiler, recovered heat, solar thermal panels and heat pumps) and the necessary equipment will remain but their heat production will be sold to NEW ESCO. Recovery heat from the RTA facility will be used as first option, if the recovery heat production is higher than the demand the excess will be stored and used later in case that the recovered heat production cannot cover the demand. If the heat stored tank cannot supply heat under the established quality (temperature level) the other heat producers will be connected.

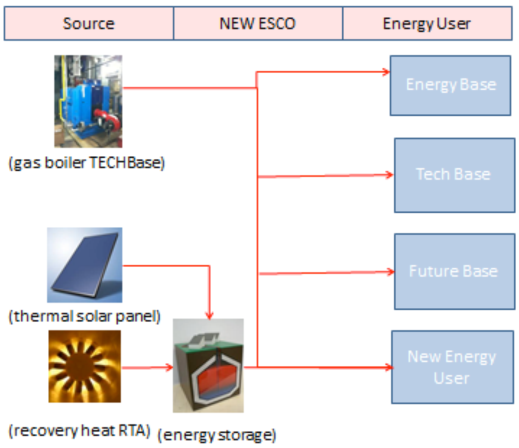

Fig. 11. Centralised Ownership concept

The implementation of this system is favourable for all the actors. The consumers will reduce the individual heat energy costs, RTA will convert its waste heat into a valuable product and the NEW ESCO will focus on the investment in the adaptation of energy generation units, the heat storage tank and the district heating network as well as a control system. Additionally, the NEW ESCO could extend the district heating network to other buildings to increase its business opportunities.

The operation will be based on long-term heat purchase and supply contracts in terms of heat quantity and quality. The possibility to supply heat at different temperature levels can increase the number of suppliers due to the inclusion of the heat pumps and the thermal solar system, which can supply "low temperature heat" to the passive office buildings to cover their space heating demands. For the implementation, the NEW ESCO has to bear large investment costs for the design of the district heating network and the adaptation of the existing heat production facilities. The payback time can last for several years or not be reached; in this case possible support from funding agencies as well as the expansion of the grid to other buildings would lower the risk

V. Conclusions

The CITYOPT planning tool and the methodology behind it for the test site of Vienna is presented. This study case is based on three office buildings which lie in close proximity to the RTA´s wind climatic tunnel. The objective is to utilise the waste heat from this facility together with the existing thermal energy system to cover the heat demand of the office buildings in an optimal way. Thermal energy storage is also considered to be linked to this network to maximise the use of the waste heat matching on this way heat production and demand. In particular the CITYOPT Planning application is a web server application able to interact with different type of energy software to optimize the design and the operation of the urban energy systems. A detailed description of the CITYOPT planning has been shown including among others, implementation concept, GUI, information required, optimization methodologies. This application will be use to optimize the design and the operation of the Viennese study case. The different elements which configure this study case have been described in detail: building, RTA´s wind climatic tunnel, current energy systems, optimization goal, interest of the stakeholders. Finally, due to the novelty of the Viennese study case a new business model has been developed. A centralized structure is considered the best solution where NEW ESCO has to be formed and will take over the different responsibilities to manage the purchase, distribution and sales of the heat.

Acknowledgment

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