Dynamic Modeling and Optimization of Energy Use in Retrofitted Buildings at District Heating Level

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Abstract

Buildings represent a significant share of global energy consumption in the European Union (EU). Heating and domestic hot water (DHW) needs account for an important part of that energy use. Considerable energy savings can be achieved by retrofitting buildings and improving heating systems. Such improvements are covered in this paper, as it presents a comprehensive retrofitting of 31 large residential buildings, within the European funded project CITyFiED. The retrofitting process consists of various measures (new renewable energy generation systems, façade retrofitting, etc.), but the focus of this paper is on district heating (DH) optimization measures, with the aim of increasing its overall system efficiency and sustainability. To that end, the actual system is modeled in a dynamic modeling software, TRNSYS, and modifications are tested. The results are a series of improvements that lead to better system performance, higher efficiency and sustainability.

Keywords: building retrofitting, district heating, dynamic modeling, efficiency, optimization, renewable energy

1. Introduction

According to European Commission data, buildings account for more than 40% of the global European Union (EU) energy use and for 36% of global greenhouse gas (GHG) emissions (Lewis et al., 2013). Similarly, heating and DHW generation alone represent 79% of total energy use (European Commission, 2016). Additionally, it is worth mentioning that 84% of heating and cooling is still produced from fossil fuels, so only 16% of the generation comes from renewable energy sources (European Commission, 2016).

All those facts give an idea of how important it is to work on the improvement of energy efficiency and sustainability in buildings in order to fulfill EU's climate and energy goals and address crucial challenges, such as reduction of GHG emissions. Measures must be taken to achieve those goals, such as energy demand reduction via better insulation in new buildings or by retrofitting existing ones, optimization of heating and cooling system control strategies, switch from fossil fuels to renewable energy sources, etc. The scope of this paper is in line with this kind of improvements, as it covers the optimization of the heating system of a district consisting of several residential buildings. One of the tools used to that end are dynamic simulations conducted in TRNSYS modeling software, aiming at an increase in efficiency and renewable energy share. Simulations allow to identify the points of the system where a room for improvement exists, resulting in guidelines for an improved and better performing system.

This optimization work is framed within a EU funded project, CITyFiED (repliCable and InnovaTive Future Efficient Districts and cities), which aims at developing a replicable, systemic and integrated strategy to contribute to the transformation of European cities into future smart cities. For that purpose, the focus is on reducing the current energy demand and GHG emissions, as well as increasing the energy efficiency and use of renewable energy sources by, among others, developing and implementing innovative technologies and methodologies for building renovation, smart grid and district heating (DH) networks.

In fact, the optimization work covered in this paper applies to a district of large retrofitted buildings which constitutes one of the three large demonstration sites of CITyFiED project. More specifically, the district, called

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Torrelago, consists of 31 residential 12-story buildings, constructed around 1980 and located in Laguna de Duero (Valladolid, Spain). All those buildings are individually analyzed and integrated into a new global control strategy. The retrofitting of the buildings and the rest of improvements made within the project have a considerable impact, on 1488 dwellings in total, corresponding to more than 4000 residents and accounting for a conditioned area of approximately 140000 m^2.

Prior to the simulation works described in this paper, some previous steps were taken, implementing various measures which have contributed to a higher energy efficiency. For example, due to the construction date of the buildings, there was a substantial room for improvement regarding insulation. Therefore, one of the major changes was the façade renovation of all the buildings, resulting in a better insulation and a lower heat demand due to the reduction of energy losses. Another key modification was the installation of new biomass-fired boilers powering the DH network and resulting in a more sustainable system, as part of the fossil fuel consumption is replaced by renewable energy sources. The main goal of the work presented in this paper is to optimize the current DH system in such a way that biomass use is increased, leading to a more efficient and sustainable system.

2. DH System and TRNSYS model description

Originally, the buildings comprising the retrofitted district were divided into two different groups ("phase I" and "phase II"), each of which having its own and separate heating system. Both systems were powered by fossil fuels, specifically, gas boilers.

However, an important retrofitting work was carried out, unifying both systems into a joint DH network and installing biomass boilers (BB) in one of the phases, as a more sustainable alternative to the existing gas boilers. In order to boost the sustainability of the whole system, the use of biomass is fostered. To that end, the global control system of the newly joint biomass and gas fired district heating system was designed to promote the consumption of biomass. Thus, the use of biomass boilers is prioritized over gas boilers with the goal of meeting the demand preferably with renewable energy sources. Ideally most of that demand would be met by biomass boilers but, in reality, the capacity is often insufficient to feed the whole system. The overall yearly goal is to generate 80% of the energy by means of biomass boilers, reducing gas consumption to a great extent. The simulation and optimization work presented in this paper aim at finding measures to contribute to that increase in the share of biomass-fired thermal energy generation.

One important feature that must be addressed, is the fact that the façades of all the buildings were refurbished with the installation of external insulation. All those modifications entail substantial changes in important parameters (e.g. reduction in energy losses resulting in lower energy demand), affecting the whole system. However, not all the buildings were retrofitted simultaneously, the progress rate of the constructions works was different for each of the 31buildings. Consequently, the energy demand was unevenly distributed throughout the system and constantly changing, posing a barrier to the optimum performance of the control. All those factors leave room for improvement on control strategy optimization, which is covered in this paper.

That optimization is achieved by means of modeling in TRNSYS (Version 17) a transient thermal energy software developed at the University of Winsconsin-Madison, used for dynamic simulation and offers great flexibility, which is very useful to test a wide range of configurations and control strategies.

The model consists of a comprehensive replication of the Torrelago DH network, including all the representative parts of the system: generation, distribution and consumption. The generation part is composed of the main biomass boilers (located in phase I, called "sector 1" in Fig. 1) and the auxiliary gas boilers (located in phase II); the distribution is made up of all the piping elements, pumps and valves; the consumption part consists of several substations, each of which corresponding to one or several buildings (up to 3) and globally split into the aforementioned two different phases. Fig. 1 shows the global hydraulic diagram of the actual system, which is then replicated in TRNSYS.

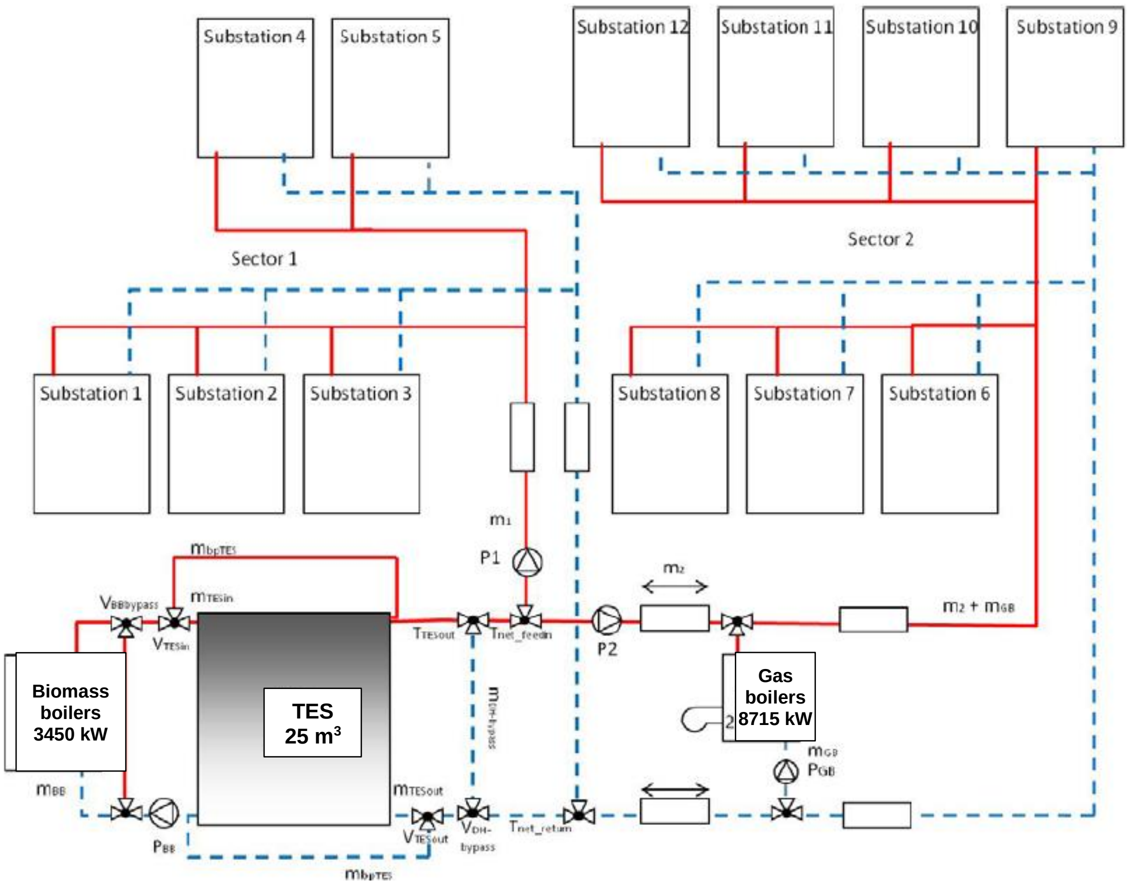

Fig. 1: Overall hydraulic schematic

It must be pointed out that the diagram in Fig. 1 represents the actual system schematically, including some simplifications. For example, in the real system there are 3 biomass boilers as well as 3 gas boilers, which are displayed as single boilers in this case (with a joint power including the addition of the single capacities). The same applies to the thermal energy storage, which in reality consists of two 12.5 m^3 water tanks connected in series. It can be observed that gas boilers have a great capacity compared to biomass boilers. However, they are currently intended only as back-up boilers and thus, they would rarely operate close to full capacity. The high capacity value is due to the fact that gas boilers were upgraded prior to the start of CITyFiED project, when biomass boiler had not been installed yet.

Every single component of the real DH system has its corresponding representation in TRNSYS, called "type". Within each type, there are many options to define its performance characteristics in terms of physical properties (e.g. temperature, flow rate, etc.), operation modes, etc. Those can be seen in the corresponding TRNSYS model shown in Fig.2.

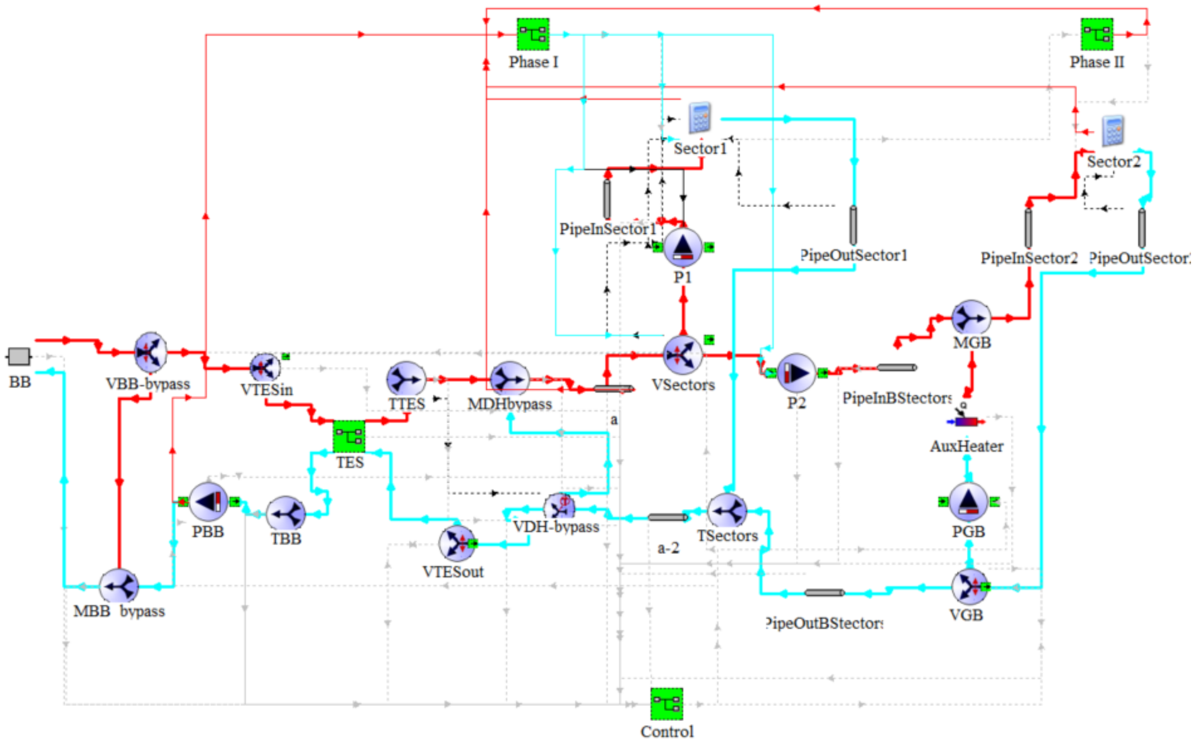

Fig. 2: Corresponding overall DH system representation in TRNSYS

The generation side consists of a heating plant with biomass boilers together with an auxiliary gas boiler supporting the main heating plant, each of which is represented by a specific type: "BB" and "AuxHeater", respectively. The main heating plant (biomass) is combined with a buffer consisting of two 12,5 m^3 tanks which, in the model, are located inside a "macro" (a submodel containing some global inputs/outputs) called "TES" containing type 340 (Drück, 2006), a non-standard type representing a multi-port thermal energy storage model. Energy provided by BB is charged at the top part of the tank and return flow to the biomass boilers is taken from the bottom part. A temperature sensor from the bottom part of the storage is used as lower input value for the hysteresis controller of the primary circuit (BB on/off). The supply flow for the district heating network (Phase I and Phase II) is taken from the top of the tank and the return flow is connected to the bottom part.

The distribution part consists of all the piping, valves, pumps, etc. required to transfer the heat from the generation to the consumers. This part of the system implies the use of a considerable amount of types to model the actual distribution system accurately: type 31 for the supply and return pipe (taking into account losses), type 110 for variable speed pumps, type 11 for tee piece and temperature valve for mixing valves. Once again, the control system ruling those components is flexible and included in macro Control. As for the generation/distribution side, the control system allows different operation modes. In this sense, the set-point temperature for the biomass boiler was identified as a parameter with a great impact on the stability of the control.

Finally, a load module is developed to simulate the consumer side of the district heating network at building level. Consumers are represented by their corresponding substations, each of which has adjustable demand parameters. They are divided into two main sectors, replicating the distribution of the actual district heating network, which in the model is represented by two different macros: Phase I and Phase II. Consumer substation "submodels" are contained within those macros. The model is able to load a unique yearly heat demand file for each of the consumer substations or two different load profiles, one per phase.

3. Simulation methodology

Once the model is created it must be validated and properly adjusted, so that it replicates the real system in the best possible way. To that end, a comprehensive set of real performance data is needed. This data is then used to feed the model, leading to a more precise replication of the reality, as comparing the results obtained in the model with those measured in the actual system shows the existing deviation and allows adjusting the model. Once the model is adjusted and validated, simulations will be representative and meaningful. Thus, this section covers an important part of the optimization process.

First, a representative period of monitored data is selected in order to feed the models with meaningful real values. In this case, taking into account that the overall objective is the maximization of the biomass generation share, a worst-case scenario was selected: the third and fourth weeks of January, when the temperature is minimum and the thermal energy demand is maximum, posing a challenge for the limited heat supply capacity of biomass boilers. The whole DH network was comprehensively monitored during the selected period of time, registering any irregularities in the normal performance of the system.

Then, an exhaustive analysis of the registered data was carried out. First, a macro analysis was performed to identify the main trends and define the following actions. In the first place, the energy generation mix (by fuel type) was checked, giving 42% gas / 58% biomass as a result. The goal for the yearly biomass generation share is set to 80%. It is normal that at the analyzed period the share was below that level, since the heat demand is much greater during winter time and the biomass boilers do not have enough capacity to meet such a high demand. Therefore, it is acceptable to have a lower share at that time, and the generation share goal for the winter season is set to around 70%. Still, there was room for improvement, which is made in the next phase of the optimization work and presented in the results section.

This kind of data analysis provide valuable information on the state of many parts of the system. For example, it was observed that 96% of the energy generation arrived the substations in phase II, while only 89% did so in phase I. Hence, substantially higher energy losses were observed in phase II, finding room for improvement, e.g. via better thermal insulation. Another example is the identification of a measuring problem which was affecting several energy meters of a certain kind and resulting in highly inaccurate readings (noise, outliers for long periods, etc.). In fact, these reading problems were relatively frequent during the measured period and affected also other kind of sensors, such as thermocouples. All of these faulty readings made it necessary to undertake a heavy filtering and data correction process so as to be able to obtain a continuous series of meaningful and “usable” data.

One especially critical problem was related to the biomass boilers, which are the core of this study. They were supposed to operate in fully automatic mode, which means that they are most of the time either in load mode or in conservation mode. However, random shutdowns were registered throughout the whole registered period. For instance, biomass boiler 1 was off during 101 registered points and boiler 3 was off during 103 instants. Taking into account that timestep between measurements is 15mins, that means that biomass boilers were off during a considerable amount of time while they were supposed to be in operation. As a consequence, not only the biomass generation dropped (going against the objective of increasing it) but the shutdowns affected the whole system, causing disturbances in many measured values. The problem with this is that TRNSYS is not able to replicate random events such as manual shutdowns, so the results of the simulations are only meaningful if the system is in full automatic mode during the registered period, otherwise the behavior of the system will not be successfully replicated. The solution was to select a period of 2 days where no random disturbances had an impact on the system, so it was a valid period representative of the normal performance of the system. The drawback was that the utilized period was short compared to the original aim of simulation 2 weeks.

Once the measured data was filtered with all necessary corrections, it was ready to be used as an input for the TRNSYS model. However, all the relevant components (types) in the model need to be properly adjusted so that the operation of the model replicates accurately the performance of the real system. The methodology for such adjustment is to validate and adjust each part of the model separately, following a logical order.

First, each biomass boiler was individually adjusted. The methodology is to adjust the parameters of the BB type so it replicates the operation of the actual boiler. Real monitored data is fed to the type (e.g. inlet temperature and mass flow rate), then the outputs of the type (e.g. outlet temperature) are read and compared to the real data monitored for those parameters. The deviation is the analyzed and corrected via type parameter adjustment, for instance, temperature set point and hysteresis. The process is repeated in an iterative manner until the output values of the type follow accurately the behavior of those of the real component.

The same process is done for other relevant types, such as thermal energy storage tanks. Then all the adjusted types are updated in the model and the behavior of the whole system is checked. Once its overall performance is equivalent to the real system, the model is ready for the optimization simulations.

This optimization simulations consist in trying different modifications with the objective of improving the performance of the system and increasing the biomass generation share. That is, modification of parameters of existing components, inclusion of new components and other variations are tried and the effect of each modification is analyzed. Again, following an iterative process trends can be identified on how the system react to certain modifications. The modified parameters (i.e. manipulated variables) are the ones that have a considerable impact on the amount of biomass energy generation (i.e. target variable). After a series of tests, those modifications that have the greater impact are identified and the best improvements can be selected as a result of the optimization simulation campaign.

4. Results

The main expected result is the development of an optimized control strategy, improving the overall performance of the system and leading to reduced energy losses and a higher share of renewables. This is achieved through the aforementioned simulations by developing improvements that prioritize the use of biomass boilers over gas boilers, meeting the energy demand in a more sustainable way.

However, some interesting results were already obtained during the measured raw data analysis and filtering process, before any simulation run. These results are related to the identification of monitoring problems and the identification of opportunities for improving the data acquisition and control system, as explained in section 3. Some of the most important findings were the following:

- Phase I has substantially higher energy losses than phase II (11% vs 4%). Therefore, some corrective actions could be taken, such as thermal insulation improvement.
- Random shutdowns were found in the biomass boilers, preventing them from operating normally in automatic mode.
- Several faulty measuring devices were pinpointed (i.e. some energy meters and thermocouples)
- Inconsistencies were observed in measured data, which could be pointing to a lack of accurate calibration.

The main results of the present work come from dynamic simulations of Torrelago district heating network, conducted under different conditions using TRNSYS software. Several modifications are analyzed with the purpose of increasing the renewable energy share (higher use of biomass boiler instead of gas-fired boilers). In order to determine which improvements, have a higher impact, results are compared to a baseline corresponding to the actual DH performance during the measured period, in terms of gas generation % vs. biomass generation %. The baseline corresponds to the integration of measured biomass boiler and gas boiler

Baseline: 37.8 % gas generation (G) vs. **62.2% biomass generation (B)**

Several cases are simulated, varying one or more property each time:

Case 1: increase of thermal energy storage (TES) capacity from 25 m^3 to 500 m^3. Obtained result:

- **1.1.** 33,9% gas / 66,1% biomass (noticeable improvement)

Case 2: Increase of the domestic hot water mode set point by 6ºC (from 84ºC to 90ºC). Obtained result:

- **2.1.** 37,6% gas / 62,4% biomass (almost no improvement)
- **2.2. Same case but with 500 m^3 TES:** 31% gas / 69% biomass (substantial improvement)

Case 3: Extension of heating mode hours (both on demand and generation side).

- **3.1. + 2 hour extension (starting 2h earlier):** 36,3% gas / 63,7% biomass (minor improvement)
- **3.2. + 4 hour extension:** 27,2% gas / 72,8% biomass (+10% in biomass use)

Case 4: Extension of heating mode hours (only in generation, same demand).

- **4.1. + 1 hour extension:** 37,5% gas / 62,5% biomass (almost no improvement)
- **4.2. + 1 hour extension and 500 m^3 TES:** 31,6% gas / 68,4% biomass (higher improvement)

- **4.3. + 3 hour extension and 500 m^3 TES:** 26,8% gas / 73,2% biomass (higher improvement)

Case 5: Increase of the biomass boiler power.

- **5.1. + 950 kW (total 4400kW):** 25,8% gas / 74,2% biomass (substantial improvement)
- **5.2. + 1250 kW (total 4700kW):** 21,2% gas / 78,8% biomass (notable improvement)

Case 6: Heat demand reduction (lower consumption).

- **6.1. - 20% demand:** 25,5% gas / 74,5% biomass (major improvement)
- **6.2. - 40% demand:** 13,3% gas / 86,7% biomass (great improvement)

All of the previous results are graphically displayed in Fig. 3 by biomass share in the thermal energy generation mix, which gives a better idea of the degree of possible improvement.

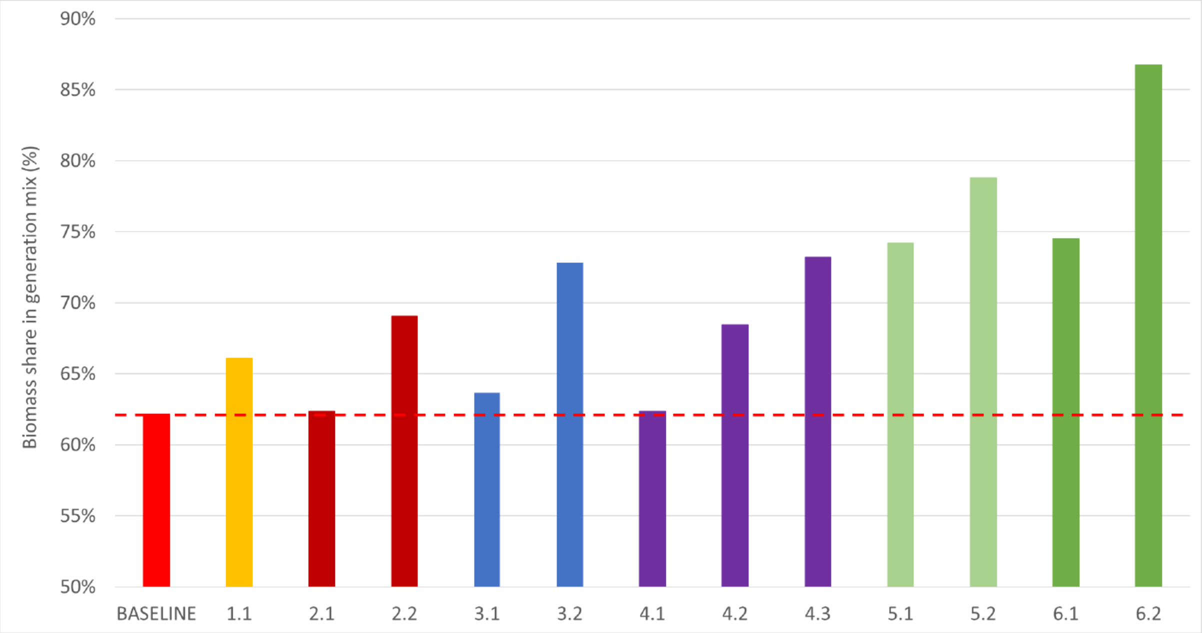

Fig. 3: Biomass generation share percentage achieved for several improvement cases

5. Conclusions

The following conclusions can be drawn from the results presented in section 4:

- Current thermal heat storage is too small to decouple the generation and demand and allow higher biomass boiler use, since the volume of hot water that can be stored represents a small buffer for such a big system.
- The two modifications that would entail greater increase in the biomass generation share, given the current circumstances, would be an increase of the biomass boiler power (i.e. by including an additional boiler) and reduction of the heat demand (not all the buildings were insulated when data was collected, thus lower demands are to be expected)

The optimization presented in this paper leads to an increase in the use of renewable energy sources which results in lower greenhouse gas emissions and thus in a more sustainable system. Additionally, economic benefits are also obtained as energy savings imply a reduction in operating costs.

Not only that, during the data analysis and filtering process undertaken prior to the actual simulations, several faults were identified, ranging from malfunctions in temperature sensors to poorly performing biomass boilers.

Therefore, this work gives as a result a series of guidelines on how to improve the district heating control strategy leading to more efficient performance, as well as various direct fixes regarding poorly performing devices.

6. References

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