Thread: Environment and Resources
Focus area: Energy and Fuels

Exploring Local Heating System Transition Dynamics

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Abstract

In order to achieve energy system transition from a system where fossil-based fuel dominates to a one with renewable energy and less carbon emissions, it is necessary to implement appropriate policy measures that can facilitate the consumers to choose a better energy alternative. Cost-based energy systems modelling is a common tool to analyze and evaluate such policy measures from a system perspective however, it is hard with this approach to capture what are the important factors affecting the energy consumers' choices when they adopt other energy alternatives. This study adopts a System Dynamics approach and presents a model of technological diffusion of 203 detached houses in a residential area of a Danish municipality Lyngby- Taarbæk. Three factors (cost, learning effect, and trust) are analyzed to investigate how fast the technological transition will happen and what are the important factors affecting the transition. Policy implications are discussed and it is found that this type of approach can support decision makers to better understand complex system and implement appropriate policy to facilitate such transition.

Keywords: Energy transition, System Dynamics, District heating, Local heating system, consumer choice, technology diffusion

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1. Introduction

1.1. Background

The building sector consumes a large fraction of the total global primary energy supply and particularly, space heating is the largest end-use in residential buildings (IEA, 2019). It implies that planning for a sustainable heating system has a high potential in reducing CO_2 emissions and reaching carbon emission targets by transitioning the system from fossil-fuel based to a heating system where renewable energy dominates. In the field of energy system planning, the most common tools for analyzing the system and supporting decision-making are energy systems models. Energy systems modellers choose different types of models which often use cost-based optimization depending on their objective, e.g., minimizing the total cost or/and the total CO_2 emissions, etc. However, such models usually do not capture non-cost aspects such as socio-political factors or individual behaviors which could have a relatively larger impact on energy systems planning (Pfenninger et al., 2014). In this regard, a system dynamics approach is expected to offer decision-makers who need to balance both system and individuals' perspectives different values and insights.

1.2. Delimitation and Problem Statement

This study explores the local scale heating system transition. Particularly, it focuses on 203 detached houses in a residential area called Jægersborgkvarteret (See Figure 1.) in the Danish municipality Lyngby-Taarbæk, located in the northern suburbs of Copenhagen. The changes to the number of houses by demolition or construction is not considered. The number of the studied houses is static in this study. The municipality heating system consists of 45 percent of district heating (DH) supply, mainly with a waste incineration plant as of 2020 and the rest is supplied by mostly individual natural gas (NG) boilers. The study area is one of the areas in the municipality with only individual natural gas boilers with a few oil boilers and it borders district heating areas on all sides which gives great demand for district heating by the residents. Transitioning the natural gas based heating to district heating is expected to play a critical role in reducing the use of natural gas which is the main contributor to CO_2 emissions in the heating sector (Lyngby Taarbæk Kommune, 2013).

However, the problem is that the municipality cannot force the citizens to connect to the district heating network and it is the citizen's choice whether to change the heating technology or stay with the current natural gas boilers (Yu et al., 2021). If appropriate measures are not implemented to facilitate the transition, the residents will keep using the natural gas boiler and the transition to district heating will take place slowly. Thus, the purpose of this study is to see what factors are important for individual housings' adoption of district heating as well as the speed of such transition with a system dynamics model. In the latter part of the study, we discuss what kind of policy measures would be important to facilitate the energy transition.

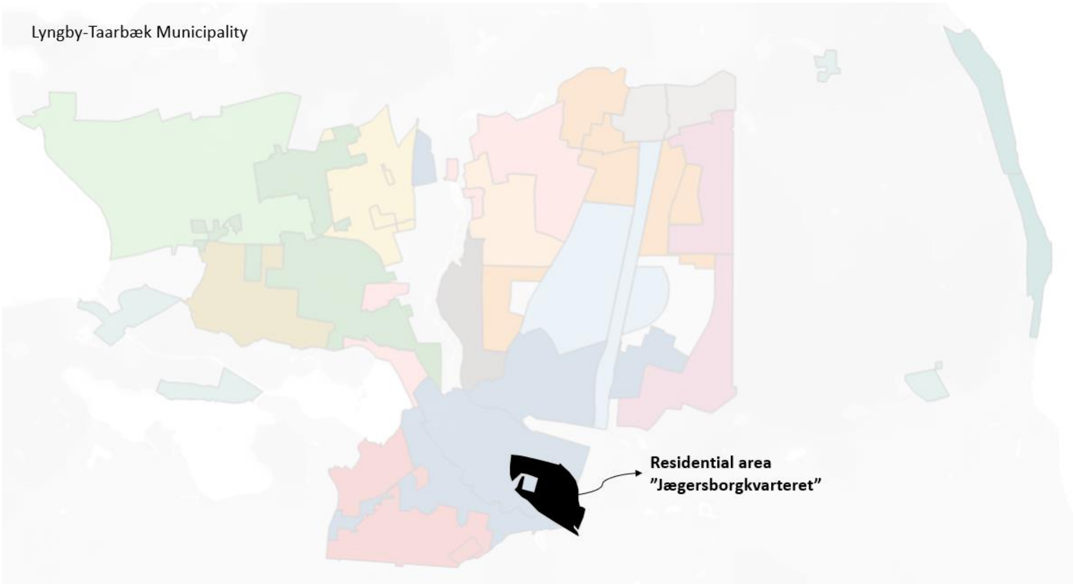

Figure 1. Study area: a residential area in Lyngby-Taarbæk municipality

2. Methods and Models

2.1. Methodology

This study has an explorative nature and is based on System Dynamics method. System Dynamics is a simulation tool that support policy makers better understand complex systems and the implication of system intervention. It was developed in the late 1950s by Jay Forrester of the Sloan School of Management at MIT (Williams, 2002). System Dynamics is based on differential equations and has its origin in control engineering and is now considered an established research direction in Management Science. System Dynamics approach has increasingly gained its popularity in recent years with the software developments and their increased availability. In this study, the model will be formulated with selected elements affecting the flows and stocks based on literatures. The structure verification can be found in Table 1. The computer simulation will be done in the Software Stella Architect.

2.2. Model Formulation

2.2.1. Stocks

The initial step the modeller takes to quantify the system elements and run simulation is to structure stock and flow diagram. The model is structured with two main stocks representing the number of houses with natural gas boilers and district heating respectively. These stocks are initialized to the actual numbers of houses connected to the district heating system and houses having natural gas boilers in the municipality. The number of houses per year which install either natural gas boilers or connect to the district heating system add to the stocks of these, respectively.

2.2.2. Flows

The rate of flow to the main stocks which is the adoption rate of district heating is affected by: the cost of district heating; learning effect of district heating adoption; and the level of trust in district heating. The adoption of district heating happens after the year of 2022 in the model because as of end of 2021, the area lacks concrete plans of converting the heating technology from the current natural gas boilers.

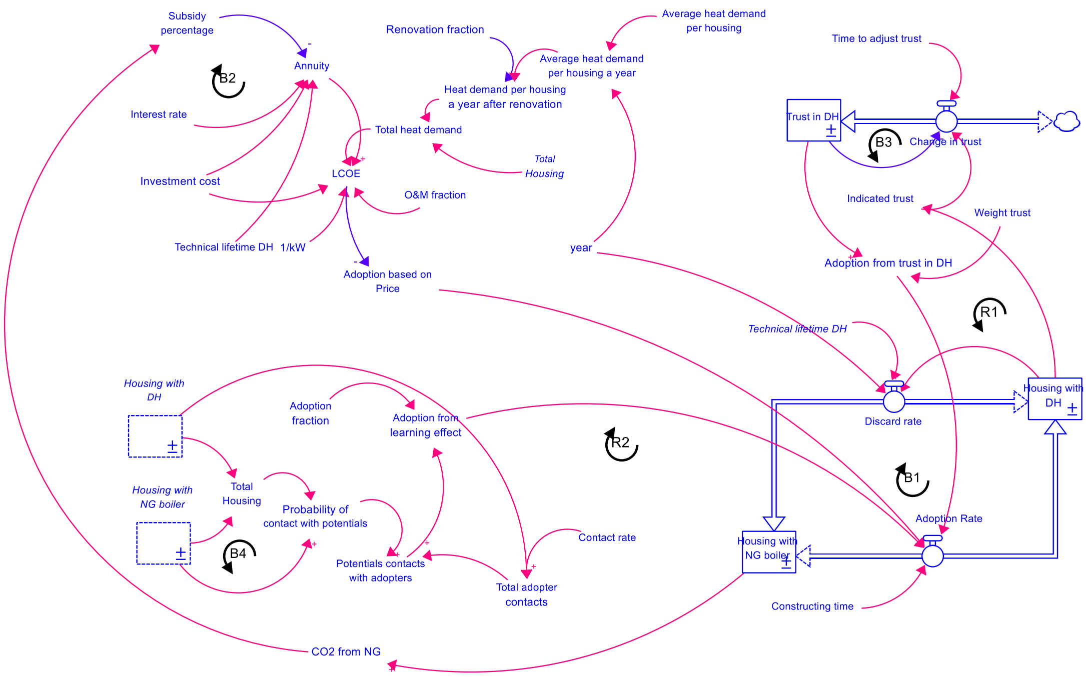

Figure 2. Stock and flow diagram and causal loop diagram combined and simplified.

The major gas utility Evida in Lyngby-Taarbæk municipality has conducted a survey on consumer's preference on heating technology and the result shows that the most important factor when people choose heating alternatives for their home is cost. Consumers are often reluctant to pay extra to adopt another "cleaner" energy technology while they still have an option to use a relatively cheaper fossil energy (Wall et al., 2021). The cost of cleaner energy, district heating in this study, usually changes with time according to various drivers: fossil phase out policy, e.g., CO_2 tax, subsidy scheme, fuel price fluctuations, demand changes, development level of technology. The cost aspect in this study indicates Levelized Cost of Energy (LCOE) which is affected by the level of subsidy among other parameters and the change in DH cost is expected to affect consumer's behavior. This cost-associated consumer's behavior, i.e., willingness to pay (WTP), on renewable energy technology has been analyzed by a number of authors (Irfan et al., 2020, Podbregar et al., 2021, Krikser et al., 2020, Ma et al., 2015, Economics, 2017). However, the level of willingness is likely dependent on how much of importance to mitigating climate change is imposed on the national priority (Irfan et al., 2020).

Another factor affecting the consumers' adoption rate for a new technology is the learning effect/network externalities. It explains the process of individuals learning through social interactions and observations and word of mouth (WOM) (Huang et al., 2017). Huang et al. (2017) have concluded in their study that social learning plays a significant role in the diffusion of a new technology. In addition to WTP and WOM, individual trust perception of a new technology is included in the model.

Trust in a new technology is considered as the individual expectation of favorable and acceptable outcomes by using the new technology (Wu et al., 2011). This element has been viewed as one of the motivations towards the adoption of a new technology since it can play a role as a catalyst towards the adoption of the technology (Wall et al., 2021; Wu et al., 2011).

The parameters in the model are calibrated using data from a technology catalogue published by Danish Energy Agency and Energinet (2020) and other official planning documents published by the municipality (Lyngby Taarbæk Kommune, 2018). The time horizon chosen for the model simulation is from 2008 to 2050. The reason for setting the end of the time horizon to 2050 is because the municipality has climate goal up to the year of 2025, 2030, and 2050. Identified feedback loops are described below.

2.3. Feedback Loops

R1. Trust reinforcing loop. This reinforcing loop describes the relationship between the number of houses which have adopted district heating and the level of trust in the new technology, i.e., district heating. If there are more housings using district heating in the area, it increases the trust in district heating by increasing the gap between the indicated trust and trust in district heating. In turn, the increased trust in district heating leads to higher rate of adoption due to trust and the same will happen to reinforce such behavior.

R2. Learning effect reinforcing loop. An increased number of houses will increase the potential contact between non-adopters and adopters. It results in increase in adoption rate from learning effect. This reinforcing loop will consequently drain housings out of the stock of housing with natural gas boilers.

B1. Energy transition loop. This balancing loop aims to drain the houses with natural gas boilers out of the stock with the adoption rate outflow. Decreased number of houses with natural gas boilers mean increased number of houses that adopted district heating. The adoption rate is positively affected by the three adoption rates that this study has a focus: Adoption based on price; Adoption from learning effect; Adoption from trust in DH. There is an outflow from the houses with district heating stock which means that when the heat demand from the houses decreases due to renovations, i.e. increased energy performance, the customers are not likely renew their DH subscriptions.

B2. District heating subsidy loop. This balancing loop describes how the level of district heating subsidy would impact the adoption rate based on cost. Subsidy is governmental financial support to lower the investment cost of district heating. In this study, it is assumed that the CO2 emitted from natural gas linearly increases the level of subsidy which means that the government would take more actions when there are more emissions from fossil fuel. When the emission level from natural gas increases, the level of subsidy will also increase which leads to decreased annual investment cost (Annuity).

B3. Trust adjustment loop. This balancing loop describes that the higher the trust in district heating, the lower the change in trust will be. In reality, it means that when there is more trust in district heating among housings, the difference between the actual trust level and the indicated trust will be reduced.

B4. Energy transition through learning effect loop. An increased number of housings with district heating means a decreased number of housings with natural gas boilers. The decreased number of natural gas boiler housings results in a reduced probability of contact between potential adopters and adopters. It means that there will not be enough potential adopters remaining in the stock of housings with natural gas boilers and consequently the speed of transition will be slowed down.

3. Analysis

3.1. Model Validation

Model validation tests using the guidelines established by Barlas (1996) were conducted to build confidence in the model. The results of model validation tests are presented in Table 1.

Table 1. Results summary of model validation. Adopted from Olovsson (2019).

Type of test	Result	Implication
Structure verification	OK	The model structure was built based on literatures found with keywords such as “energy choices”, “consumer choice and preference”, “renewable energy adoption”, “willingness to pay”, “consumer behavior”, “consumer acceptance and energy transition”, “factors influencing adoption of district heating”. The authors tried to look at the field of renewable energy in general, i.e., not only heating sector but also electricity generation, so that the model becomes applicable for different cases if needed. The details of the structure and each component are described in the model documentation in Appendix B.

Parameter confirmation	OK	Parameter values are based on official publications on the municipality's energy planning document as well as the national statistics published by the Danish Energy Agency and Energinet (2020). In case the appropriate values were missing in the mentioned references, the authors made assumptions grounded on related literatures.
Dimensional consistency	OK	All units are consistent and unit errors in the model are cleared. Right-hand side and left-hand side of every equation is checked and dimensionally consistent.
Behavior sensitivity	OK	The model reacts reasonable and expected behavior under extreme parameter values. There are parameters that the model particularly reacts sensitively: Initial NG; Initial DH; Contact rate; Constructing time; Adoption fraction; NG CO2 factor; NG efficiency; DH CO2 factor; DH efficiency; Absorption fraction; Renovation fraction; and Average heat demand per housing a year.

3.2. Base Case Simulation

The model simulation results of the base case are presented in Figure 3. In this study, the base case means that the houses in the study area are given the option to adopt district heating from the year of 2022. The model behavior will be analyzed in three intervals of years: 2008 to 2022; 2021 to 2037; and 2038 to 2050. The main result of the model simulation is the year when transition to hundred percent of district heating adoption is achieved and how the CO_2 emissions change over time accordingly. Key parameters will be adjusted in different scenarios in the next chapter to explore which elements affect the speed of such transition and what kind policy would be appropriate to facilitate the individuals' adoption and the transition.

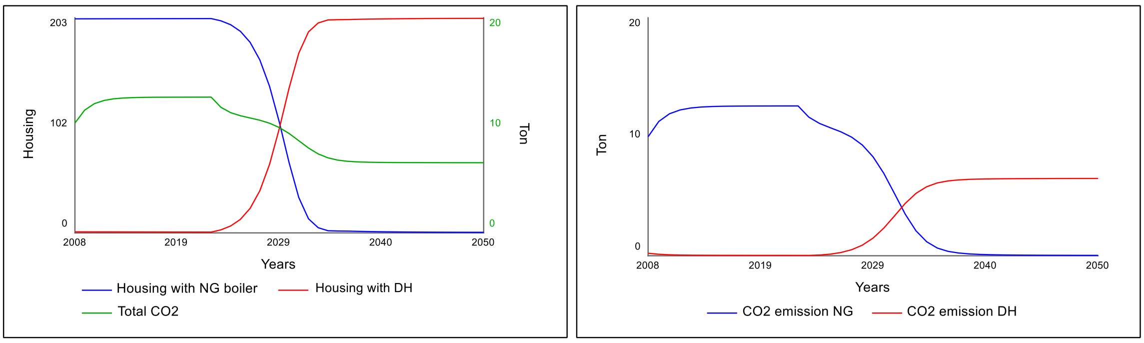

Figure 3. The main simulation results of the base case scenario over the entire time horizon.

From 2008 to 2021 – Depending on Fossil Energy

In this period of time, all the housings in the study area are supplied by natural gas heating. It reproduces the reference mode of behavior which was based on the historical data. In the model, the option of the district heating adoption is given after the year of 2021 which is applicable for the reality. Since it is assumed that renovation of buildings, i.e., through renovation, building energy performance can be improved so that buildings use less energy, are also introduced after the year of 2021, the heat demand per housing per year in the study area is constant.

From 2022 to 2037 – Starting the Adoption and Transition

After the year of 2021, the housings in the study area are given the option to adopt district heating. This starts to give whole different dynamics to the heating system in the area. First of all, the number of housings with natural gas boilers starts decreasing and the number of housings with district heating is increasing. This is because, as seen in Figure 4 upper-left graph, the adoption rates from learning effect, trust in district heating, and cost start to have different behaviors from the year of 2022. The respective behaviors can be explained with the loop R2 (Learning effect reinforcing loop), R1 (Trust reinforcing loop), and B2 (District heating subsidy loop). With respect to CO2 emission, natural gas-based emission starts decreasing as the number of housings with natural gas boilers are reduced. On the other hand, municipal solid waste-based, i.e., fuel for waste incineration plant which distributes the heat through the district heating network, starts increasing as the number of housings with district heating is increased. The total adoption rate (see Figure 4. The bottom-left graph) drastically increases from the year of 2022 and after it reaches its peak in 2029, the adoption rate sharply drops because there are not enough non-adopters, i.e., the housings with natural gas boilers, left in the study area. Also, as the renovation is introduced, the heat demand per housing per year is reduced (see Figure 4. the bottom-right graph).

From 2038 to 2050 – After the Transition

This period of time represents the period after the hundred percent district heating transition is achieved. The number of housings with both natural gas boilers and district heating are stabilized to the end of the time horizon. Interestingly, the adoption rate from trust in district heating kept increasing during this period of time while the adoption rates of learning effect and cost are decreased close to zero. It means that the loop R1 (Trust reinforcing loop) becomes the dominant reinforcing loop and plays a critical role in the hundred percent district heating transition. The heat demand per housing per year remains the same level as in the previous period because the renovation rate remained the same. With respect to the emission, the total CO2 emission is decreasing and stabilized when all the housings are finally using district heating. This is because municipal solid waste contains three time less CO2 compared to natural gas which indicates that by avoiding the usage of natural gas as heating source, the municipality will be able to reach closer to their CO2 reduction targets.

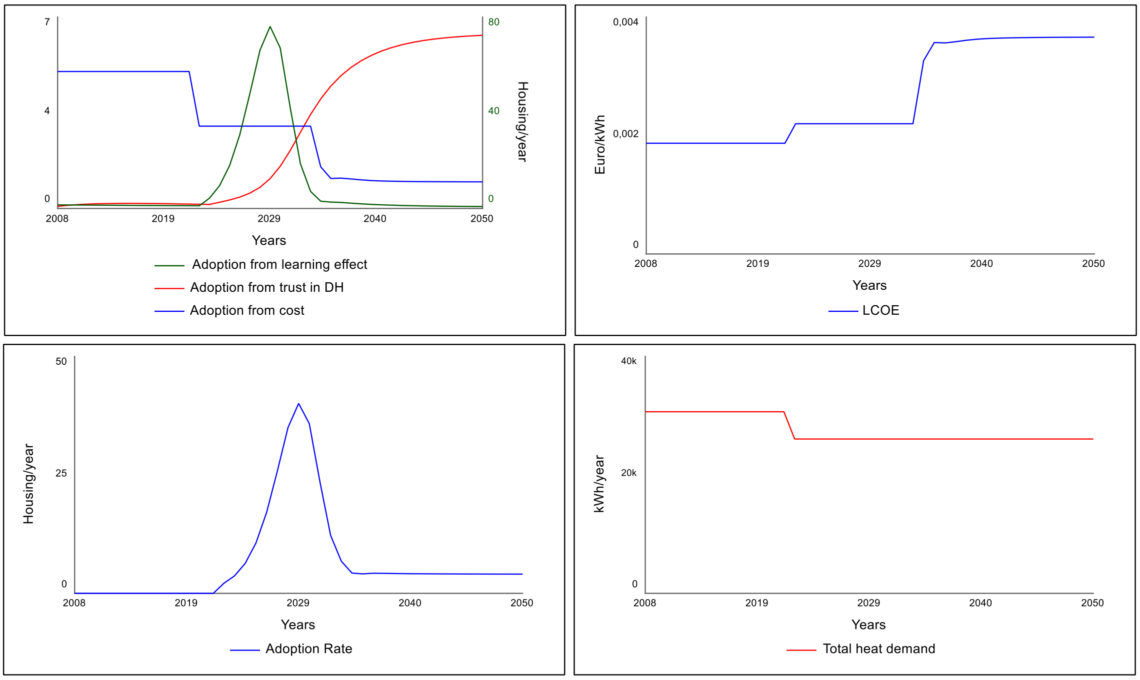

Figure 4. Model simulation results of different variables. LCOE means the levelized cost of energy, i.e., the average net present cost of energy generation for a generating plant over its lifetime.

3.3. Scenario Analysis

To explore what factors are important for the speed of the hundred percent district heating transition and mitigation of CO2 emission, four different scenarios are analyzed and compared to the base case scenario: No subsidy scenario (S1); Renovation scenario (S2); Higher learning effect scenarios (S3); and Lower trust scenario (S4). The adjusted parameters are presented in Table 2. and the different scenarios are explained below.

Table 2. Parameter adjustment for the different scenarios.

Parameter	Subsidy	Renovation fraction	Adoption fraction from learning	Weight trust
Base case	Yes	0,15	0,015	0,26
S1	No	0,15	0,015	0,26
S2	Yes	0,30	0,015	0,26
S3	Yes	0,15	0,020	0,26
S4	Yes	0,15	0,015	0,002

Scenarios 1 will look into the case where there is no subsidy for adopting district heating. No subsidy would mean higher investment cost and it is expected to play a role in the transition phase since the cost element is one of the important factors affecting consumer's decision. Moreover, adjusting the subsidy range and analyzing its results would be beneficial for policy makers to set an effective level of subsidy but it is beyond the scope of this study. Scenario 2 investigates how higher renovation rate would impact the energy generation cost as well as the CO2 emission since the purpose of the renovation in this study is to improve building energy performance so that the buildings consume less energy. Scenario 3 assumes that more portion of people who had contacts with adopters will be willing to adopt district heating. Scenario 4 will look at the impact of trust by adjusting the weight trust to a very low level. The variable of weight trust indicates how much trust can be weighted and thus affect the adoption rate from trust in district heating. It has a unit of per year and positively affect the rate of adoption rate from trust by multiplying the variable Trust in DH.

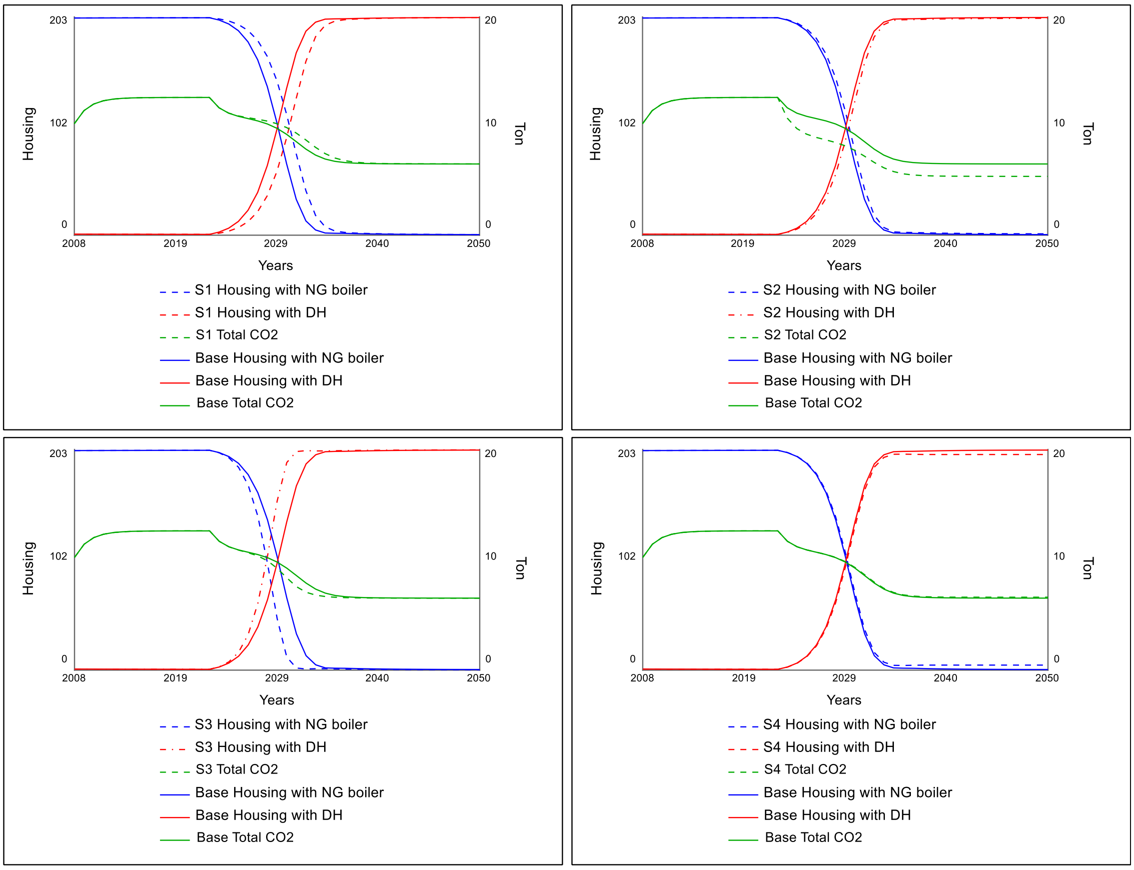

Figure 5. Simulation results of the four scenarios and its comparison to the base case.

The main simulation results of the four scenarios and its comparisons to the base case are presented in Figure 5. Scenario 1 shows that the hundred percent district heating transition is achieved later without subsidy. In other words, an appropriate subsidy scheme can facilitate the speed of such transition. The renovation scenario (S2) indicates that the renovation rate might not be a significant factor for speed up the transition however, the level of the total CO2 emission is lower compared to the base case from the year of introduction of renovation measure. Such measure could be very important in reaching CO2 targets however, the cost of such renovation from a system point of view is not considered in this study. The third scenario (S3) indicates that higher adoption fraction from learning effect can positively affect the speed of the energy transition. This indication aligns with the conclusion of above-mentioned literatures. Since the hundred percent district heating transition is achieved earlier compared to the base case, the total CO2 emission could also be stabilized earlier. Lastly, scenario 4 shows that the weight trust does not play a role in speeding up the transition however, it affects whether all of the housings in the study area would become adopters or there will always a portion of non-adopters remained. It indicates that the high level of individuals trust in a new technology is essential for a complete energy transition.

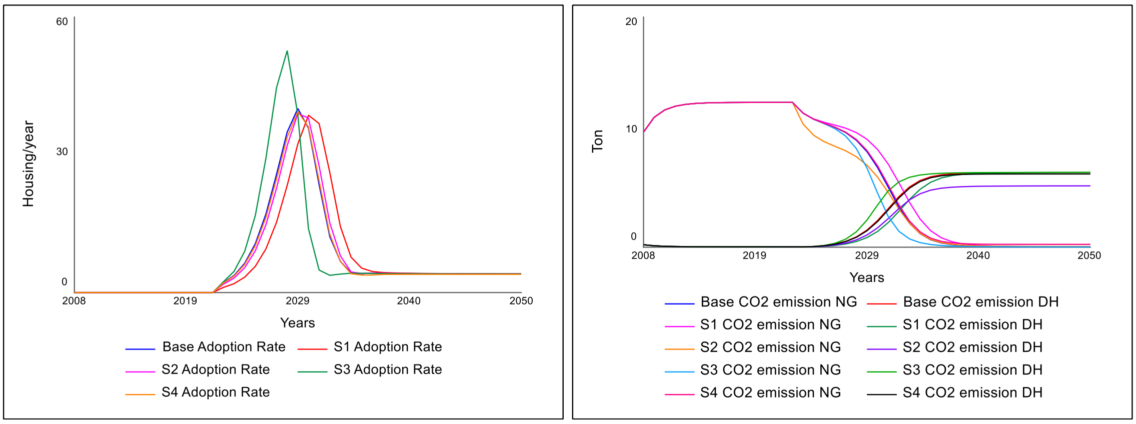

Figure 6. Simulation results of the four scenarios and its comparison to the base case. Adoption Rate in the left-hand side graph means the sum of the three adoption rates: adoption from cost; adoption from learning effect; and adoption from trust in district heating.

Figure 6. presents the adoption rate and the CO2 emission from both natural gas and district heating. Overall, the behavior patterns do not significantly differ from one to another. This kind of scenarios analysis can be a good starting point to discuss policy implications in the next chapter.

4. Discussion and Conclusion

4.1. Policy Implication

The scenario analysis in the previous chapter offers insights on possible policy implementations. First, government's financial support of a certain technology which leads to lower costs can help individuals consider a renewable energy alternative. As individuals would not even consider other heating options when the price is not affordable even if they have high trust on the new technology and enough information to learn about it. Finding an appropriate level of subsidy through sensitive analysis could be a good practice to discuss the specific impact of such subsidy scheme but again, it is not within the scope of this study. Second, extensive renovation measure is helpful for reaching CO2 reduction targets faster. There are different kinds of renovations depending on purpose and in this study, the renovation means deep energy renovation, e.g., improving insulation, using sustainable building materials, which improves energy efficiency. Currently, European Union's recommend its countries to higher the renovation rate from 1,5% of building stock up to 2-3% a year. In this study, it is assumed that 1,5% leads to up to 15% of heat savings even though the renovation cost is not reflected in the model. Third, the scenario analysis shows that the learning effect plays an important role in the speed of transition. It would be helpful if there is a kind of knowledge and experience sharing platform and campaign established at the municipal level where the non-adopters can have a chance to learn about the motivations and benefits of the new technology. This kind of technology adoption behavior of peer to peer through social learning has been already discussed in previous research (Song & Walden, 2003, Huang et al., 2017). Lastly, trust in a new technology is a critical factor in whether all of the housings in the area will be willing to adopt district heating or there will be still a small portion of non-adopters remained. For the individuals to get higher trust in a new technology, citizens should be able to access related information easily. Public seminars and reforming school educational materials to include information on renewable heating would be something to consider for a long-term effect in addition to those knowledge and experience sharing platform and campaign mentioned above.

4.2. Limitations and Future Research

There was only one renewable energy alternative option, i.e., district heating using municipal solid waste, given in the model. However, the municipality is looking into various alternatives depending on their resource and technology availability. Large scale air-source heat pump, electric boiler, geo-thermal, and solar thermal collector are the examples. These different technologies could be formulated in the model using the Array function. Next, the model does not take seasonal variations in heat demand per housing into account, but rather used an annual average value for simplification. Since this could give different dynamics in the system, it could be reflected in future research. Finally, more extensive literature reviews would be beneficial in structuring the model. As an example, individual environmental friendliness which are affected by various demographic features such as education, age, gender, and income etc. would be an interesting adoption factor to look into.

4.3. Conclusion

The aim of this model is to investigate how fast the hundred percent district heating transition will happen in the study area and what are the important factors affecting it. Even though there are several limitations that could be addressed in future research to get more robust and extensive model, this study attempted to suggest useful insights on policy implications. It would be beneficial if the model could be expanded reflecting other elements and applicable for other cases in different contexts.

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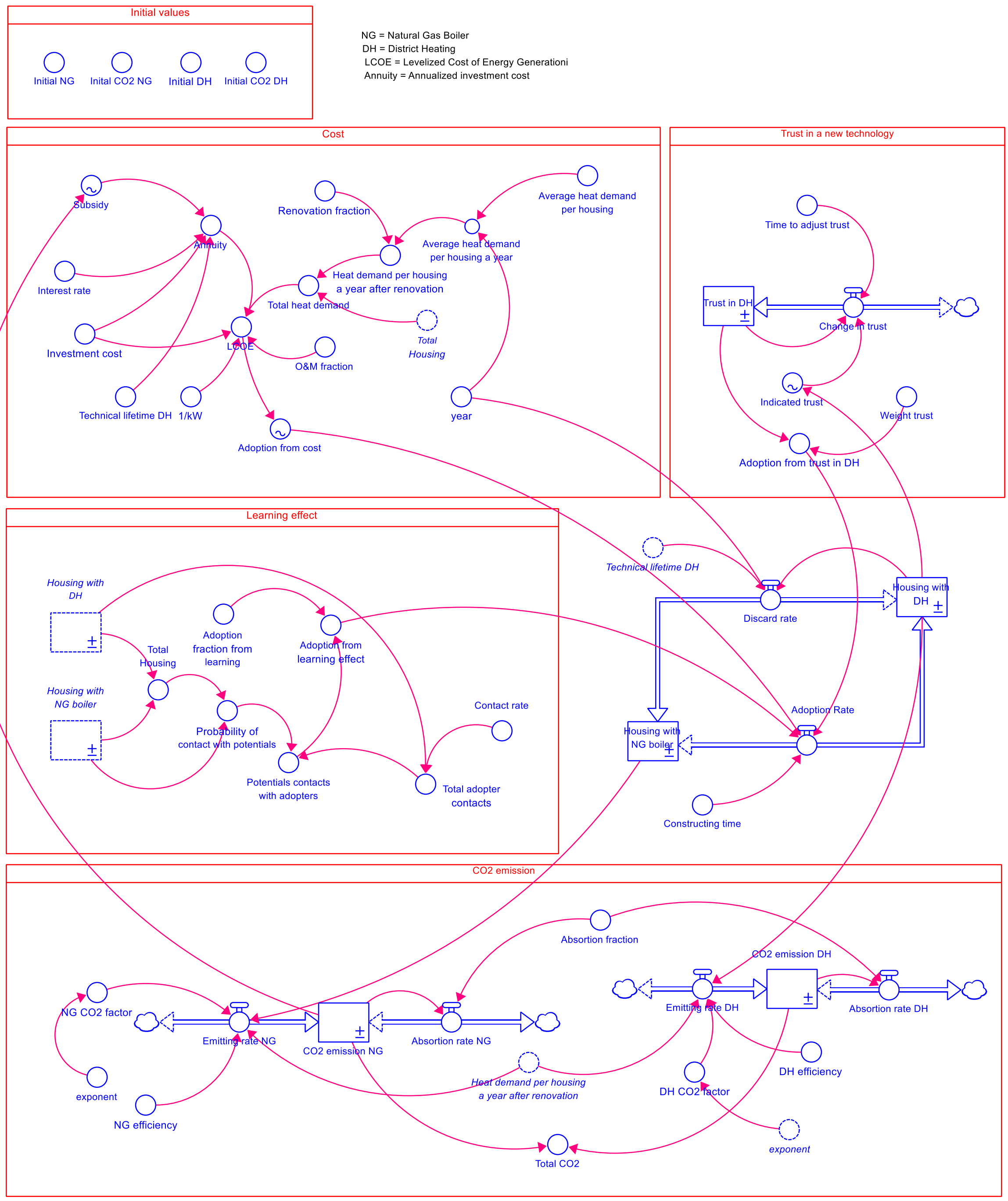
Appendix A. Model Structure



Appendix B. Model Documentation

Adoption_Rate = IF TIME<2022 THEN 0 ELSE ((Adoption_from_learning_effect+Adoption_from_cost+Adoption_from_trust_in_DH)//Constructing_time) UNITS: Housing/year DOCUMENT: Adoption rate is the sum of the three adoption rates from cost, trust in district heating, and learning effect. It indicates the number of housings adopting district heating per year. It is delayed by the constructing time since the full adoption does not happen instantly.
Constructing_time = 2 UNITS: year
Discard_rate = Housing_with_DH/Technical_lifetime_DH/year UNITS: Housing/year DOCUMENT: It indicates the number of housings with district heating discarding it when the district heating pipeline reaches its technical lifetime. The technical lifetime is set to 50 years which is beyond the time horizon of this model therefore, discard rate remains zero.
Housing_with_DH(t) = Housing_with_DH(t - dt) + (Adoption_Rate - Discard_rate) * dt INIT Housing_with_DH = MAX (Initial_DH; 0) UNITS: Housing DOCUMENT: This is the number of housings connected to the existing district heating network in the study area. It can be also expressed as adopters.
Housing_with_NG_boiler(t) = Housing_with_NG_boiler(t - dt) + (Discard_rate - Adoption_Rate) * dt INIT Housing_with_NG_boiler = Initial_NG UNITS: Housing DOCUMENT: This is the number of housings using natural gas boilers in the study area. It can be also expressed as non-adopters.
****
CO2_emission:
****

Absortion_fraction = 0,5

UNITS: 1/year

DOCUMENT: 50% of CO2 emission remains in the atmosphere and the rest is absorbed by land plants or by parts of oceans. It means that 50% of the CO2 emission will be absorbed, i.e., drained out of the CO2 emission stocks.

Absortion_rate_DH = CO2_emission_DH*Absortion_fraction

UNITS: ton/year

DOCUMENT: Outflow of the emission stock. It drains the CO2 by the absortion rate.

Absortion_rate_NG = CO2_emission_NG*Absortion_fraction

UNITS: ton/year

DOCUMENT: Outflow of the emission stock. It drains the CO2 by the absortion rate.

CO2_emission_DH(t) = CO2_emission_DH(t - dt) + (Emitting_rate_DH - Absortion_rate_DH) * dt

INIT CO2_emission_DH = Initial_CO2_DH

UNITS: Ton

DOCUMENT: This shows how much CO2 emission emitted from district heating is accumulated over time. The inflow of emitting rate DH add the emission to this stock and the outflow of absortion rate DH drains the emission out of this stock.

CO2_emission_NG(t) = CO2_emission_NG(t - dt) + (Emitting_rate_NG - Absortion_rate_NG) * dt

INIT CO2_emission_NG = Inital_CO2_NG

UNITS: ton

DOCUMENT: This shows how much CO2 emission emitted from natural gas is accumulated over time. The inflow of emitting rate NG add the emission to this stock and the outflow of absortion rate NG drains the emission out of this stock.

DH_CO2_factor = 70*10^(exponent)

UNITS: Ton/kWh

DOCUMENT: It indicates the amount of CO2 contained in a unit of municipal solid waste.

DH_efficiency = 0,56

UNITS: Dimensionless

DOCUMENT: It is efficiency of the waste incineration plant being used to distribute heat through the district heating network.

Emitting_rate_DH = (Housing_with_DH*Heat_demand_per_housing_a_year_after_renovation/DH_efficiency) *DH_CO2_factor UNITS: ton/year DOCUMENT: Inflow of CO2 emission of district heating to the stock of CO2 emission DH.
Emitting_rate_NG = ((Housing_with_NG_boiler*Heat_demand_per_housing_a_year_after_renovation)//NG_efficiency)*NG_CO2_factor UNITS: ton/year DOCUMENT: Inflow of CO2 emission of natural gas to the stock of CO2 emission NG.
exponent = -6 UNITS: Dimensionless
NG_CO2_factor = 200*10^(exponent) UNITS: Ton/kWh DOCUMENT: It indicates the amount of CO2 contained in a unit of natural gas.
NG_efficiency = 0,97 UNITS: Dimensionless DOCUMENT: It is efficiency of the natural gas boilers.
Total_CO2 = CO2_emission_DH+CO2_emission_NG UNITS: Ton DOCUMENT: The sum of CO2 emission both from natural gas and district heating.
****
Cost:
****
"1/kW" = 1 UNITS: 1/Kw
Adoption_from_cost = GRAPH(LCOE) Points: (0,00187, 5,000), (0,0022, 3,000), (0,00364, 1,000) UNITS: Housing/year DOCUMENT: It indicates the number of housings adopting district heating based on cost. It is assumed that when the LCOE increases, adoption rate decreases.

Annuity = (Investment_cost*(1-Subsidy)) *
(Interest_rate*((1+Interest_rate)^Technical_lifetime_DH)) //
((1+Interest_rate)^Technical_lifetime_DH)-1

UNITS: euro/kW/year

DOCUMENT: Annuity is annualized investment cost. It takes technical lifetime and interest rate into account and gives an annual cost for the investment.

Average_heat_demand_per_housing = 151

UNITS: kWh/housing

DOCUMENT: It means the average heat demand per housing per year. In this study, the housings mean detached houses. For unit's sake, 1/year is separately multiplied with a separate variable.

Average_heat_demand_per_housing_a_year = Average_heat_demand_per_housing/year

UNITS: kWh/Housing/year

DOCUMENT: It indicates the average annual heat demand per housing.

Heat_demand_per_housing_a_year_after_renovation = IF TIME< 2022 THEN
Average_heat_demand_per_housing_a_year ELSE (1-Renovation_fraction) *
Average_heat_demand_per_housing_a_year

UNITS: kWh/Housing/year

DOCUMENT: This is the reduced annual average heat demand per housing.

Interest_rate = 0,04

UNITS: Dimensionless

DOCUMENT: It is the amount of interest due per period as a proportion of the amount lent, deposited, or borrowed.

Investment_cost = 2149

UNITS: euro/kW/year

DOCUMENT: Investment cost to construct the pipeline connecting to the existing district heating network. It is calculated by hand taking the average floor area and the peak heat demand and substation cost for a detached house into account.

LCOE = (Annuity+Investment_cost*O&M_fraction)//(Total_heat_demand*"1/kW")

UNITS: Euro/kWh

DOCUMENT: It indicates that levelized cost of energy generated. It is a useful value when comparing the economic competitiveness of different technologies.

O&M_fraction = 0,02 UNITS: Dimensionless DOCUMENT: This variable indicates the fraction of O&M cost (Operation and Maintenance cost). O&M cost is usually 2% of investment cost.
Renovation_fraction = 0,15 UNITS: Dimensionless DOCUMENT: This value indicates how much heat savings can be achieved, i.e., how much heat demand could be reduced through renovation. In this study, it is assumed that renovation of 1,5% of the building stock per year could reduce up to 15% of the heat demand.
Subsidy = GRAPH(CO2_emission_NG) Points: (0,000, 0,000), (0,200, 0,026), (0,400, 0,035), (0,600, 0,018), (0,800, 0,079), (1,000, 0,132), (1,200, 0,123), (1,400, 0,184), (1,600, 0,228), (1,800, 0,263), (2,000, 0,447) UNITS: Dimensionless DOCUMENT: It is a function of CO2 emission from natural gas. It is assumed that when the CO2 emission especially emitted from natural gas increases, government would take more action, i.e., higher subsidy to lower the cost of renewable energy.
Technical_lifetime_DH = 50 UNITS: Dimensionless DOCUMENT: Technical lifetime indicates the total period of time which a plant can be technically operated before it needs to be replaced.
Total_heat_demand = Total_Housing*Heat_demand_per_housing_a_year_after_renovation UNITS: kWh/year DOCUMENT: By multiplying by the total number of housings, this variable indicates the total annual average heat demand in the study area.
year = 1 UNITS: year
****
Initial_values:
****
Inital_CO2_NG = 10 UNITS: Ton DOCUMENT: The CO2 emissions emitted by using natural gas for heating. The value was calculated by hand.

Initial_CO2_DH = 0,213 UNITS: ton DOCUMENT: The CO2 emissions emitted by using municipal solid waste for district heating. The value was calculated by hand.
Initial_DH = 1 UNITS: Housing DOCUMENT: It indicates the number of housings that are already connected to the existing district heating network from the beginning of the model time horizon. The initial value is set to 1 for the model's sake even though there is no housing in the study area in reality. This is because if the initial value is set to 0, there is no chance for the housings in the area to contact with housings connected to the district heating network. In reality, it would be possible to contact with district heating housings in other areas but in this model, the geographical boundary is set to the study area thus it is assumed that there are no housings outside of the study area.
Initial_NG = 202 UNITS: Housing DOCUMENT: The number of housings that have been using natural gas boilers even before the beginning of the model time horizon. The data is extracted from the Danish Building Registry System (BBR, 2020).
****
Learning_effect:
****
Adoption_fraction_from_learning = 0,015 UNITS: dimensionless DOCUMENT: The probability that an adopter contact converts a potential adopter (the conversion rate).
Adoption_from_learning_effect = Adoption_fraction_from_learning*Potentials_contacts_with_adopters UNITS: Housing/year DOCUMENT: (people contacted by adopters)*(probability of each of those people being a potential adopter)*(fraction that adopt as a result of that contact)
Contact_rate = 100 UNITS: Per year DOCUMENT: This indicates how many contacts the adopters can make per year.

Potentials_contacts_with_adopters = Probability_of_contact_with_potentials*Total_adopter_contacts UNITS: Housing/year DOCUMENT: This indicates how many non-adopters contact with adopters per year.
Probability_of_contact_with_potentials = Housing_with_NG_boiler//Total_Housing UNITS: dimensionless DOCUMENT: This indicates the portion of non-adopters who has potential to adopt district heating.
Total_adopter_contacts = Contact_rate*Housing_with_DH UNITS: Housing/year DOCUMENT: This indicates the number of housings with district heating who get to contact with non-adopters per yer.
Total_Housing = Housing_with_DH+Housing_with_NG_boiler UNITS: Housing DOCUMENT: The total number of housings in the study area. Since there are only two heating options existing in this model, this variable can be expressed as the sum of the number of housings with natural gas boilers and district heating.
****
Trust_in_a_new_technology:
****
Adoption_from_trust_in_DH = Trust_in_DH*Weight_trust UNITS: 1/year DOCUMENT: This indicates how many housings per year would be adopting district heating based on trust in district heating.
Change_in_trust = (Indicated_trust-Trust_in_DH)/Time_to_adjust_trust UNITS: Per year DOCUMENT: This flow indicates the difference between indicated trust and the stock of trust in district heating. It is delayed by the adjustment time "Time to adjust trust" to process new information.
Indicated_trust = GRAPH(Housing_with_DH) Points: (0,000, 0,0133857018486), (0,200, 0,0359724199242), (0,400, 0,0948517463551), (0,600, 0,238405844044), (0,800, 0,53788284274), (1,000, 1,000), (1,200, 1,46211715726), (1,400, 1,76159415596), (1,600, 1,90514825364), (1,800, 1,96402758008), (2,000, 1,98661429815)

UNITS: Dimensionless DOCUMENT: It is a function of the stock Housing with district heating. When the number of housing with district heating increases, indicated trust also increases in the society.
Time_to_adjust_trust = 5 UNITS: year DOCUMENT: It is an adjustment time to process the difference between indicated trust and the actual trust in district heating.
Trust_in_DH(t) = Trust_in_DH(t - dt) + (Change_in_trust) * dt INIT Trust_in_DH = 0,3 UNITS: Dimensionless DOCUMENT: This stock accumulated the level of people's trust in district heating. It is multiplied by the weight trust and it positively affects the adoption rate from trust in district heating.
Weight_trust = 0,26 UNITS: Per year DOCUMENT: This variable indicates how much trust can be weighted and thus affect the adoption rate from trust in district heating.