RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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Gatis ŽOGLA
Doctoral Program in Environmental Science

USING INNOVATIVE APPROACHES FOR MODELING POLITICAL AND TECHNOLOGICAL SOLUTIONS FOR ENERGY EFFICIENCY IN BUILDINGS

Summary of thesis

Scientific supervisor

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**DISSERTATION PROPOSED FOR DR.SC.ING.
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AT RIGA TECHNICAL UNIVERSITY**

This study is proposed for attaining the degree of Dr.sc.ing. in Environmental Engineering and will be defended on 17 December 2012 at the faculty of Power and Electrical Engineering, Kronvalda Boulevard 1, Room 21.

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CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this dissertation, which is submitted for consideration at Riga Technical University, for attaining the degree of Dr.sc.ing. in Environmental Engineering. This study has not been submitted to any other university or institution for the purpose of attaining scientific degrees.

Gatis Žogla …………………………….

Date: ………………………

The dissertation is written in Latvian and contains: an introduction, 3 chapters, conclusions, a bibliography, 4 appendices, 122 figures, 16 tables and 163 pages. The bibliography contains 68 references.

TABLE OF CONTENTS

Background and current situation

Energy consumption in households accounts for 40% of total European Union energy consumption. The existing building energy efficiency level is very low: the average energy consumption for space heating is as much as ten times higher than in passive houses, which are built using the latest technological solutions for energy efficiency.

To promote the energy efficiency of buildings, European Parliament and Council Directive 2010/31/EU on the energy performance of buildings was approved in 19 May 2010. This Directive lays down the requirements for the construction of near-zero-energy buildings and establishes that from 2020 all new buildings must comply with this near-zero-energy level. Each EU Member State has to define what a near-zero-energy building is. To fulfill this task, there needs to be an awareness of the technological solutions that have to be used to move towards near-zero-energy consumption.

To achieve the goal laid down in European Parliament and Council Directive 2006/32/EC on energy end-use efficiency and energy services, i.e. to reduce national energy consumption by 9% by 2016, it is necessary to make many energy efficiency improvements. Since the housing sector comprises mainly Soviet-era apartment buildings, the renovation of existing buildings is very important for increasing energy efficiency in the housing sector, reducing national energy consumption and mitigating climate change. European Union co-financing for building renovation is one of the policy instruments used to encourage the renovation of buildings, but it is important to be aware of other policy instruments and their impact on this process.

Objectives of the thesis

To reduce the energy consumption of buildings and the impact on climate change, it is necessary to investigate the structure and behavior of the energy efficiency market in the housing sector and to develop an innovative technological solution for achieving the policy objectives.

The following research objectives were established:

- carry out a study on the structure and behavior of the housing energy efficiency market, looking at the factors that affect the rate of building renovation and defining the parameters that contribute to changes in the rate of building renovation;

- develop a system dynamics model of the housing energy efficiency market, taking into account the non-linearity of the renovation process and the mutual interaction of various factors and parameters;
- based on this system dynamics model, consider, the impact of various policy instruments on building renovation, looking at whether it is possible to achieve the reduction in energy consumption in the housing sector laid down in the First Latvian Energy Efficiency Action Plan;
- develop a technological solution that uses the water phase transition latent heat and contributes to the development of near-zero-energy buildings;
- construct an experimental rig to help determine the impact of the technological solution on the energy consumption of buildings.

Research methodology

The methodology of the thesis is divided into two interrelated parts:

1) development of a system dynamics model of the housing energy efficiency market. This was done during project " System thinking integration in environmental policy", funded from the European Economic Area Financial Mechanism. The system dynamics model was constructed in the Powersim software environment;
2) development of a theoretical model and experimental rig of a water wall. When developing the theoretical model of the water wall, the methodology for determining system sizewas examined by looking at the reduction of heat loss through the building envelope and at the heat recovery from a low-potential heat source. A dynamic hourly theoretical model of the water wall technology was created in MS Excel. The development of the experimental rig and the heat flux density and temperature distribution measurements allowed the efficiency and operational constraints of the new technological solution to be established.

Scientific significance

This thesis examines the structure and behaviour of the the housing sector energy efficiency market. Based on the results of this research, a system dynamics model of energy efficiency in the housing sector market was designed in the Powersim environment. Modeling and validation of the model enabled theinfluence on the building renovation rate of various building energy efficiency policy instruments to be determined.

A technological solution using the latent heat of the water phase transition and reducing the energy consumption for heating and cooling in buildings was created.

Practical significance

This doctoral thesis is of great practical importance. The results of this work are intended for different target groups:

• policy Planners: this thesis deals with various policy tools and their impact on the the rate of building renovation. The results can be used for planning policy on the energy efficiency of buildings and for modeling the impact of the policy instruments chosen;

• energy service companies: this thesis deals with the impact of energy service companies on building renovation. Using the system dynamics model, it is possible to identify measures that promote the entry of energy service companies onto the building renovation market;

• energy efficiency technology manufacturers: the technological solution developed in the thesis can be used to decrease the energy consumption of buildings. Energy efficiency technology manufacturers are interested in the development and implementation of innovative solutions.

• building residents: this doctoral work contains solutions that help to reduce the energy consumption of buildings. Reduced energy consumption means that building residents have less to pay for space heating and cooling.

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1. System dynamics model for modeling building energy efficiency policy instruments

This chapter describes the Latvian housing sector and its energy efficiency. A system dynamics model was developed to analyse the impact of various policy instruments on the energy efficiency level in buildings. This model analyses existing energy policy instruments and policy instruments that have not yet been used in Latvia for improving energy efficiency in buildings.

The insulation process for multi-apartment buildings in Latvia up till now has taken place very slowly, and significant changes over time are not noticeable. This is why a representation of hypothetical problem behaviour is used to define a problem. The selected time period for the model is 70 years (from 2010 to 2080). The period to 2010 is not being reviewed as changes in the multi-apartment building insulation process have been minor. It has been assumed that 70 years is a sufficiently long period to be able to evaluate delays and the effect of the policy used.

Dynamic hypothesis development

The building insulation process is in a technology diffusion in market – technology spreads in the market along an S-shaped curve: initially technology is accepted slowly, followed by an exponential growth and the attainment of an asymptotic stability. In real life the maximum is never reached. The structure which creates the S-shaped growth, is a combination of positive and balancing feedback loops – both loops struggle over the dominance until the struggle ends with a long-term equilibrium.

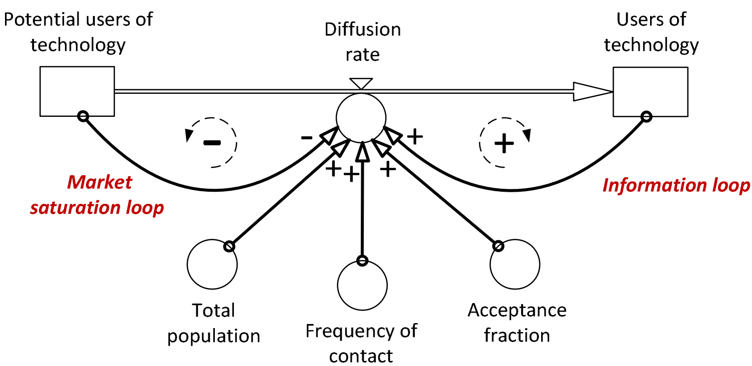

Fig. 1.1. General technology diffusion model

Figure 1.1. shows a general technology diffusion model formed by two stocks – potential users of technology and users of technology. The flow which regulates the growth in the numbers of users is diffusion rate and depends on the total population, the frequency of contact and percentage of acceptance. Potential users of technology make contact with others who have already introduced the technology. The frequency of contact describes how often representatives of both groups are in contact with each other. A number of these contacts will be successful, and potential users will begin to use the new technology, but a number don't. The acceptance fraction describes how many potential technology users who have been in contact with technology users begin using the new technology. The reinforcing loop is the information spreading loop, but the negative one – the market saturation loop: initially information spreads about the new technology which boosts the diffusion speed, but its operation is dampened by the balancing loop, which begins to operate at the moment when the market is approaching saturation.

Main variables

At the base of the multi-apartment building insulation process dynamic hypothesis is the general diffusion model, which is supplemented by a number of reinforcing loops

The main stocks are uninsulated buildings (m2) and insulated buildings (m2). The flow, which brings these stocks together is the rate of insulation. This is dependent on a number of parameters:

1) Awareness – just like in the general diffusion model, this parameter creates a reinforcing loop – as the number of insulated buildings increases, the frequency of contact between insulated and uninsulated building residents grows, as does the number of residents of uninsulated buildings who accept and introduce the idea of building insulation.
2) Net benefit – each individual's benefit from building insulation, which is made up of the difference between energy costs before insulation and energy costs after insulation, plus investment in the building's insulation. This parameter forms the other reinforcing loop – the more insulated buildings and the lower the insulation costs, and the higher the quality of the insulation work, the more the buildings will get insulated.
3) 4) Uncertainty costs – in reality the maximum possible net benefits aren't often reached, as many factors (barriers) exist which substantially reduce the net benefits – the reduction in energy use is noticably lower than calculated as the quality of the construction work is very low; the real insulation costs exceed the quote; a lot of time is wasted in

overcoming administrative barriers connected with the building insulation process; a lot of time is wasted in convincing apartment owners to agree on the insulation of a building; time is wasted searching for funding etc. The more of these factors there are, the greater the uncertainty costs. Uncertainty costs are the expression in money terms of the existing barrier to building insulation. For example, to overcome the distrust barrier – how much money a person living in an uninsulated building wishes to receive in order to agree with his neighbours about a decision to insulate a building. Figure 1.2. shows energy costs before energy efficiency measures and costs after energy efficiency measures. These are made up of the sum of energy costs after the building's insulation, investments and uncertainty costs. For a person to choose to insulate a building, the costs before energy efficiency measures must be larger than or equal with the costs after the introduction of the measures. If the costs after the introduction of the measures are greater than the costs before, then most likely the building will not get insulated

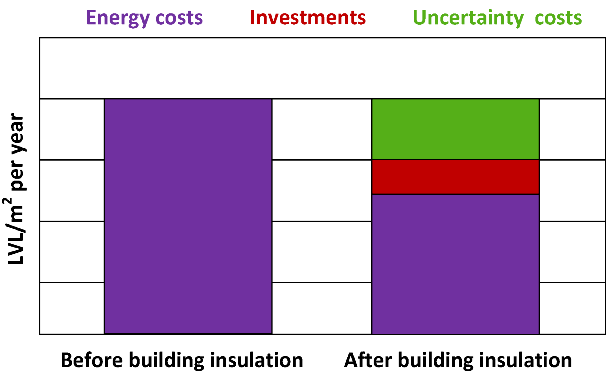

Fig. 1.2. Costs before and after energy efficiency measures

The net benefits are of varying size as they're dependent on a variety of factors which change over time: energy tariffs, outside air temperature, inside temperature and insulation costs. A person is unable to immediately perceive the change in the net benefits – this takes time. That's why an additional stock is created in the system – perceived net benefits (information, which is accumulated in a person's mind). The rate of perception is dependent on the perception time. This time period, which is required for the perception and processing of information and action after receiving the information, creates information delay.

Like net benefits, a person also perceives uncertainty costs, processes them and acts, and this process needs time, creating a information delay in the system and that's why the fourth stock is the perceived uncertainty costs.

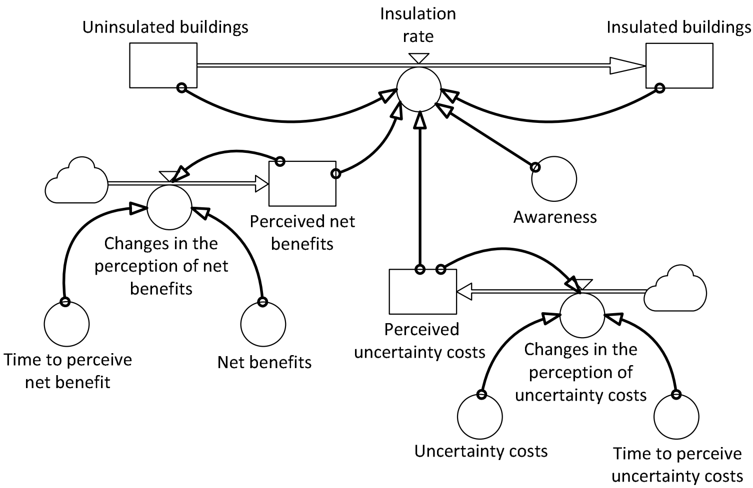

Fig. 1.3. Structure of a hypothetical building insulation system

Figure 1.3. shows the hypothetical system's structure: the stocks, the flow, the main parameters and the feedback loops.

Causual loop diagram

The hypothetical system's structure, which is transformed in the causal loop diagram, can be seen in Figure 1.4., and it illustrates the hypothetical system's structure's main loops.

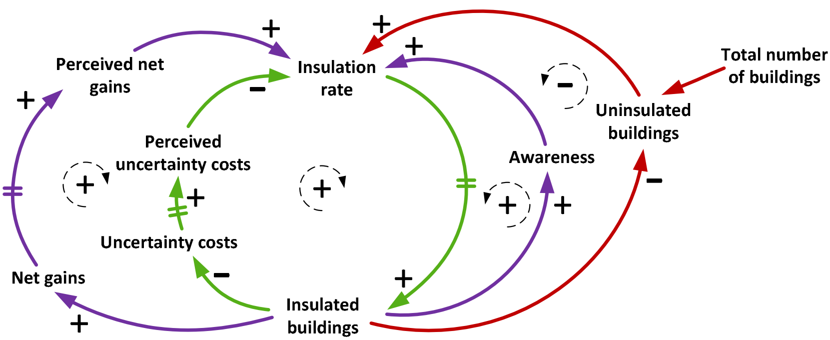

Fig. 1.4. Causal loop diagram for building energy efficiency process

The diagram consists of three reinforcing loops and one balancing loop. The most important parameter in these loops is the rate of insulation – that is, the decision to start the insulation process. With an increase in the number of insulated buildings in reinforcing loop P1 (net benefits loop), the net benefits increase. Time passes from the real situation and the moment when it's perceived by a person's brain, with this period often being relatively long, which is why a information delay occurs. In the model this delay is pictured in the loop between net benefits and perceived net benefits. This delay can even last for many years, and the possibility of some people completely ignoring this information exists. With an increase in net benefits, perceived net benefits increase, but, with an increase in perceived net benefits, the rate of insulation increases. With an increase in the rate of insulation, the number of insulated buildings increases, but this happens with a delay, as time passes while organizational and building insulation work gets done (material delay). Many ignore this loop, and that's why the process takes place very slowly.

With an increase in the number of insulated buildings in reinforcing loop P2 (uncertainty cost loop), uncertainty costs decrease. Between the real situation and the moment when it's perceived by a person's brain, time passes, and often this period is relatively long which is why a information delay occurs. In the model this delay is pictured in the loop between uncertainty costs and perceived uncertainty costs. This delay can even last for many years, and the possibility of some people completely ignoring this information exists. With a decrease in uncertainty costs, perceived uncertainty costs decrease. With a decrease in uncertainty costs, the rate of insulation increases. With an increase in the rate of insulation, the number of insulated buildings increase, but it occurs with a delay (material delay).

With an increase in the number of insulated buildings in reinforcing loop P3 ("word of mouth" or the information distribution loop), resident awareness increases. With an increase in awareness, the rate of insulation increases. With an increase in building insulation, the number of insulated buildings increase, with a delay.

Balancing loop N slows down all three reinforcing loops with a delay. With an increase in the number of insulated buildings, the number of uninsulated buildings decreases, that's why the rate of insulation decreases, as there are no longer buildings to insulate. The number of uninsulated buildings is affected by the overall number of buildings. This loop comes into operation very late – it operates at the very end of the diffusion process.

Policy development and testing

The causal loop diagram shown in Figure 1.5. is the same causal loop diagram shown in Figure 1.4., which is supplemented by various policies. They are utilzed to change three parameter values: to increase net benefits, reduce uncertainty costs, increase awareness and investment in insulation.

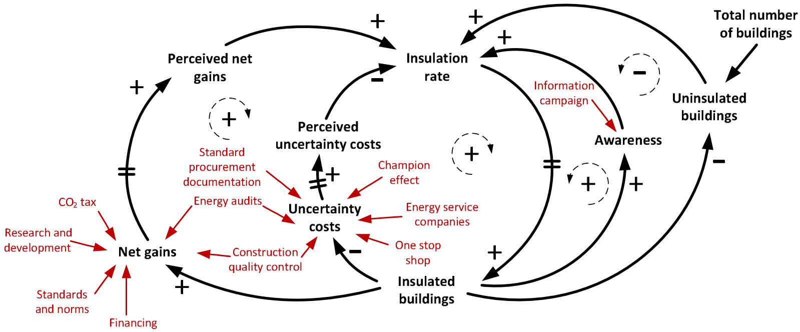

Fig. 1.5. Causal loop diagram, supplemented by policies

It is possible to increase the net benefits under these conditions:

- If energy use standards are developed – the minimum specific energy consumption (kWh/m^2 year) for the insulation of existing buildings is determined by legislation for various buildings, e.g., new buildings. This is a way of ensuring that energy consumption is reduced to the required level – this prevents the possibility that the material or technology used in building construction or insulation provides only a small reduction in energy consumption, thereby reducing potential net benefits.
- If high quality energy audits are done – an energy audit is the first step in the introduction chain of energy efficiency measures, and all of the subsequent process is dependent on its quality. A badly done energy audit provides misleading information about the theoretically achievable reduction in energy consumption and the cost which is required to achieve this reduction. The lower the quality of the energy audit, the smaller the net benefits. That’s why it’s necessary to develop a system in the nation, which guarantees the control of the conduct of energy audits – a national level institution should supervise energy auditors and their work and punish those who do bad quality work. Such a system has successfully functioned in Finland for many years.
- If research and development is supported – this is a policy measure, the operation of which, is visible in the long term. The creation of new technology and materials which would allow a greater reduction in energy consumption than is provided by current technology would increase net benefits. A targeted national programme supporting research and development is required for the introduction of this instrument.

- If standard procurement documentation and contracts are developed – the quality of construction is one of the most important factors influencing net benefits. This is directly dependent on the building owner's and the construction company's mutual legal relationship, the core of which is the building owner's demands on the reduction in energy use attainable and the quality of the insulation work. If this isn't included in the procurement documentation, it's very likely that net benefits will be much lower than planned. Standard procurement and contract documentation must be developed at a national level and made available to every building owner to remove this barrier.
- If construction supervision is done – in Latvia experience in building insulation shows that it's not possible to achieve the planned savings due to low construction quality, with the net benefits being lower than those theoretically possible. This shows that the services of construction supervisors have either not been used in the insulation process or they have been of low quality. A system should be developed to overcome these barriers, ensuring that the work of construction supervisors is controlled – a national level institution which supervises the work of construction supervisors, and punishes those who do bad quality work.
- If subsidies are introduced – this is a policy instrument which directly influences net benefits: the greater the subsidies, the greater the net benefits.
- If the tariff is increased – the tariff is increased through the introduction of a CO2 tax: the higher the tax, the more savings there are after a building's insulation with the net benefits being higher.

By reducing uncertainty costs, building insulation process barriers which are connected with people's distrust that are based on incorrect, or a lack of information, are reduced. Barriers can be reduced in several ways:

- By conducting high quality energy audits – building owners, who are not specialists in the energy efficiency area in most cases, require objective information about what kinds of measures can be undertaken and what the planned costs and energy savings could be. That's why energy audits providing this information are required. For them to be credible, energy audits must be of a high quality and that's why a system needs to be created nationally, ensuring that the conduct of energy audits is controlled – a national level institution supervising the work of energy auditors and their work, and punishing those who do bad quality work. This will reduces uncertainty costs.
- Increase construction works quality control – one of the main barriers to the introduction of insulation project is the risk of low construction quality associated with it – building owners are afraid to commence insulation, as a great risk of low quality construction work exists, and

energy consumption will not be reduced as planned. This in turn affects the future flow of money and will impact on plans for paying off loans. The higher the risk, the higher the uncertainty costs. That's why measures must be taken at the national level to reduce this risk, for example, by the improvement of construction monitoring, creating an institutional and legislative base which can successfully address this problem.

- Raise the awareness level –uncertainty costs are reduced with an increase in the awareness level because the building insulation process is explained with the help of information. The benefits, risks and the other information required by a building owner to be able to decide to insulate a building is provided.
- By developing a one stop shop – one of the barriers raising uncertainty costs is connected with negotiating the bureaucratic hurdles in the course of the insulation process. The approval of project documentation by local councils is included in this. Local councils could set up one stop shop as the only contact point with local council representatives, therby eliminating these hurdles.
- Using the "champion effect" – a popular and influential person in the community provides a positive view about the problem's solution and everyone follows suit – this will immediately reduce uncertainty costs.
- Using (ESCO) energy service company services – an ESCO signs a contract for a defined period, investing its resources and recovering these from the saved energy costs. Savings in uncertainty costs are reduced to zero as they eliminate all of the mentioned barriers. With the use of ESCO the net benefits are zero.

One of the hurdles in the building insulation process is the size of available investments. This can be increased by taking measures which attract or channel financing for building insulation.

Model structure's principal scheme

Various leverage point application methods are used for the inclusion of policy measures in the model – changing constants and parameter values, material stocks and flow structures, system regulations, the information flow structure and by strengthening reinforcing loops. That's why the initial model structure has been changed, with its principal scheme being shown in Figure 1.6.. The stock of uninsulated buildings in the decision making process is divided into two groups – buildings insulated by energy service companies, and buildings insulated by construction companies. Not all buildings insulated are successful projects, and information about these, as well as the successful projects enters the market, being received by those building owners who have not insulated their buildings. This information influences the uncertainty cost value – the more unsuccessful projects, the higher the uncertainty costs and the fewer buildings get insulated. The rate of insulation is dependent on demand and supply both for energy service companies, as well as for construction companies, but there are different factors affecting them. Construction company supply is dependent on company capacity, but the supply by an energy service company - operations, information, net benefits and uncertainty costs. The scope of net benefits can be changed by making changes to tariffs, introducing a CO_2 tax, by funding research and development, raising standards and norm requirements and through the receipt of finance or subsidies. Uncertainty costs can be reduced by the introduction of a one stop shop, the "champion effect" and the availability of standard procurement documentation. Information about unsuccessful insulation projects ends up with quality control institutions which take action to improve construction company operations, and indirectly increase net benefits and reduce uncertainty costs. With energy service companies, supply is dependent on company capacity and available funding, but demand – on construction company operations and uncertainty costs. Information campaigns can be used to begin and encourage the insulation process.

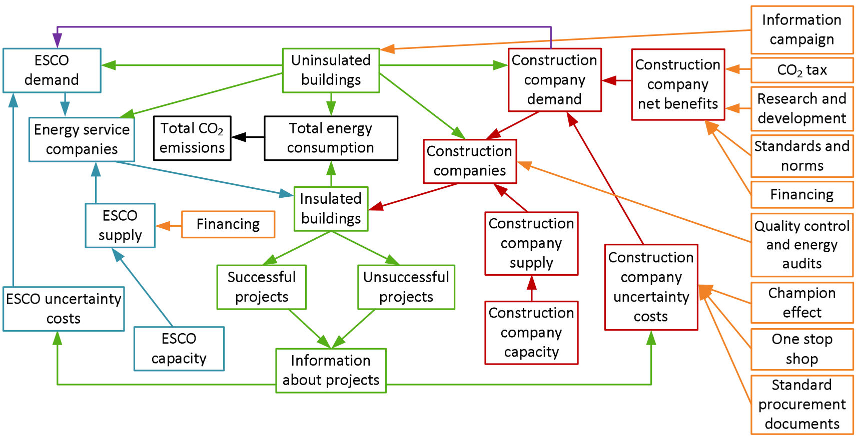

Fig. 1.6. The altered principal scheme of the initial model structure

Systemdynamics model was created using Powersim software environment. One of the submodels (Insulation diffusion submodel) of the model can be seen in Figure 1.7.

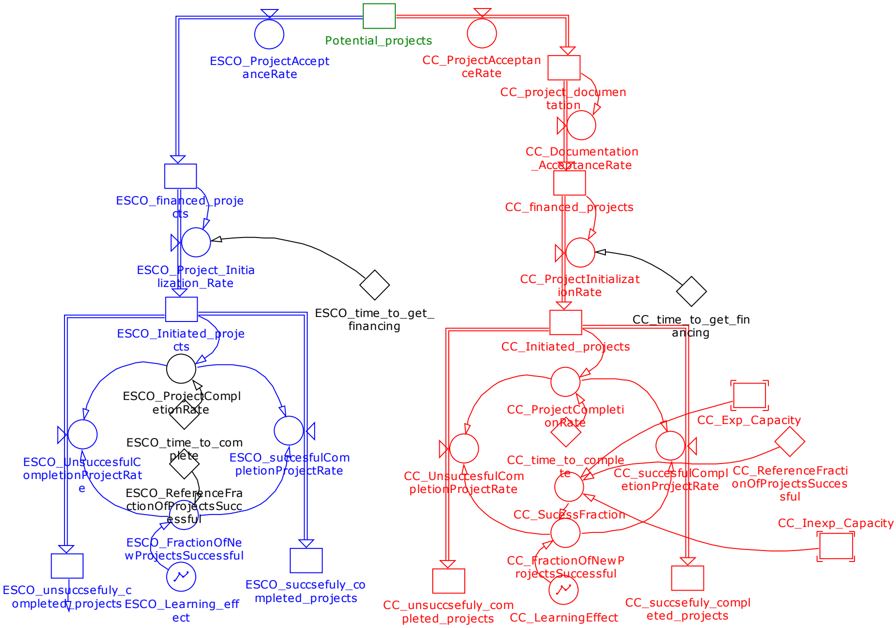

Fig. 1.7. Insulation diffusion submodel scheme

In the insulation diffusion submodel it can be seen how uninsulated buildings turn into insulated buildings. Insulation of buildings can be done wether by building companies or ESCO's (Energy Service Companies). The rest submodels, the whole model and mathematical relationships between different parameters and flows are shown in the full version of this PhD Thesis.

Results

The goals of the building energy efficiency system dynamic model are:

- to simulate the policy measures result described in Latvia's First Energy Efficiency Action Plan and to determine whether the goals set in the plan are achieveable;
- to analyze the impact of the policies not included in Latvia's First Energy Efficiency Action Plan on the insulation process.

Existing energy efficiency policy analysis

The main measures of the current policy are the attraction of EU co-financing for increasing building energy efficiency, the undertaking of energy audits in buildings and building energy certification, providing information to energy consumers, as well as the development of legislation for energy efficiency increases in buildings in accordance with Directive 2002/91/EC on the energy performance of buildings and requirements on energy efficiency laws.

In 2010, Latvia's government confirmed that the size of EU structural funds available for multi-apartment building insulation was around 44 million lats. In the evaluation of current policy, the other measures are not taken into account as their separate impact in the action plan has not been analyzed, and that's why the expected energy saving after informative events and the development of normative documents has been determined for the sector as a whole. The saving is calculated based on the number of participants involved in the campaign and the evaluation of the influential part of the implemented activities in the sector, when compared with a base scenario where such events were not undertaken. By entering the current situation's introductory values in the model, a result was obtained which can be seen in Figure 1.8. A significant increase in the rate of building insulation is predicted around 2014 through the use of energy efficiency policy measures. Around 2022, the rate of building insulation tails off, as the available co-financing for building insulation will have been exhausted, and the building insulation process will continue slowly. As result buildings with a total area of 16.5 million m2 will have been insulated by 2080.

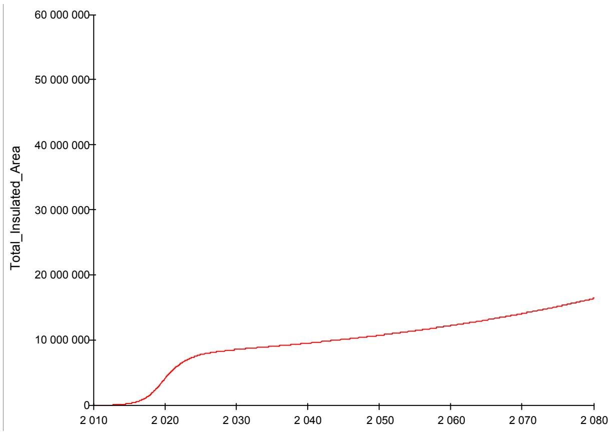

Fig. 1.8. Rate of expected building insulation as a result of current energy efficiency policy

The parameters which directly influence changes in the area insulated are looked at in order to analyze the impact of energy efficiency policy on the building insulation process in more detail. In the model, these are demand for building insulation and the supply of building insulation or construction company capacity. Figure 1.9. shows building insulation demand and changes in supply if the policy measures mentioned in the LR First Energy Efficiency Action Plan are used. In it one can see that demand for building insulation in the first five years grows rapidly and after that tails off. This large demand for building insulation can be explained by the available co-financing for building insulation. In Latvia building insulation co-financing has been available since 2009, and that's why when looking at the number of applications submitted for project co-financing at the Investment and Development Agency of Latvia, one can see that the real growth trend in application numbers is similar to the model's predicted result – initially the number of applications is smaller and gradually increases even though no significant changes in the regulations for receiving co-financing have been made. Construction company capacity or building insulation supply is unable to cope with the large demand due to delay and only reaches demand after eight years. The fall in demand is connected with the expiry of available co-financing and the growth in the insulated building area.

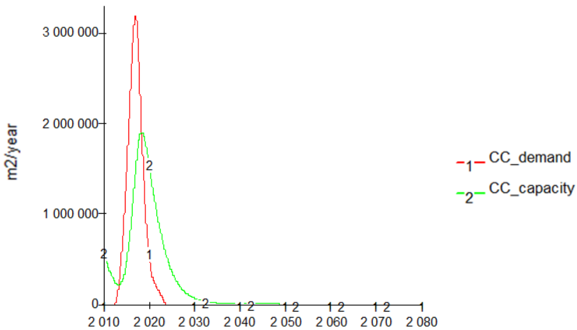

Fig. 1.9. Building insulation demand and supply changes with current energy efficiency policy

A situation where EU financing is not available was modelled in order to evaluate the impact of an increase in available co-financing for building energy efficiency on the rate of building insulation. The result of this analysis is shown in Figure 1.10. In it one can see that without co-financing (No.2 in the chart), the building insulation process takes place at a constant rate as building insulation is not stimulated. In Figure 1.10., one can see that after all the EU structure fund co-financing has been used (No.1 in the chart), the building insulation process takes place at the same rate as if building insulation had not received ES structure fund co-financing (No.2 in the chart).

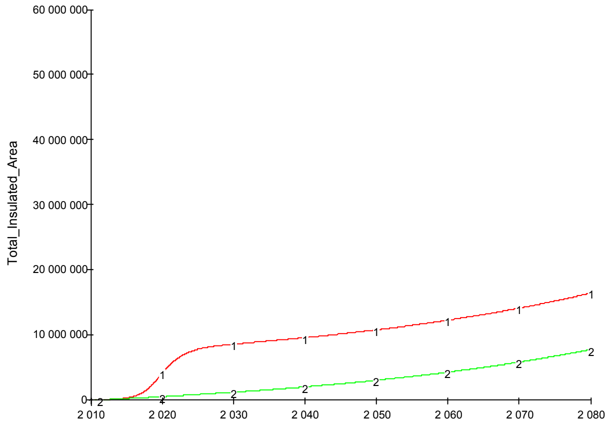

Fig. 1.10. Rate of building insulation with EU structure fund co-financing (No.1 in the chart) and without it (No.2 in the chart)

The goal defined in Latvia's First Energy Efficiency Action Plan is a reduction of energy use in the residential sector of 2701 GWh by 2016. The heating energy consumption benefited, using the energy efficiency policy defined by the energy efficiency action plan, is indicated by the model in Figure 1.11. In it one can see that in 2010, the heating energy consumption used for heating all buildings is 10,800 TWh year, but, using the policy measures mentioned in the action plan, the heating energy consumption in 2016 will be 10,745 TWh year. That means, that it is possible to save only 55 GWh in this period, which is 2% of the planned saving. The required reduction in consumption using this policy, could not even be achieved by 2080. This proves that these aren't the only policy measures which can be used in energy efficiency policy to achieve the planned goals in Latvia.

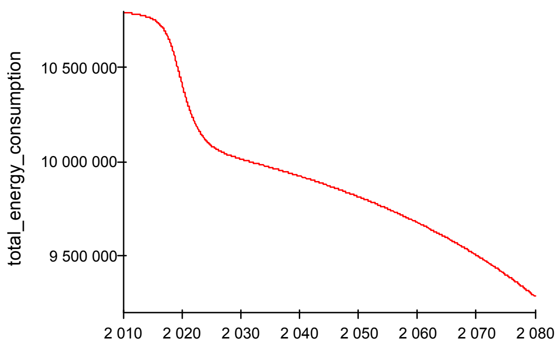

Fig. 1.11. Heating energy use changes (MWh year)

Analysis of possible energy efficiency policy

To determine the impact of various energy efficiency policies on the rate of building insulation and a reduction in energy consumption, introductory values of factor are changed in the created model's submodels, strengthening or weakening the specific energy efficiency policy. All energy efficiency policies supplement the energy efficiency policy, offered by Latvia's First Energy Efficiency Action Plan.

In 2010, all building heating energy consumption was 10,800 TWh year, but by using all the mentioned policy measures simultaneously, heating energy consumption could be 10,217 TWh year. This means that it is possible to save only 583 GWh by 2016, which is 21.6% of the planned saving. The required reduction in consumption using this policy could only be achieved about 2019. That proves that that these aren't the only policy measures which should be used in energy efficiency policy to achieve the planned goals in Latvia. Table 1.1. shows each individual energy efficiency policy's impact on energy consumption in buildings in 2016 and the implementation of Latvia's First Energy Efficiency Action Plan.

Table 1.1.

Each energy efficiency policy's impact on buildings by 2016

No.	Energy efficiency policy	Total building energy consumption in 2016, GWh	Energy savings by 2016, GWh	Implementation of First Energy Efficiency Action Plan, %
1.	Development of one stop shop	10710	90.0	3.3%
2.	Introduction of CO2 tax	10713	86.9	3.2%
3.	Increase in minimum energy efficiency requirements	10745	55.1	2.0%
4.	Increase in research and development support	10648	152.0	5.6%
5.	Development of standard procurements documentation and contracts	10706	93.3	3.5%
6.	Introduction of	10732	68.1	2.5%

	information campaign			
7.	All energy efficiency policies simultaneously	10217	582.5	21.6%
8.	Only ERDF co-financing	10745	55.1	2.0%

Figure 1.12. shows all energy efficiency policies and their impact on the area of buildings which are insulated.

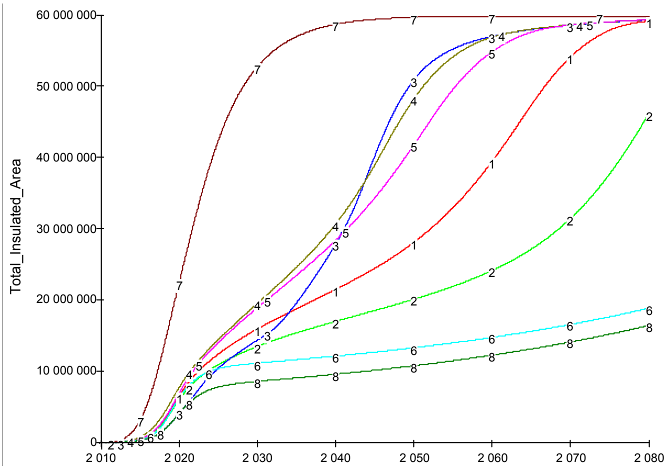

Fig. 1.12. All energy efficiency policies (Numeration in accordance with Table 1.1.)

In the figure total insulated area of buildings and the rate of insultion change can be seen. Practicaly all policy instruments need tame to reach considerable insulation rate.

Validation of the model

Since the building renovation process in Latvia has started relatively recently, the validation of the model with historical data is difficult. The developed system dynamics model was validated using available data from the Latvian Investment and Development Agency, which oversees all financing of household renovation with European structural funding.

The model validation data shows that the developed system dynamics model works adequately and simulation results can be used for modeling policy instruments on energy efficiency in buildings.

2. Water wall for reducing buildings energy consumption

To promote the development of zero energy buildings, it is necessary to develop new technological solutions for minimizing building energy consumption. This chapter describes an innovative technological solution, which makes it possible to significantly reduce building's energy loss by heat conduction through the building envelope in cold climatic conditions. The innovative technological solution includes the use of latent heat of water phase transition and the recovery of the lost energy using low-potential heat sources (such as ground heat).

Description of the proposed technological solution

This section describes the technological solution the aim of which is to reduce the space heating and cooling energy consumption in the building. Chapter describes the principles of operation of the model and processes that are happening during the operation. Assumptions, which have to be fulfilled while calculating processes that are happening in the new technological solution that decrease heat energy consumption of the building, are defined.

It is proposed to install circulating water layer on the external surface of the building envelope. The aim of this water layer is to reduce heat loss through the outer envelope of the building. Despite the fact that the outside air temperature varies and in Latvia during winter it can drop to -30 ^{0}C, the temperature on the outer wall remains constant, which is due to the fact that the water is freezing at 0 °C. During the freezing of water large amounts of energy (latent energy) are released, which can be used to reduce heat conduction losses through the building envelope.

Principle of operation of the techological solution

Latvian winter conditions tend to have very dramatic outdoor temperature fluctuations, which affect the heat loss through the exterior walls of the building. Heat transfer through the walls of the building are affected by the thermal resistance of the walls and the temperature difference between the outside air and room. The higher the thermal resistance of the walls of the building, the lower the heat loss. The lower the temperature difference between the two environments, the lower the heat loss. In Latvian weather conditions the temperature difference between indoor and outdoor air can reach up to 50 ^{0}C, therefore, to provide a high thermal resistance and low heat losses, the buildings have to be built with thick walls.

In this thesis it is proposed to insert a heat source into the wall. The function of the heat source would be to ensure a constant temperature on the outer surface of the wall of the building, regardless of the outdoor temperature. The main components of the system are the ground circuit and the water layer on the external surface of building envelope. In winter conditions when the lowest outdoor temperatures are observed, the water layer prevents the outer wall temperature to drop below 0 ^{0}C. This is achieved by water flowing along the wall and giving off the stored latent heat. It is assumed that part of the latent energy of water moving from the liquid phase to the solid phase will be used. The expected result is that at the initial moment τ_0 and the initial temperature t_0, which is higher than the crystallization temperature of water T_{KR} = 0 ^{0}C, water begins to flow downwards from the upper edge of the wall. At a certain point in time τ water has cooled to crystallization temperature T_{KR} and the releasing of the latent energy at a constant temperature begins. After a while water reaches the lower part of the wall, and has given off part of the latent energy of water-ice phase transition. At this point it is expected that instead of pure water a water-ice mixture will flow along the wall where water and ice mass ratio is the same as the used latent energy component. For example, if 1 kg of water flows along the wall and gives off 20% of its latent heat, it is expected that the obtained water-ice mixture will be composed of 800 g of water and 200 g of ice. In the developed calculation model the amount of latent energy used during solid - liquid phase transition is included as one of the variables.

Once the water has released part of the latent heat of fusion of phase change it flows into the ground loop where it recovers the amount of energy that was lost while water was flowing along the wall.

Structure of the system

The whole system consists of two separate systems. One is located on the external facade of the building, it will be referred to as a water layer or water wall and the other is that part which ensures the recovery of heat through the ground heat exchanger, which in turn will be called a ground loop. These are not the only systems that ensure functioning of the whole system. In the middle of these systems is a system that provides heat carrier circulation in the ground loop and on the wall. This system includes components such as a circulation pump and expansion vessel. Expansion vessel is required to compensate for the increase in volume which happens in the result of water changing from liquid to solid phase. The main system, which affects the rest of the system operation, is located on the external facade of the building. Schematically, it can be seen in Figure 2.1.

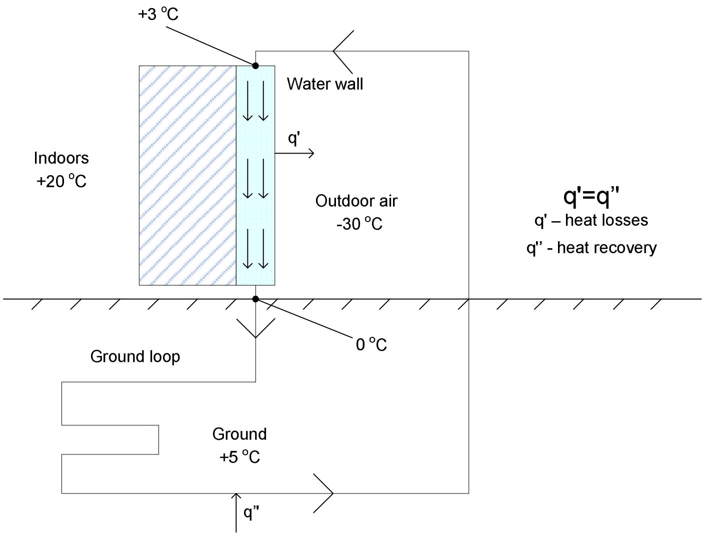

Fig. 2.1. Structure of the whole water wall system

The operation of circulation circuit system depends from the losses through walls. The bigger the losses, the faster heat carrier has to circulate through the system components to prevent heat carrier from freezing and to ensure efficient heat recovery.

It is expected that in summer the operation of the system will be different. Heat carrier serves not as a heat source, but as a heat sink. Heat carrier with the accumulated heat from the walls flows to the ground heat exchanger and heat is stored in the ground, so the heat carrier is cooled and prepared for recirculating to the wall. Heat carrier can be cooled down to about 8 ^{0}C.

Algorithm for reching the set target

To develop a new technological solution that uses the latent heat of water phase transition and reduces heat losses in buildings, an algorithm of operations for achieving the set target was designed.

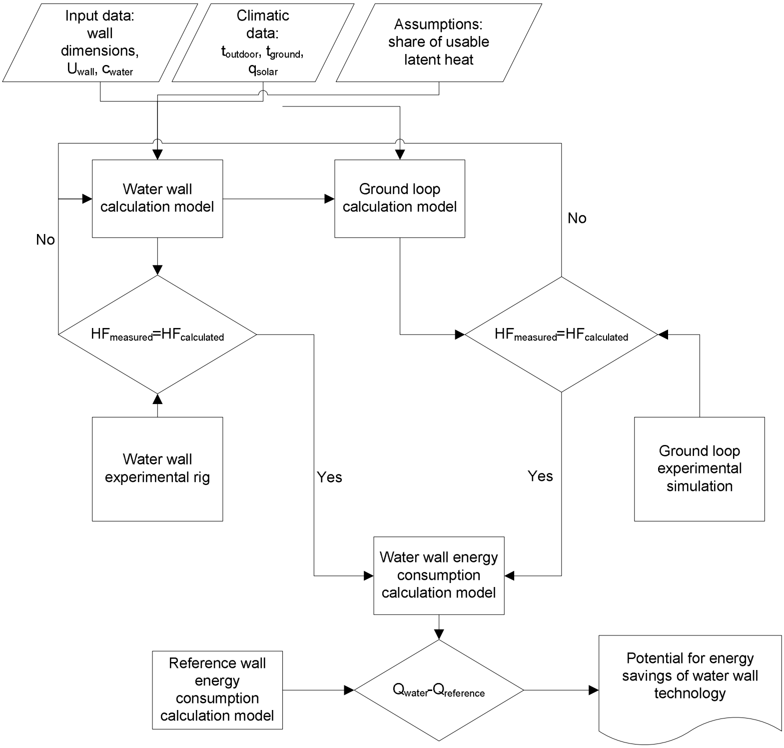

Fig. 2.2. Algorithm for developing the innovative technological water wall solution

Two water wall system calculation models were created for determining the potential for reducing energy consumption of water wall technology:

1. Water wall calculation model - to reduce the losses through heat conduction;
2. Ground loop heat exchanger model - heat recovery of the lost latent energy of phase transition.

Measurements for validating both calculation models were carried out. The calculation model is validated if the calculated heat flux ($HF_{calculated}$) in the building envelope coincides with the measured heat flux ($HF_{measured}$).

After validating both calculation models using measurement data, a dynamic calculation model for two walls (with water wall and without water wall) was created. The dynamic calculation model allowed to calculate the potential of energy savings of he new water wall technological solution.

Development of energy consumption model

After development of water wall calculation model and validation of this model with experimental data, energy consumption model for showing the potential of energy savings of the new water wall technological solution was made.

The energy consumption model was developed for a wall with the area of 32 m^2 (4m x 8m). Such wall dimensions were chosen, since this area is likely to be found in a single-family building wall.

While the calculation model for winter period was analysed, it was decided to opt for such operating modes, the use of which requires a lower load on the circulation pump. During the summer period the most appropriate mode of operation was searched by evaluating the circulation pump operation and temperature variation on the outer wall. Table 2.1. summarizes the selected system modes at different outdoor temperatures.

Table 2.1.

System operating parameters for different outdoor temperatures

$t_{outdoor}$ [^{0}C]	$t_{water\ wall}$ [^{0}C]	x	t_{turp} [^{0}C]	t_{atg} [^{0}C]	t_{gr} [^{0}C]	m [kg/s]
-30	0,19	0,3	0	3,3	6,5	0,04
-25	0,72	0,2	0	5,9	6,5	0,04
-20	1,00	0,15	0	6,4	6,5	0,04
-15	1,27	0,1	0	6,4	6,5	0,04
-10	1,75	0,05	0	6,4	6,5	0,04
-5	3,2	0	0	6,4	6,5	0,04
0	3,2	0	0	6,4	6,5	0,02
20	16,9	0	19	14,8	7	0,39
25	17,7	0	22	13,5	7	0,21
30	18,6	0	27	10,2	7	0,11

The table shows that during the winter circulation system can be operated in steady state mode, thus allowing for efficient operation. The x, in the third column is the fraction of the latent energy of water, which is used to operate the system. Latent phase transition energy will be used to -5 ^{0}C temperature. During the summer the system starts to operate, when the outdoor temperature is at least 20 ^{0}C. At lower outdoor temperatures, the system is not working effectively. Table 2.1. does not show outdoor temperatures at which the system does not run, 5 ^{0}C, 10 ^{0}C and 15 ^{0}C. At these temperatures, it is considered that the temperature on the wall is the same as the outdoor temperature. Based on the data shown in table 2.1. and on the outdoor temperatures at which the system does not run, temperature chart that can be seen in Figure 2.3. was created. Water wall temperature depending on the outdoor temperature is described by a fourth-degree polynomial equation. In the calculation model it is assumed that at outdoor temperature of -30

^{0}C indoor temperature is set at 18 ^{0}C and at the outdoor temperature of 30 ^{0}C, indoor temperature is 24 ^{0}C.

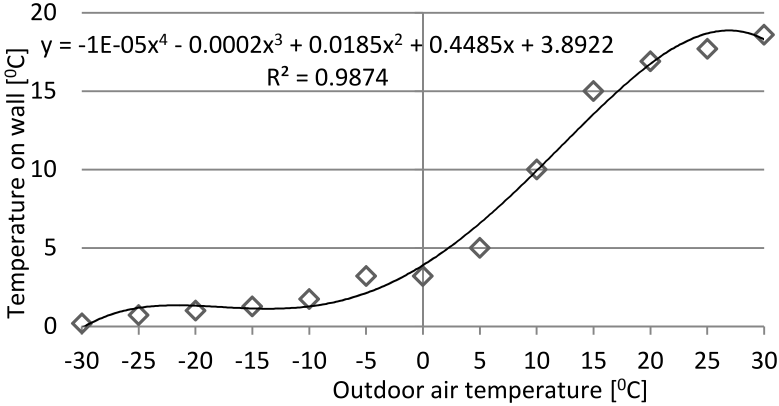

Fig. 2.3. Temperature on the water wall, depending on the outdoor temperature

After calculating temperature distribution on the wall at different outdoor temperatures for both cases (construction with water wall and without water wall), it is necessary to create a comparative model. It is compared how much heat is lost through the wall by heat transfer in the case with a water wall and in the case without it. Heat loss through the wall is calculated using the expression 2.1.:

$$Q = k * S * \Delta t \quad (2.1.),$$

where
Q – heat loss through walls, W;
k – heat transfer coefficient, $W/(m^2K)$;
S – surface area, m^2,
Δt – temperature difference between both sides of the building envelope, °C.

The equation consists of three components, two of which for both walls are constant, and the third different. The heat transfer coefficient k and surface area S ar the same for both walls. Heat transfer coefficient k is assumed 1 W/(m^{2}K), which corresponds to thermal properties of a wall in an old building. Wall area is 32 m^2, which is made up by a wall with height of 4 m and a width of 8 meters.

Climatic data from different places and different years in Latvia were used for obtaining the outdoor temperature. Temperature data with one hour time step were used. This was done to see the potential of water wall technological solution in Latvian climate. This led to a dynamic model, which takes into account the change in the temperature. In the case without water wall, the temperature on the wall is changing every hour and is equal to the outdoor temperature. In the case of water wall, the wall temperature was calculated according to the equation that can be seen in Figure 2.3. The calculation model did not take into account the thermal inertia of the wall, which means that there is no heat accumulation in the wall and thus immediately stationary heat transfer mode is entered.

Heat losses for the case with water wall and without it can be seen in the chart in Figure 2.4. When the average heat flow is zero, the indoor temperature and the temperature on the outside wall of the building are the same. In those areas where the heat flow is positive, the heat flows through the walls of the building into the surrounding area, which means the need for space heating for ensuring desired indoor temperature conditions. If the average hourly heat flow is below 0, there is a necessity for space cooling. Figure 2.4. shows that in the case without water wall heat flow peaks during the winter months can be observed. This can be explained by the fact that there is a big difference between indoor and outdoor temperatures.

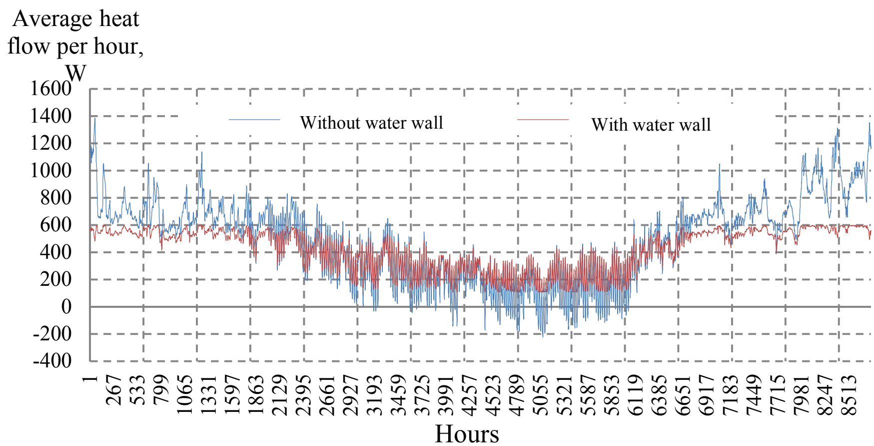

Fig. 2.4. Comparison of construction with water wall technology and without it (climate - Gulbene, 2002)

The figure also shows that in the case of construction with installed water wall, the heat flow at no time is above 550 W. This is due to the fact that in this case, the lowest temperature on the wall can only be 0 ^{0}C. So the temperature difference between the two environments, when the outdoor temperature is -30 ^{0}C, is 18 ^{0}C, Which at the current system parameters means that the maximum heat flux is 576 W (according to equation 2.1.). Figure 2.4. shows that if the water wall is installed, it will significantly reduce the energy loss range. This means that it would be possible to design a real building and to predict the maximum heat loss and peak load with a higher accuracy, and thus it should be possible to select the optimum power of the heating system. Each hourly average heat flow multiplied by one hour results in heat loss or gain in one hour. Heat gains and heat losses are counted separately. The results are summarized in Table 2.2.

Table 2.2.

System performance comparison in Gulbene year 2002

	Without water wall	With water wall
Space heating (whole year), MWh	4,35	3,71
Cooling, kWh	29,29	0
Space heating (heating season), MWh	3,37	2,55
Energy savings in heating season, %	24,4	

The most important result is the heat loss during the heating season, which lasts from the 1st January till 15th April and the 1st October till 31st December.

Results of the performance of the system

This chapter summarizes the performance of the system at different outdoor temperatures. Using the previously described comparative calculation model average hourly heat flow from the walls in various Latvian cities was derived. If the water wall is installed the maximum heat flux in is about 576 W. Figure 2.5 shows the outdoor temperature and the temperature on the wall in the case of installed water wall in Gulbene in 2002. Results were obtained using equation shown in Figure 2.3.

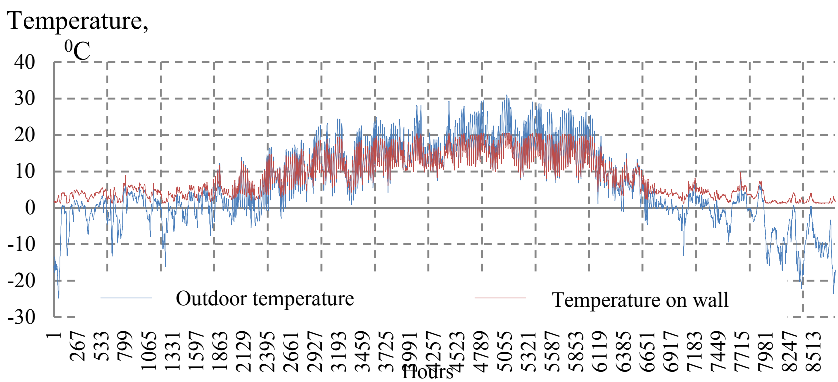

Fig. 2.5. The temperature on the water wall, depending on the outdoor temperature in Gulbene in 2002

The figure 2.5 shows that during winter months the temperature on the wall all the time is greater than 0 ^{0}C. During the summer, it is ensured that the highest temperature on the outer wall of the building is 20 ^{0}C, which is 10 ^{0}C lower than the highest outdoor temperature. Such temperature regime alows to reduce cooling loads. In some cases the water wall may be operated to remove excess heat.

In Latvian climatic conditions such system would produce significant savings of heat during the heating season. Average savings of installing water wall system is about 20%, but this is very dependent on how warm or cold the year was. Table 2.3. summarizes the saved energy during the heating season for various climatic conditions in Latvia. Heating season lasts from 1st January till 15th April and from 1st October till 31st December.

Table 2.3.

Energy savings in various climatic conditions in Latvia

City	Year	Energy savings, %	Energy savings, kWh
Gulbene	2002	24,3	819,4
Jelgava	2006	22,1	680,2
Dobele	2007	19,0	556,4
Riga	2008	14,4	392,8
Ventspils	2008	12,5	328,0
Priekuli	2009	21,5	690,7

The table shows that the average savings of installing the water wall system is about 20%, but this value is highly dependent on what the outdoor temperature is. In the case if the water wall system was not used, each summer space cooling was required, but where the water wall system is installed there is no need for additional cooling loads.

The main advantages of using water wall system is that temperature variations on the outside wall of the building are reduced. During the summer the maximum temperature on the outer wall of the building was reduced by 10 ^{0}C, which means that there is no need for additional cooling of the building. It is ensured that the heat loss through the walls of the building during the winter period with installed water wall system are never greater than a certain value. In this way it is possible to predict what could be the maximum building heat loss with high accuracy, which in turn means that the choice of boiler is easier and it ensures that the boiler will not be installed with too high power.

Experimental rig for the water wall technological solution

Experimental testing of the water wall was done by setting up an experimental rig that imitates building with water wall on one of the surfaces of building envelope.

It is necessary to determine the heat transfer coefficient of building envelope to carry out analysis of water wall operation. Two heat flux density sensors and seven different temperature measuring devices were used in the measurements.

To confirm the hypothesis that latent heat of water-ice phase transition can be used in reducing heat conduction heat losses, heat flux density measurements on the building envelope without water wall on the outer surface (the reference wall) and with water wall on the outer surface on building envelope (water wall) were carried out.

The measurement with freezing water layer on outer surface of building envelope

To determine how freezing of water and using latent heat of phase transition affects heat loss from the building envelope, a measurement where the water wall structure was filled with 120mm thick layer of water was carried out. Measurement results allowed to validate the calculation model of the water wall. The measurement was conducted from February 6 to February 13, 2012. The total measurement time was 176 hours (7days 8h). Measurement length was determined by the duration of the water freezing process. It was necessary to ensure that the entire water layer will freeze during measurement. Measurements of completely frozen water wall construction were also carried out. During measurement water loses the latent phase transition energy and turns into ice. This can be seen in Figure 2.6.

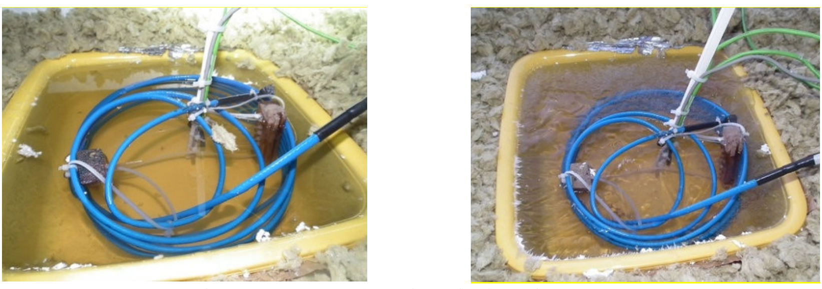

Fig. 2.6. Water freezing during the measurement

K-type thermocouples and PT100 type temperature sensor were used for water temperature measurements. Heating element was placed in the water tank. Heating element was turned off during the measurement. The heating element is needed to melt frozen water and to recover temperature sensors and to repeat the measurement. This heating element also is used in the measurement when ground loop and the whole system is simulated.

The measured air and water temperatures are shown in Figure 2.7.

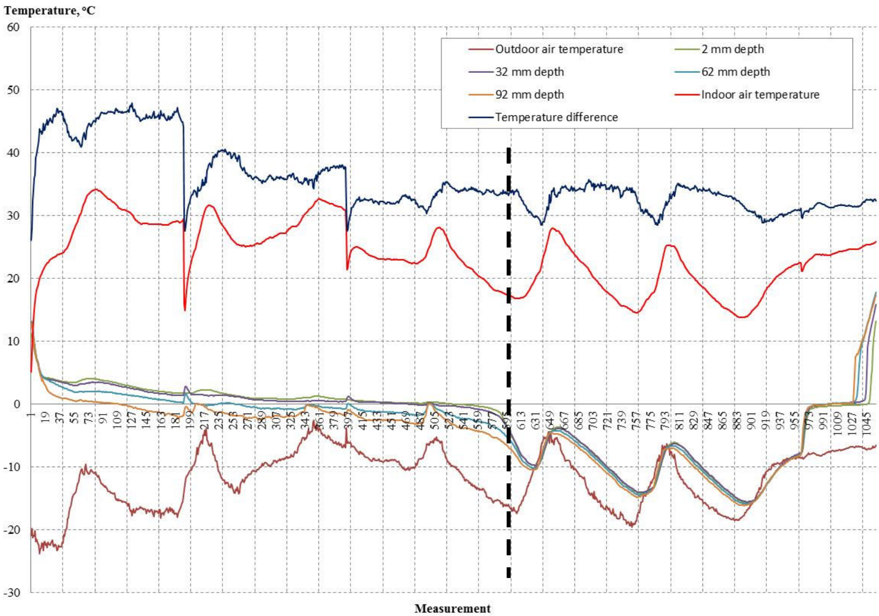

Fig. 2.7. The measured air and water temperatures

During measurement outdoor air temperature was in range from -2.53 ° C to -23.85 °C. Cyclic overnight outdoor air temperature changes can be seen. An electric heater with a constant power was chosen to maintain room air temperature. Therefore cyclic overnight temperature changes in the observed room air temperature can be seen.

Changes in water temperature show that the water is freezing from the upper layers and gradually freezes into deeper water layers. At the given outdoor temperatures 56 hours were required for the entire water layer to freeze (vertical water freezing speed - 2.143 mm/h).

After all the water layer is frozen, the ice temperature at different depths converges and no more latent heat is used. At the end of measurement (begining from 960th measurement point) electric water heater was turned on and the ice was melted.

Heat flux densities through the reference wall and water wall during the measurement are shown in Figure 2.8.

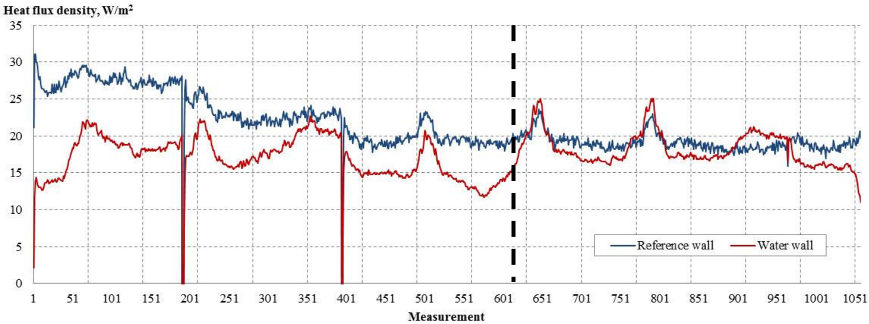

Fig. 2.8. Heat flux density measurement results

The measurement results demonstrate that the heat flow in building envelope with the water wall is significantly lower than in the reference wall (a wall without water on the outer surface), which shows that the water phase transition latent energy can be used to reduce the heat conduction losses through the building envelope in cold climates. After all the water is frozen (black dashed vertical line in Figure 2.8.) heat flow in the reference wall and water wall converge, because all the phase transition latent energy is used.

Overall heat transfer coefficient of the water wall

The measured heat flow density through reference wall and temperature diference between indoor air and outdoor air temperature was used to determine the heat transfer coefficient of the reference wall.

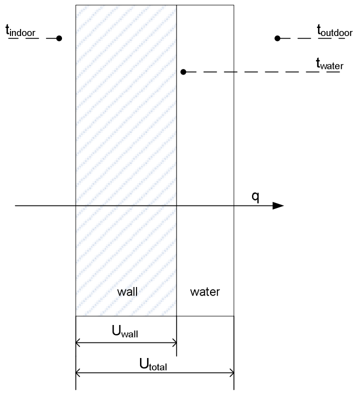

Fig. 2.9. Temperature measurement spots for water wall

To determine the heat transfer coefficient of wall with installed water wall technological solution, following equation can be used:

$$U_{wall} = \frac{q}{t_{indoor} - t_{water}}, W/(m^2K) \quad (2.2.)$$

where
U_{wall} – heat transfer coefficient of wall, W/(m^{2}K);
q – heat flux density, W/m^2;
t_{indoor} – indoor air temperature, ^{o}C;
t_{water} – temperature of the water layer on the outer surface of the wall, ^{o}C.

Following equation has to be used to determine the total heat transfer coefficient of the water wall that includes the use of latent energy of phase transition and reduces heat conduction heat losses,:

$$U_{tot} = \frac{q}{t_{indoors} - t_{outdoor}}, W/(m^2K) \quad (2.3)$$

where
U_{tot} – total heat transfer coefficient of the water wall, W/(m^{2}K);
$t_{outdoor}$ – outdoor air temperature, ^{o}C.

Water wall measurement data can be analysed by not using the water temperature on the surface of the wall, but the outdoor air temperature. In this way it is possible to determine the total water wall heat transfer coefficient, which includes the water layer and the use of latent energy of phase transition for reducing heat conduction heat losses. By doing this analysis it was concluded how the total heat transfer coefficient of the water wall changes depending on the outdoor temperature. The heat transfer coefficient for wall with no water layer is not dependent on the outdoor temperature and it is constant. For the water wall the total heat transfer coefficient varies depending on the outdoor temperature. The lower the outdoor temperature, the lower the total heat transfer coefficient of water wall. Results of measurements of the total heat transfer coefficient of the water wall are shown in Figure 2.10.

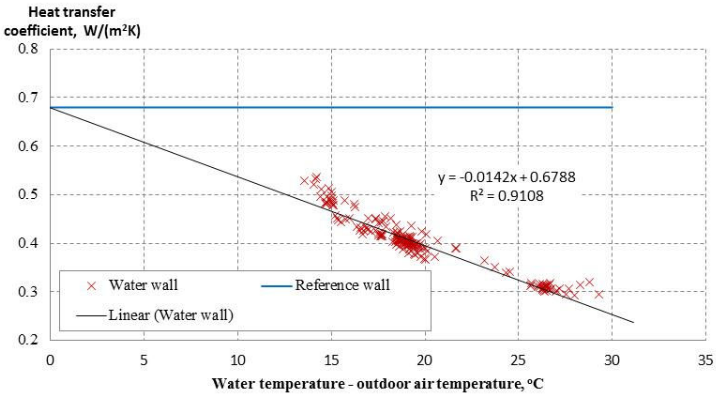

Fig. 2.10. The total heat transfer coefficient of water wall dependending on outdoor air temperature

The figure shows the dependence of the total heat transfer coefficient of the water wall on outdoor air temperature. The X-axis shows water temperature and outdoor air temperature difference instead of the room air and outdoor air temperature difference. This is done to show that, if the temperature difference is 0 ° C, the total heat transfer coefficient of water wall is the same as for the refernce wall (a wall without water layer on outer surface). The measurement data show very good correlation between the total heat transfer coefficient of water wall and water temperature and outdoor temperature difference. The total heat transfer coefficient of water wall decreases by 0.0142 W/(m^2 K) if outdoor temperature is decreased by one degree. The difference between conventional insulation material with a constant heat transfer coefficient and the water wall, with the heat transfer coefficient being dependent on the outside air temperature can be clearly seen. The proposed technology is used in cold climates, because the lower outdoor air temperatures decrease the total heat transfer coefficient of water wall.

Conclusions

1. Increasing the energy efficiency level in existing buildings is dependent not only on economic aspects (investment, building renovation project payback time, heat savings, etc.), but also on social aspects (public awareness of the need for renovation, confidence level in energy auditors and construction companies, public relations, etc.). Existing building energy efficiency market simulation models take into account only the economic aspects. The system dynamics model developed in this dissertation takes into account both economic and social aspects; it is an accurate description of the building energy efficiency market and all of the factors influencing it.
2. The results of the system dynamics model show that, using the existing policy instruments for increasing the energy efficiency of buildings, it is not possible to achieve the goals laid down in the First Latvian Energy Efficiency Action Plan. The projections of the system dynamics model show that use of existing policy instruments leads to only 2% of the set goal being achieved. The use of all the policy instruments analysed in the system dynamics model enables only 21.6% of the goal set for year 2016 to be achieved. So it can be concluded that the present approach, under which the majority of energy savings (that have to be achieved pursuant to European Parliament and Council Directive 2006/32/EC on energy end-use efficiency and energy services) are to be achieved by implementing energy efficiency-enhancing measures in the housing sector, is not feasible.
3. To reduce the energy consumption of buildings and come closer to fulfilling the objectives laid down in European Parliament and Council Directive 2010/31/EU on the construction of near-zero-energy buildings from 2020, it is necessary to develop an innovative energy efficiency technology based on principles other than those underpinning the previously existing energy efficiency techniques.
4. The technological solution developed in the course of the dissertation, i.e. a water wall, enables the latent heat energy of the water phase transition to be used to reduce energy consumption in buildings. Installing a water layer on the outer surface of the building envelope can reduce losses due to heat conduction through the building envelope; as the water layer freezes, the latent heat energy of the water phase change is used to reduce the losses due to heat conduction. Low-potential heat sources (ground heat) can be used to recover the heat energy lost during the water phase transition.

5. Using the new technology under Latvian climatic conditions, heat loss due to heat conduction through the building envelope can be reduced by as much as 25%.
6. This technology will reduce peak heating loads. This is because during the heating season, the temperature on the surface of the cold side of the building envelope does not drop below the phase transition temperature of water, i.e. 0 ° C.
7. Combining the water wall with certain elements of passive buildings enables standards for passive houses to be achieved under Latvian climatic conditions. This has not been practically possible up until now because of high peak heating loads during the coldest part of the heating season.

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Summary of Thesis

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