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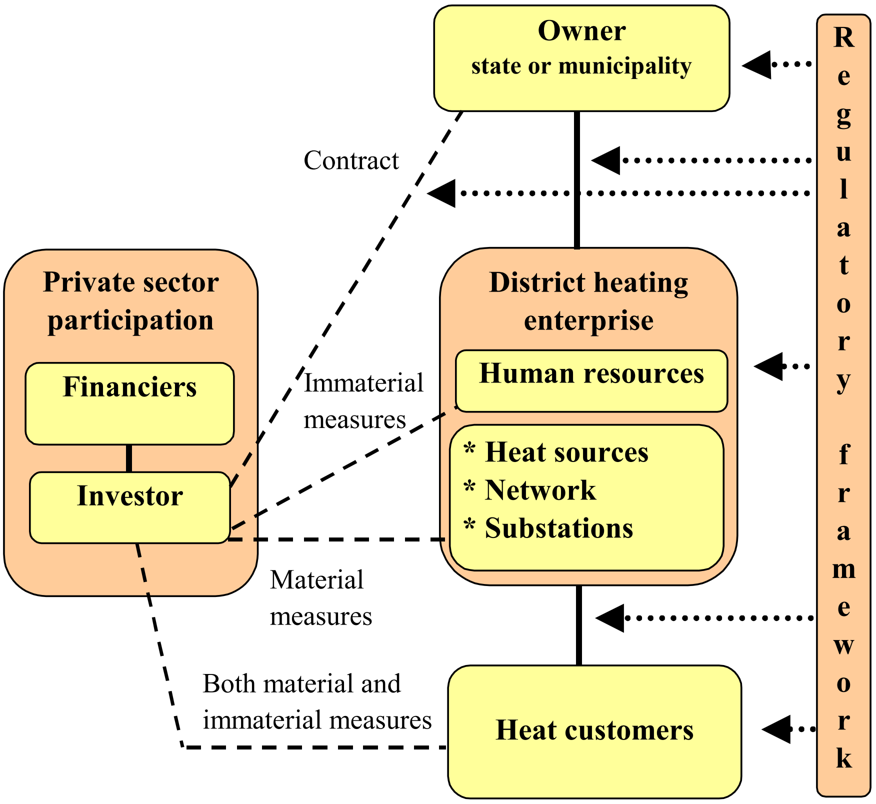
TO THE REHABILITATION STRATEGY OF DISTRICT HEATING IN ECONOMIES IN TRANSITION

Arto Nuorkivi



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To the Rehabilitation Strategy of District Heating in Economies in Transition

Arto Nuorkivi

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Helsinki University of Technology
Department of Mechanical Engineering
Laboratory of Energy Economics and Power Plant Engineering

Distribution:

Helsinki University of Technology
Laboratory of Energy Economics and Power Plant Engineering
P.O. Box 4100
FIN-02015 HUT
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Author's address:

Perintökaarentie 2
FIN-00690 Helsinki
Tel. +358 9 72 49 202
Mobile: +358 41 456 88 93
Email: arto.nuorkivi@tkk.fi

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ABSTRACT

Rehabilitation of district heating systems in the economies in transition requires private sector participation due to insufficiency of the resources of the local authorities and the international financing institutions. The investment needs of rehabilitating the district heating systems is Russia, for instance, are estimated at US$ 70 billion by year 2030. In order to address some of the barriers faced by the private sector, an analysis of the already completed rehabilitation cases, financed by the World Bank, and development of a strategic planning tool using the results of the analyses was considered useful. The model was developed in four stages as follows: (i) A simple linear regression analysis of the material measures, e.g. the investments, and the obtained economic benefits of the completed projects has provided estimates about the relations between the individual measures and the related benefits. The author has had a rare opportunity to participate in preparing and analyzing the database of the World Bank, the largest co-financier of the rehabilitation cases so far, comprising the analysis results of the completed rehabilitation cases, mainly located in Poland. (ii) Regarding the obtained benefits of rehabilitation, the impact of the immaterial measures has been substantial on the success of the rehabilitation cases. In order to create quantitative estimates of the benefits of the immaterial measures for model building, a questionnaire analysis was carried out among the key specialists in the district heating enterprises, in which such a comprehensive rehabilitation had been completed recently. Each specialist was requested to personally assess how much of the measured quantitative economic benefits was gained by the material measures compared with immaterial measures, on which areas of knowledge the benefits were achieved and which sources had produced the benefits. Given the overall economy of the rehabilitation case, the benefits of the immaterial measures could be estimated in quantitative terms. (iii) Using the analyzed information about the benefits provided by both material and immaterial measures, a model consisting of LP and NLP was created by means of the GAMS programming tool. (iv) The model performance has been demonstrated in a fictive Russian DH system. Due to the basis of analyzed data and the testing results, the model may offer encouraging opportunities to assist private sector and other financiers in planning district heating rehabilitation in economies in transition on strategic level.

PREFACE

This thesis for the degree of Doctor of Technology has been prepared in the Laboratory of Energy Economics and Power Plant Engineering at the Helsinki University of Technology during the years 2001-2005.

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Arto Nuorkivi

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NOMENCLATURE

a	Single parameter
B	Benefit (M€)
b	Set of parameters
C	Costs (M€)
c	Component of the thermal chain
D	Depreciation of investments (M€)
d	Number of days
e	Natural constant equal to 2.71…
f	Function describing the general set of variables
f	Index specific for fuels
g	Gravitation constant, 9.81 (kg / m s^2)
h	Height (m)
I	Immaterial measures
i	Index specific for an energy source
K	Unit price of energy (€/MWh)
k	Index specific for an energy source
L	Length of DH network (km)
M	Man power, human resources, HR (man-year)
m	Index specific for a type of emission
N	New replacement value of fixed assets (M€)
n	Number of heat sources
P	Electric energy (GWh)
p	Pressure [Pa]
Q	Heat energy (GWh)
$\hat{Q}$	Maximum heat flow (MW)
R	Rehabilitation rate
r	Interest rate (%/a)
s	Season of year (summer, fall, winter, spring)
t	Time (a)
t	Temperature (^{o}C)
V	Volume of water content in the DH system, the thermal chain (m^3)
W	Water consumption (km^3)
w	Water treatment
Z	Spare parts, lubricants and other maintenance materials (k€/a)

Greek

Δ	Difference of the current to the previous value
Θ	Benefit weighing function
Π	Excess heat production capacity (MW)
Σ	Summarizing operator
Φ	Fuel energy (GWh)
Ψ	Emissions (Mg)
α	Power-to-heat ratio of a CHP plant
β	Relative potential of savings in need of resource
ε	Escalation of the unit price (%/a)
η	Efficiency of the energy system component
κ	Connection rate of radiators out of all radiators in the DH system in the

	base year (%)
λ	Thermal conductivity (W/m K)
ξ	Sensitivity of α relative to water temperature variation (%/^{o}C)
π	Equivalent to 3.14…
ρ	Density of water (kg/m^3)
ς	Availability of the DH network based on sectioning as the actual per the initial break-off time (%)
τ	Time (h)
υ	Number of network sectioning valves
ψ	Weighing factor of losses (%)

Subscripts

a	ambient
av	average
b	buying, purchasing
b	base, basic
bo	break-off
c	component of the thermal chain
ca	capacity
chp	combined heat and power
cm	commercial
co	control of substations
de	sales (demand)
dh	district heat
di	distribution pipes up to DN 200
e	electric power
el	expected lifetime of fixed assets
em	emission
ex	extended lifetime of fixed assets
f	fuel
g	soil
he	heat exchanger
hr	human resources, HR
l	losses
m	minimum
me	metering
rm	remaining lifetime without rehabilitation measures
ex	extra lifetime due to the proposed measures
i	index specific to an energy source
in	investment
k	index specific to a resource
n	nominal
o	base or reference year before rehabilitation has started
pl	peak load duration
pr	production
pu	pumping in DH system (pump and drive together)
r	return side
re	residual
s	supply side
tot	total

tl	transmission with large pipes, larger than DN 400
tm	transmission with medium size pipes, larger than DN 200 up to DN 400
u	undelivered heat energy
v	valves used for network sectioning
w	water
y	yearly

List of Abbreviations

BAT	Best available technology (best practice)
BLS	Building level substation with heat meter, heat exchangers and temperature control systems
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District heating
DHE	District heating enterprise
DHW	Domestic hot water as a part of DH services
DN	Nominal dimension (of pipe)
DSM	Demand side management
EBRD	European Bank for Reconstruction and Development
EIB	European Investment Bank
ESMAP	Energy Sector Management Assistance Program of the WB
ET	Economy in transition (FSU and countries, which have accessed EU in May 2004 or are in the accession process to join soon)
ERR	Economic rate of return
ESCO	Energy service company
FRR	Financial rate of return
FSU	The former Soviet Union
GAMS	General Algebraic Modeling System (developed by the WB)
GS	Group substation supplying DH to several buildings with 4-pipes
HFO	Heavy fuel oil, mazut
HoB	Heat-only-boiler
HR	Human resources, staffing
IEA	International Energy Agency
IFI	International financing institution
IRR	Internal rate of return (covers both FRR and ERR)
IT	Information Technology
LFO	Light fuel oil, diesel oil
NIB	Nordic Investment Bank
LP	Linear programming
NLP	Non-linear programming
NO_x	Nitrogen oxides in general
PLN	Polish złoty
PPP	Public private partnership
PSP	Private sector participation
SCADA	System for control and data acquisition
SH	Space heating as a part of DH services
SIDA	Swedish International Development Agency
SO_2	Sulfur dioxide
TA	Technical assistance, mainly consulting services
WB	The World Bank

1. Background

Heating of room space and domestic hot water is a necessity in most northern countries in the world, comparable to food, drinking water and clothing. The DH systems in the economies in transition - the region mainly comprising the Former Soviet Union (FSU) and Central and Eastern Europe - badly suffer from insufficient financing, which is necessary for sustainable operation and development of the DH systems. Extensive private sector participation is essential in order to finance and organize rehabilitation of the DH systems of the aforementioned region in the years and decades to come, as public financing alone will not be sufficient. Various risks, institutional ones in particular, have led to strong hesitation of the private sector to participate in the system rehabilitation due to unsecured revenues and uncontrollable costs of such business.

During the time of the FSU, the prices of resources were artificially low and little concern was given to the efficient use of any resource. Such an attitude has resulted in inefficient district heating (DH) and combined heat and power (CHP) systems. After the collapse of the FSU, the previous satellite countries became ordinary importers of fuels at considerably high commercial prices, thus creating the affordability problem in those countries. The consumers in these countries could not afford to pay for the overly expensive heating services, and a huge public subsidy system was created as compensation. The subsidy system, however, did not offer any incentives for energy efficiency to the district heating enterprises (DHEs) or to the customers. The amount of the annual subsidy was set at the end of the year to cover the difference of the accrued costs and revenues whatever they may have been in course of the year.

In the densely populated cities, DH together with CHP production has been demonstrated to be the least-cost heating option in the long term. On the free energy market of the northern EU, DH has managed to become an economically, financially and environmentally preferred heat product. The comparable benefits of the centralized DH/CHP accrue from high energy efficiency due to an integrated system, flexibility for using a variety of fuels and effective flue gas cleaning benefiting from the economics of scale. Out of the total residential and public heating market in Europe DH covers 70% in Russia and Lithuania, 68% in Latvia, 53% in Poland, 52% in Estonia, and 50% in Denmark and in Finland. The high values of Russia, Latvia and Lithuania may represent the urban areas only, thus neglecting the rural areas. Moreover, out of the total heat supply of DH the bulk is produced in a CHP process representing 79% in Germany, and 75% both in Finland and Denmark. In Europe, DH supplies heat to more than 100 million people (Russia excluded), thus covering a substantial share of the heating demand in the countries (Euroheat&Power, 2003).

Due to poor technology and insufficient maintenance in a number of the northern economies in transition (ETs), and after the collapse of the FSU in particular, the heating systems have badly deteriorated. The design of the DH systems in the ETs is rather uniform and is based on old standards of the FSU. The same standards have been used practically in all northern ETs extending from China and Afghanistan to Estonia and Serbia, for instance. Poor design, neglected maintenance and insufficient renewal of the fixed assets have provided high operational losses and have caused low availability and poor performance of the heating services. During the past decade, such problems have caused customers in many countries to shift in large numbers from DH to other heating systems, which often has been unfortunate for the economy and the sustainability of the entire energy system in the long term.

As DH systems are the least-cost option in the long term but in a poor condition at present, rehabilitation of outdated systems has become an economically and environmentally justified policy. The worldwide rehabilitation process started in year 1991, when the World Bank (WB) approved the loans to finance DH rehabilitation in five cities in Poland. Thereafter, the WB and other international financing institutions (IFIs), such as NIB, EU, EIB and EBRD have continued with rehabilitation projects in other locations. Most of the rehabilitation has been based on public financing, whereas the private sector has mainly kept distance to large rehabilitation projects.

After a decade, a large number of DH systems in the ETs still wait for rehabilitation. In Russia alone, some 50,000 DH systems (Bashmakov, 2004) in about 10,000 towns and cities (Velikanova, 2004) wait for rehabilitation. Due to industrial collapse, many of those systems may not be eligible for rehabilitation. The economic living conditions have become questionable in the long term and people have started moving elsewhere in search of work.

In addition to the about 10,000 towns and cities indicated in Russia, there are about 2,000 cities in Central Europe (Euroheat&Power) with outdated DH systems. In Europe, the IFIs have financed a few cities per country but the other cities still struggle with the outdated systems and have little resources to finance even the annual repairs.

In Russia, the rehabilitation has hardly begun. The DH network damages in Russia, for example, have reached the annual frequency of 2 damages per km; a very high number and equal to the Warsaw DH system before the rehabilitation started in 1991 (Bashmakov, 2004; The World Bank, 2000). The DH system of Warsaw used to represent a kind of negative benchmarking in early 1990's with the thermal losses about six times, water losses even 80 times, and the number of the human resources (HR) at least five times higher than in the modern systems (The World Bank, 2000). Simultaneously, the heat customers in Warsaw paid only about 10% of the heating costs, whereas the government funded the balance. Ten years later the situation in Warsaw was much better, thanks to comprehensive rehabilitation, as indicated in Appendix1.

In Russia, there are various estimates about the investments needed for DH system rehabilitation. First, the costs of rehabilitation of the DH systems in the next ten years to come covering the system from supply to demand is estimated at US$ 50 billion. This is equal to US$ 5 billion a year, ten-fold of the amount used for DH system rehabilitation at present (Bashmakov, 2004). Second, the World Bank has lent US$ 85 million for the Municipal Heating Project for heating system rehabilitation in about ten cities (The World Bank, 2000). The measures financed by the loan cover only about 0.2% of the DH market in Russia. Based on this, one may roughly estimate that US$ 40 billion would be needed to rehabilitate all DH systems in Russia, excluding CHP plants and indoor heating systems of buildings. Finally, the energy strategy of the Russian Federation estimates that development of the DH systems will require US$ 70 million during 2003-2030, equal to US$ 2.6 billion a year, and such funds will be collected from the budgets of the oblasts and municipalities, heat sales to customers and from investors (Energy Charter, 2004). Despite being different, the three estimates above are in the same magnitude. Obviously, such huge amounts of funds cannot be provided by the IFIs not the municipalities alone, but private sector participation (PSP) and the public-private partnership (PPP) will be necessary approaches for co-financing of the DH rehabilitation in Russia.

The CHP plants are usually owned by a state enterprise but in many countries are being privatized. Given the importance of heating to the people and CHP to the countries, the market future looks promising for DH system rehabilitation with possibilities of both centralized and decentralized CHP.

Due to the huge investment need in system rehabilitation, and desirably in further development of the system as well, involvement of private capital is necessary to foster rehabilitation. However, compared with the water and sanitary sector, where PSP has become a common practice, there have been rather few cases where private capital has participated in rehabilitation. The French Dalkia, however, operates a large number of DHEs all over Europe, including the large DH systems of Tallinn and Vilnius. No other companies aside Dalkia have penetrated to the market in such a large scale. However some Finnish, German and Swedish companies have exercised small rehabilitation cases in the ETs recently. In Russia, the recently established enterprise Russian Kommunal Services partly owned by RAO-UES, large governmental power utility, has entered agreements with a number of municipalities regarding concession of the local utilities, DH included.

The experiences from the completed large DH rehabilitation projects have resulted in substantial benefits - the worse the economic level in the starting point, the higher the expected economic benefits. The DH rehabilitation projects in Poland, Latvia and Estonia have resulted in savings of 20-35% in energy, more than 60% in water, about 20% in HR, and even 70% in electricity consumption. Such substantial benefits offer better service to the customers at an even 50% lower heat price in real terms than before the rehabilitation had started (The World Bank, 2000, 2001).

Despite experiencing some PSP on the rehabilitation market already, the market is generally not yet considered attractive. A number of reasons for the low attractiveness prevail, as will be listed later in the document on hand. One of the important technical reasons is that considerations about DH system rehabilitation in ETs so far have been based on rather theoretical methods and on general information, as the experience from the large completed rehabilitation projects became available only in year 2000 and thereafter. TEKES (The National Technology Agency in Finland) together with the DH sector in Finland, for instance, has organized two programs, one for product development (MODiS – Modular District Heating System) and the other for financial tool development (TESCO – Total Energy Service Company) for the DH sector in the ETs. In the programs theoretical models were developed but practical demonstrations were not implemented. One of the reasons for not having practical demonstrations has been the lack of data and information about the realistic benefits having hampered the tuning of the developed models respective to the real world.

This research project was motivated in order to improve accuracy and to reduce risks in planning and implementing rehabilitation projects. The objective of this project is to provide analyzed data and a model aimed at designing the rehabilitation project on the strategic level under the prevailing constraints in a DH system wherever located in the ETs. The document at hand is aimed at addressing technical, economic and financial risks of rehabilitation. The author has had an opportunity to prepare and use the unique files of the World Bank comprising experience in the completed comprehensive DH rehabilitation projects. A computerized model using such experience was considered useful for strategic planning of rehabilitation. Such a model was finally created and adjusted to the analyzed experiences collected from the already completed comprehensive rehabilitation cases in the region. The model is aimed at robust planning of the DH rehabilitation strategy for a selected period of time under the local conditions prevailing in a system.

2. Basic Features of District Heating

2.1. *Comparison of District Heating Systems*

Four main reasons for the DH system rehabilitation in the ETs can be summarized as the needs (i) to improve the energy efficiency, (ii) to reduce heating costs, (iii) to improve technical performance in terms of adjusted water temperatures and increased availability, and (iv) to reduce emissions to the environment. In order to understand the potential for improving the DH system performance, a comparison of the basic features of the systems will be presented below.

The main differences between the DH systems in the ETs and the Nordic EU countries are strongly linked to two operation philosophies as follows:

1. In the ETs the DH system is typically production driven. The heat production plant collectively controls the heat delivered to the customers. In practice, there are no control systems at the consumers, but only at the heat source. This results in an imbalance of the production and the real need of heating, because little or no metering information is available from the customers' side. The only technical means for the customer to compensate for the imbalance is to ventilate the excess heat out from the windows or to add personal clothing while the deficit of heat prevails.
2. In the Nordic EU member countries, the DH systems are demand driven. The consumer substation located in the basement of each building is equipped with a water temperature controller. The controller automatically adjusts the supply temperature of the space heating (SH) circuit according to the outdoor temperature and the building's specific heating needs. Therefore, the substation takes heat from the network as much as needed, not more and not less. The heat sources have to continually follow the actual needs caused by the substations and thus adjust the heat production accordingly.

The above differences in the operation philosophy have resulted in a number of implications on four areas given below with reference to (a) the ETs and (b) the Nordic EU countries, mainly Finland and Sweden, as follows:

1. Load dispatch

(a) In the ETs, the heat transmission networks are operated in a radial mode. In the radial system, only one heat source is allowed to supply heat to the network at the time. There is no load dispatch except inside the heat source between the individual boilers units. The physical loops in the network are closed with valves. The customer can obtain heat from one direction only: from the single heat source.

(b) In the modern looped system, a number of different heat sources can operate in a united network in parallel, thus allowing the free load dispatch to maximize economy. Usually, the customer may obtain heat from various directions in a looped system, which improves both reliability and economy. Basically, a looped system in demand driven mode offers a theoretical opportunity to third-party access in heat production.

2. Reserve capacity

(a) In the radial system, typical for the ETs, the reserve capacity has to be located at the same site where the main (single) heat source stays and has been usually sized at 50-100% or more of the real heat load (Bashmakov, 2004). If a critical transmission pipe is broken, the reserve capacity may not be more helpful than the operative capacity. In urban areas typically a number of separate radial systems exist, each requiring their own reserve capacity. Therefore the construction and maintenance costs of such a large reserve production capacity are relatively high.

(b) On the other hand, the heat sources in the looped system typical for the Nordic EU countries can be located all over the city and connected to one united network, thus supporting each other. Therefore, little excess reserve capacity is needed - about 10% of the real heat load or the size of the largest production unit. The different locations of heat sources are redundant during the network damages. This way, the costs of reserve capacity have remained modest in the modern looped networks.

3. Sizing of the DH network

(a) The water flow rates in the radial systems are relatively high, since the cooling (difference of the supply and return water temperatures) is low, only a few centigrade in summer time. In a system with such a production driven mode, the radial network and the tube heat exchangers with poor cooling properties cause high water flow rates, thus requiring large and expensive pipelines as well as leading to high costs of DH pumping.

(b) The water flow rates in the modern systems are reasonably small, because the cooling is relatively high and the heating networks are looped. Even in summer time, the typical cooling ranges from 30 °C to 40°C. Therefore, the diameter of the pipelines is relatively small, thus contributing to relatively low investment and operation costs.

4. Control of room temperature

(a) In the buildings in the ETs, the SH circuit is usually controlled by means of hydroelevators, which mix the water in a constant ratio. The only way to adjust the temperature of the SH circuit during operation is to change the set value of the supply temperature at the heat source collectively to all customers.

(b) In the buildings of the Nordic EU countries, the water temperature controller connected to the DH substation adjusts the actual heat input on the building level according to the actual building-specific requirements.

Therefore, to change the operation philosophy from the old production to the modern demand driven one, the substation rehabilitation is the key element to start with.

2.2. Target of District Heating Rehabilitation

The Nordic DH systems represented by Finland and Sweden have been selected as bench-marking systems of DH rehabilitation for the reasons, for instance, as follows:

1. High energy efficiency of the buildings, 45 kWh/m^3 of building volume, compared with about 100 kWh/m^3 in Poland, for instance. The high efficiency of

the Nordic buildings is based on heat metering, room temperature control and to advanced national building codes (SKY, 1999; The World Bank, 2000);

2. High efficiency of the DH networks in terms of relatively low water and thermal losses. In the Nordic systems the water volume of the networks changes about once a year compared with 10-20 times typical in ETs. The Nordic thermal losses of the networks are about 6% compared with 10 to 15%, when the heat load of the DH system is 1,000 MW and more (Schmitt, 2003; The World Bank, 2000);
3. Relatively low network operation and maintenance costs compared with ETs, Germany and Denmark, for instance (Schmitt, 2003); and,
4. Finally, low heat tariffs for heat consumers due to unbundling of the DH sector compared with the regulated DH sector in Denmark with higher consumer prices, for instance (Evans, 2004).

There are, however, a number of various barriers preventing fast enhancement of the DH systems of the ETs to meet the bench-marking systems, as will be discussed later in Chapter 3.

2.3. *Links between District Heating and Cogeneration of Heat and Power*

Despite the obvious physical link between the CHP plant and the DH system, there are a number of economic links which have to be taken into account when optimizing the CHP/DH system as follows:

1. The heat source sets the supply temperature, but the customer defines the water flow and the return temperature;
2. The supply temperature of the heat source has a direct impact on the thermal losses of the heat transmission and distribution network;
3. The supply and return water temperature of the system, the latter controlled by the customer, usually have a direct impact on the power-to-heat ratio of the CHP plant. More electricity can be generated with CHP at low water temperatures or the total plant efficiency is improved. The quantitative impact depends on the type and size of the CHP plant;
4. The cooling, determined by the customers, has an adverse linear impact on the water flow rate needed for heat supply at the heat source;
5. The water flow rate, determined by the customers, has an impact on the pumping need at the heat source and the optimal size of the pipelines in the network; and,
6. The pressure difference required by the consumer substations has a direct impact on the electricity consumption of the DH circulation pumps at the heat source and the possible booster pumps in the network.

In a demand driven system, the consumer substations supplying SH and domestic hot water (DHW) services to the buildings are the key elements that specify the entire DH system parameters. Further, the parameters of the substations are affected by the indoor installations of the buildings that are usually oversized relative to the modern time demand of heat.

2.4. *Hydroelevator*

In a typical DH system in an ET, the SH is operated by means of hydroelevators (synonyms: injectors, jet pumps, siphons, Strahlpumpen) located in the building basement, usually one for each raiser pipe. The hydroelevator mixes the DH supply water with the return water of the SH circuit in a constant ratio in order to reduce the SH supply water temperature to the allowed level. Since the pressure of the DH supply pipe is the driving force, the hydroelevator also reduces the pressure level more tolerable to the SH network. Since the same water is circulated both in the DH and SH, the system is “directly connected”. Correspondingly, in case the SH and DH are hydraulically separated by means of heat exchangers, the substation is “indirectly connected”.

There are two main problems with the traditional hydroelevator, because it:

1. Requires a high pressure difference of about 150 kPa to function properly, whereas a modern controller requires less than a third of it; and,
2. Does not control anything but mixes water flows in a constant ratio, thus not providing any technical means for energy conservation.

Advanced hydroelevators with needle-type temperature controllers offer an interesting opportunity to a simplified temperature control at the substations. There are indications that the investment costs, operation costs and the operation related maintenance costs would be lower compared to using traditional solutions with heat exchangers, circulation pumps and control valves (Euroheat&Power Spezial, 1998; Lang et al, 2002; Olsson, 2001). The controlling hydroelevators, however, are useless if one has to use a heat exchanger to separate the network water from the SH circuit. Heat exchangers have been widely demonstrated to be the most effective way to eliminate the water losses at the building side, which is the main reason for huge water losses in the systems in ETs (The World Bank, 2000 and 2001). Therefore, such advanced technologies should be introduced comprehensively in the EU first before introducing them in the ETs, where both quality and loss of water are acute problems.

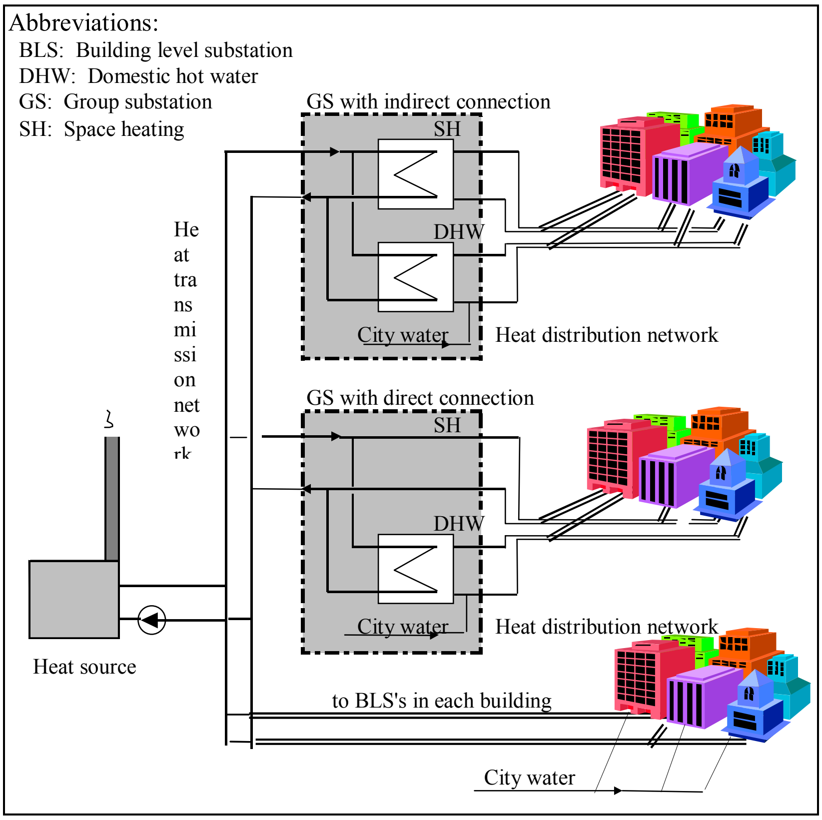


Figure 1. Three types of substations; from above: two group substations with indirect and direct connection, respectively, and a building level substation.

2.5. *Four- and Two-pipe Systems*

In a four-pipe system, a group substation (GS) to which a number of buildings are connected, administratively and physically separates the water circulation of the primary side DH from the SH and the DHW circuits of the secondary side. The DHW supply is typically isolated from the primary network with heat exchangers, whereas the space heating is often connected directly without heat exchanger, or in some cases indirectly with a heat exchanger. Both variants of space heating are illustrated in Fig. 1 above.

The main problems of the four-pipe system are as follows:

1. Short lifetime of the DHW pipes, because the city water contains Oxygen, thus corroding and blocking the distribution pipes and heat exchanger tubes made of iron;
2. Doubled thermal losses compared with the two-pipe system;
3. Doubled investment costs in pipe replacement;
4. High maintenance costs due to frequent repairs; and,
5. Based on all above, poor service quality to the customer.

Due to the serious problems with the four-pipe system, rehabilitation of the four-pipe system with the same old technology does not usually make sense. Elimination of the four pipe system and installation of a modern compact substation to each building typically yields short pay-back times, ranging from one to four years depending on the economic or financial point of view and the energy cost level in the particular country. Therefore, in most case the GSs have been eliminated and the BLSs have been installed instead (The World Bank, 2000 and 2001)

In the ETs, demolishing of old blocks of flats will probably take place in the near future, because people start moving out from the old deteriorating blocks leaving empty blocks behind. Demolishing of the empty blocks connected with a four-pipe system to the GSs will raise a problem of whether to redirect the four-pipe system or to use two pipes and building level substations (BLS) instead, thus step-by-step turning the system from a four- to a two-pipe system. In Zwickau, Germany, where demolishing of old blocks has started already, the problem with the four-pipe system has already arisen. Based on the experience from Zwickau, the investment costs of the two options, either redirecting the four-pipe system or turning the system to a two-pipe system, did not substantially differ from each other. Due to the substantially better operation economy, the two-pipe system with BLSs was adopted, thus supporting the approach selected in this document (Schreck, 2001).

In some cases of high heat load density, replacing the DHW pipelines of the GS with plastic ones, which are more expensive than the steel pipes, will eliminate the corrosion problem and may become economically justified (Klöpsch and Zinko, 2001).

In practice, elimination of the four-pipe system means that

1. Individual BLSs with controlling properties will be installed in each building to supply both SH and DHW loads of the particular building;
2. The existing SH circuit will be used for primary heat supply for the BLSs;
3. The new BLSs will be connected to the existing city water and electricity supply;
4. The existing city water pipe connected to each building would supply the water for DHW needs as well. In general, the city water pipe is oversized and sufficient to cover the DHW load; and,
5. The idle DHW pipes between the GSs and the buildings may be removed.

Due to substantial benefits in thermal efficiency and maintenance, the IRR of the four-pipe system elimination usually is higher than rehabilitation of the GSs, and thus should be prioritized.

Based on experience, the least-cost measures for a building to be disconnected from the four-pipe system have been:

1. Water temperature controller to the SH circuit with necessary valves and pumps;
2. Heat meter to record the heat energy of both DHW and SH circuits;
3. Heat exchanger and circulation pump for the DHW circuit; and,
4. Water meter to record the make-up water tapping in case the DH water losses are high.

2.6. Small Boilers with Solid Fuel

In cases where solid fuel is used in large scale, such as in Poland, typically a large number of small boilers operate using solid fuel at low efficiency, thus substantially polluting the surrounding environment. Such combustion from small solid fuel fired boilers should be eliminated either by (i) connecting the customers to the existing DH system and demolishing the boiler, (ii) converting the boiler to gas firing or (iii) by replacing the boiler with a brand new boiler. Such a decision should be taken case by case depending on the arguments as follows:

1. Distance to the nearest DH network branch and the costs of the connecting pipeline and the new consumer substations;
2. Availability and prices of different fuels at present and as predicted in the future;
3. Estimated costs and impacts of fuel conversion;
4. Costs of new boilers;
5. Costs of demolishing the existing boilers; and,
6. Future of the existing heat customers due to industrial recession, for instance.

Based on the decisions taken, the boilers selected for a certain elimination measure should be summarized to a virtual boiler representing the type of elimination. The benefits of the particular elimination measure should be modeled by means of a linear or a non-linear function for the LP and NLP applications, respectively.

For instance, conversion of the current polluting fuel combustion to a local or less polluting one in most cases requires either installation of a brand-new boiler or modification of the existing boiler.

The other two options of either connecting the existing customers of the boiler to the DH system or constructing a brand new boiler to replace the old one can be modeled in a similar way.

The problem of small boilers is a location specific issue, (i) elimination of the boilers may require investments in substations and network, which depend on the geographical location of the boilers in the case city, and (ii) some fuels may not be available city wide for fuel conversion. In order to deal with the small boiler issue, a separate worksheet should be designed, which, however, has been excluded from the scope of this research.

3. Barriers and Remedies of Rehabilitation

In general, the target of the DH rehabilitation is to improve efficiency, availability, temperature control and environmental performance of the DH system as a means to deliver heat to the customers at lower costs and improved quality. Due to the huge demand of resources and know-how needed for rehabilitation, active participation of the private sector is necessary. There are, however, a number of barriers for PSP to step in to the local DH market in any of the ETs. A brief discussion of such barriers and remedies is necessary in order to put the focus of the research to its right context. The barriers and their remedies have been allocated to five categories; institutional, heat market related, social, financial and technological. In order to understand the framework of the problems and the needs, the barriers and remedies are listed as follows:

Institutional

Barriers

1. The retail tariffs, usually created according to the "cost plus" principle, are regulated but reflect neither structure nor level of heat supply costs and market requirements (competition);
2. The regulator does not want to increase the unit price of the retail tariff, often a necessary action when customers start saving energy, even though the heating cost of the customers would still be reduced;
3. The DH and CHP operations are organized in separate municipal and governmental companies respectively, which hampers holistic optimization of the DH/CHP system operation and development;
4. The technical regulations in the country may be outdated: excess production capacity, excess transmission capacity, double pumps and heat exchangers at consumer level, etc.;
5. Often, the DHE is responsible for O&M of in house installations that may be owned by customers;
6. The HR are usually technically skilled but lack experience in modern management practices, such as financial management, economic analysis, marketing and preventive maintenance, for example;
7. A strong local political involvement in investment, operation and management functions overruns the decisions of DHE management; and,
8. The billing & collection is often organized through intermediaries and not by the DHE, which introduces difficulties for the DHE in establishing direct relationships with consumers and applying sanctions for non-payment. In some cases, the fees of the intermediates are about on the level, corresponding to the energy saving benefits to the customers. Therefore, the benefits go to the intermediates rather than to the DHEs and the customers, reducing the motivation of the two latter parties to invest in energy conservation.

Remedies

1. The national regulator should require two-tier tariffs for heating covering the costs of the years to come. The DHE should be made responsible for billing and collecting, and the subsidies should be turned to social support directly targeted to the poor. The public buildings should be enabled and forced to pay their heating bills in time;
2. The boundaries between the local DHE and the CHP company should be set under a common ownership. If the common ownership is not possible, the heat contract between the organizations should ensure a holistic optimization of the entire system operation and development. The political influence on the DHE should be limited to strategic level and no impact on operational decisions should be allowed;

3. Technical regulations should be updated according to the level of technology, which would improve cost effectiveness and energy efficiency;
4. Any DHE should not be responsible for O&M of the indoor piping of the buildings; and,
5. The key HR should be educated with modern business skills and facilitated with modern IT tools before the start of comprehensive rehabilitation.

Heat Market Related

Barriers

1. Competition to gas will extract customers from DH if the price and quality of DH are not competitive;
2. Compared to the market monopoly on water and sanitary sector, the heating market is more challenging for PSP;
3. High losses of the DH system results in high costs to the customer, who finally has to pay for the losses;
4. Pricing of CHP products, power and heat, often allocates the major part of the costs to heat, thus making the heat product overly expensive in the heating market when comparing to competitors;
5. The customers have no means to control the heating while connected to the DH system in the production driven case, but would have full control when connected to gas or electricity heating; and,
6. The DHE management may not be aware (and earlier did not even care) about what their customers' preferences for heating regarding control, metering, availability and costs/performance of the heating services might be.

Remedies

1. The DHE should improve their competitiveness on the market by improving the quality of the services and by reducing their operational costs, and,
2. The customers should be given technical means and appropriate incentives to control their heating.

Financial

Barriers

1. A heavy investment program is needed, but it would destroy the financial performance of the DHE in the short term;
2. Declining sales in first years and limited growth opportunities later on restrict the financial recovery of the DHE;
3. The actual pricing of CHP products usually gives the benefits to the consumers of electricity, whereas the heat customers have to pay more than is justified. Costs of heat energy typically cover 70% of the heat retail bill, and the CHP plant is usually the dominant (or even the only) heat source. Therefore, the appropriate cost allocation of the CHP products is one of the major conditions for sustainable CHP/DH operation;
4. A long pay-back time of some core investments, such as pipes, reduces financial attraction;
5. The heating business is capital intensive and therefore a relatively high annual investment level is necessary in the long term, especially during the first years;

6. The affordability of people and municipalities to pay for the heating services is usually limited;
7. Compared to water and sanitary system rehabilitations where corporate leasing is every day business, high financial risks of DH reduce its attractiveness to PSP; and,
8. The uncertainty caused by all barriers listed in this Chapter increases risks to PSP and, therefore, the price of financing.

Remedies
1. The rehabilitation program with both material and immaterial measures should be designed in a way maintaining the financial performance of the DHE in the medium and the long term. Moreover, the DHE should aim at converting economic benefits of the rehabilitation program to financial ones;
2. Often, the DH customers living in blocks of flats connected to DH, are better off than the citizens in the city on average. The DHE should prevent the escaping of such customers from the DH system and leaving only the poorest ones connected, thus worsening the affordability (Lampietti and Meyer, 2002);
3. The DHE should use all economic opportunities to expand their business with new services and new customers;
4. Pricing of CHP products should be revised in order to offer reasonable benefits to the heat consumers; and,
5. Technical and financial means should be developed to help the poor to adjust their heat consumption according to their affordability.

Social

Barriers
1. Typically, the heat customers are poor and most of them hardly afford the DH services currently offered; and,
2. The subsidies are usually paid to the DHE directly as a lump sum, which will be used to keep the heat tariff low, thus relatively benefiting the well-off customers with large consumption rather than the poor ones with low consumption.

Remedies
1. The subsidy system should be turned to a social support system targeted to the poor, and,
2. The service level together with the planned rehabilitation measures should be consistent with the affordability requirements, prevailing now and expected in the near future.

Technological

Barriers
1. The customers do not have any technical means to control their heat consumption, but to take what was delivered;
2. Huge losses of heat energy, water and electricity combined with low productivity of the HR and high maintenance needs altogether make the heating product overly expensive and the technical performance unsatisfactory; and,

3. Lack of technical and operational data hampers quantification of the measure/benefit relations, thus providing uncertainty to design and timing of the rehabilitation measures.

Remedies

1. The DHE should introduce preventive maintenance practices by means of a computerized database together with regular and systematic control of the key components of the heat sources, the network and the substations;
2. Experiences from other similar and already completed rehabilitation cases, policies to give guidelines to the implementation order as well as size and timing of the available rehabilitation measures should be used to provide accurate estimates to compensate for the missing data.

Most barriers/remedies listed above require regulatory decisions on the national level. National regulation is necessary to address not only institutional, social and market related but also many financial barriers. In general, the best practices and lessons learned for national regulation are already known, but changing the DH sector regulation in ETs, where the entire society is in comprehensive transition, often has not been the priority (Evans, 2004; DHCAN, 2004). Research, on the other hand, can address the technical and some financial barriers of DH rehabilitation, as will be discussed in later Chapters.

4. Links to Other Research on District Heating

Any recent system level rehabilitation research about the DH systems in the ETs was not identified in the universities of the countries being the main representatives of modern DH in the world, such as the Nordic countries and Germany. In the universities in ETs, scientific research about DH rehabilitation may have taken place but has not been published in English or German. A reason for the lacking system level research may be that the results of the completed large rehabilitation projects are relatively new, from year 2000 and after. Moreover, only a limited number of financiers are available for such large projects. The most important IFI having financed such rehabilitation has been the WB with about US$ 1.3 billion towards the early DH and energy efficiency projects, which has catalyzed another US$ 1.7 billion in a number of countries since the early 1990’s (Gochenour, 2002). The outcome of the WB financed completed cases has provided encouraging experiences to continue with such rehabilitation elsewhere (Benmessaoud et al., 2000; Author, 2001 and 2002), whereas little or nothing has been published about the smaller projects financed by the other IFIs.

On the other hand, there are a number of books about the system level research, both on the old (supply driven) and the modern (demand driven) systems without any aspect of transition from the old to the modern one. For instance, the old DH systems in ETs have been specified (Munser, 1980; Glűck, 1985) but without reference to the modern systems. On the other hand, in the thermodynamic analysis of the modern DH system little or none has been connected to the old DH systems located in ETs (Frederiksen, 1982). An attempt to adapt hydroelevator technology, typical in the old systems to the modern system by using more advanced controlling hydroelevators has provided interesting results for further development (Euroheat & Power Spezial, 2001; Lang et al, 2002; Olsson, 2001). However, such controlling hydroelevators may be problematic in conditions of poor water quality, as still prevailing in the ETs in general.

The International Energy Agency, IEA, the largest international research organization of DH, has completed seven research annexes by the end of 2004 and the VIII Annex is scheduled for the years 2005-2008. The focus of IEA has been on developing modern DH and cooling systems for the benefit of the member countries, but without a particular emphasis on the ETs. Recently IEA has organized two roundtables on DH in ETs, one in 2002 and the other one in 2004 discussing the priorities and best policy practices. A book from IEA addressing the DH policy issues became available in late 2004 (Evans, 2004).

The EU has organized a number of studies regarding DH system rehabilitation their energy assistance programs, mainly in TACIS and in PHARE. In the project DHCAN, the EU has published a set of booklets, which are aimed at offering guidance to the national authorities and the DHE management when addressing the rehabilitation issues (DHCAN, 2004).

The Nordic Council of Ministers has funded a comprehensive research program on DH and CHP since the year 1985. The focus of the research reports, including more than 10 dissertations, range from modeling of Nordic DH systems to optimization of a variety of components in an advanced technical environment, which is not the case yet in the ETs. Since the early results from years 1985 to 1992 have been summarized (Author, 1992) no further summary covering the later years has been issued. In the program, no focus on the DHEs in the ETs has been adopted so far.

Some of the phenomena of economic behavior of the DH systems have been investigated more than the others. *Thermal losses* of the pipelines, for instance, have been investigated more (Werner, 1982; Bøhm, 1999) than those losses taking place in buildings, caused by poor or missing control properties of the consumer substations, even though the losses in the network and in the buildings are of same magnitude. Further on, no analysis about the *water losses* of the DH systems in the ETs has been identified, even though such high water losses is one of the major problems of the DH system maintenance in the ETs. High water losses usually exceed the water treatment capacity, which often is technically outdated even for the rated capacity, thus resulting in poor quality of the circulation water of the DH network. Moreover, no analysis was identified either regarding the *productivity of HR* in different functions of the DHEs in the ETs and elsewhere. The costs of HR are usually 5-10% of the turnover of the heat sales regardless the location of the DHE in the world. The productivity, however, differs a lot between the DHEs depending on whether located in an ET or elsewhere (Author, 2002). No discussion about the immaterial measures in DH rehabilitation in ETs was identified either. Based on the experience, the immaterial measures have had a substantial impact on the economy of the completed projects. In general, optimization of municipal energy systems on the strategic level has recently focused on optimization of the CHP production with a variety of fuels, plant types and size in an unbundled electricity market, but has left the heating network unattended (Sundberg, 2001).

Despite knowing the technical measures for DH rehabilitation, the national energy sector regulation may hamper using them. Comprehensive regulation may give discouraging signals to heat customers, DHEs and potential investors to invest, which results in a low level of private investments in energy efficiency, as has been the case in Poland, for instance (Rączka, 2001).

5. Objective of Research

The ultimate objective of rehabilitation is to provide the customers in ETs with cost-efficient, comfortable and reliable DH. Due to huge investment needs, financial resources of the locals and the IFIs are not sufficient to cover the needs. Therefore, attraction of PSP to participate in the DH rehabilitation is necessary in order to speed up the comprehensive rehabilitation process. In order to do that, the barriers listed in Chapter 3 shall be phased out or their impact should be alleviated at least. Most of the barriers require institutional reforms on the heating sector. Some of the barriers related to uncertainty of the economy and the priority of a variety of candidate measures - both material and immaterial - of rehabilitation may be addressed by research.

The objective of the research project was further focused on developing methods and tools for planning the rehabilitation strategy for a DH system located in an ET in order to lower some barriers faced by the PSP.

6. General Approach

In general, the approach to meet the objective has been considered as follows:

1. Providing technical facts and best estimates based on the analyses carried out about the already completed rehabilitation projects to phase out the current uncertainty on technical and economic information;
2. Specifying the technical ways to respond to the economic requirements at least-cost;
3. Quantifying impacts and designing contents of immaterial measures on improving the overall performance of the system rehabilitation;
4. Optimizing the DH system in light of long term sustainability and under both economic and financial circumstances;
5. Prioritizing the material and immaterial measures to improve profitability under the financial constraints;
6. Offering guidelines to overcome institutional barriers of financing and implementing DH system rehabilitation.

Any kind of PSP (concession, acquisition, performance contracting, ESCO, leasing) requires accurate estimates on expected energy savings, accurately measurable results and, perhaps most importantly, a sound institutional environment.

Basically, optimization of the existing DH system includes a few phases as illustrated in Fig. 2 below, which are discussed in Chapters to follow.

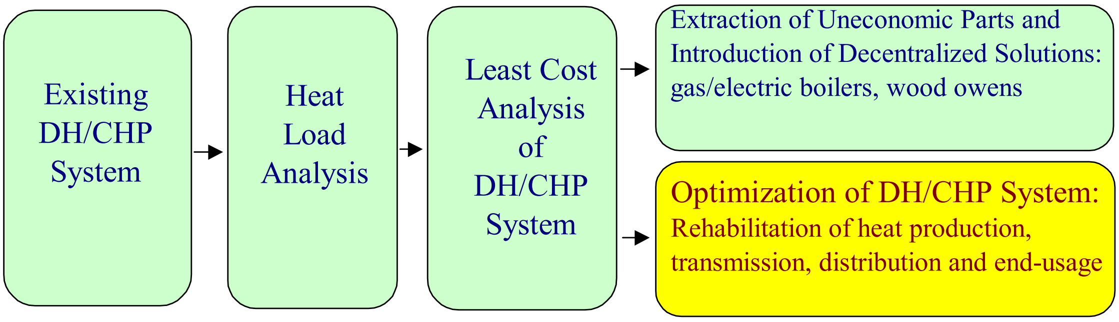


Figure 2. Steps from the existing DH system to the system level optimization.

6.1. *Heat Load Analysis*

The heat load analysis (Fig. 2) will create a basis for the rehabilitation needs and the resizing of equipment. The factors listed below should be taken into account while predicting the heat load of any DH system:

1. Demography; population age breakdown, number in the past, at present and prediction over 10 years to come;
2. Type and size of 3-5 typical residential buildings and their coverage in the city;
3. Energy audit of the typical residential buildings;
4. Connected floor area/space and number of people enjoying space heating and DHW;
5. Industrial load;
6. Gas network and expansion plans;
7. Construction: on going, decided and planned buildings; and,
8. Energy conservation based on planned investments and expected consumer behavior.

The heat demand can be manipulated by means of the four factors (a, b, c and d) explained below.

a) The connection rate of heat load defines how many of the radiators are connected to the system out of the total number of radiators. In some ETs the legislation of private rights has changed from the rather communistic one to an extreme respect on private rights and ownership. Such an exaggeration has taken place in Lithuania, Moldova and Bulgaria. Such a high respect has resulted in legislation according to which an apartment owner has full rights regarding his apartment, covering the selection of the heating method as well. Such right has caused numerous situations where individual apartments in a block connected to the DH system have disconnected from the DH supply and turned to other heating methods, most commonly to gas heating or even have remained disconnected. If an apartment in a block has been disconnected from the DH system, the neighbors still being connected to the system will actually heat up the disconnected apartment, since heat transfers through the non-insulated internal walls. Such a heating of the disconnected customers is called a free-rider problem, since the disconnected customers receive heat free of charge but their neighbors should pay for the increased heat consumption.

DH, however, is a collective heating system, where individual solutions poorly fit with the system rationale.

In Bulgaria, for example, the DH system rehabilitation has started with the demand side management (DSM) measures. First, all the BLSs were equipped with heat meters, totaling up to over 22,000 meters. Second, the substations were equipped with temperature control systems, and in cases were the existing tube heat exchangers were worn out, with plate heat exchangers. Simultaneously, the private sector was offered an opportunity to agree with the house owner associations or building administrators on installing thermostatic valves and cost allocators to radiators in apartments and organizing the allocator reading and invoicing of heat bills according to the readings. Such a PSP approach was supported by a strong public information campaign. Based on the PSP in DSM development in Bulgaria, the heat energy consumption of the apartments has dropped some 25% compared with earlier times without DSM in total. Simultaneously, the connection rate has risen from the level of 50-80% in 1999 to almost 100% in 2003 (Salminen, 2003).

Therefore, the connection rate is assumed to approach the value “1”, while the customers being physically connected to DH already will become hydraulically connected as well. The assumption presumes that both the rehabilitation rate of DSM measures and the heat metering rate to approach “1” as well, because the customer will obtain tools as well as incentives to control their heat consumption. Such an assumption is based on the Bulgarian experience, according to which practically no customer will remain disconnected if he has full means to control his own heat consumption and if the bills are based on the real consumption. The assumption should be supported by an institutional measure: the customer needs to pay for a fixed charge regardless of whether consuming heat or not in order to cover the fixed costs of the DHE responsible for keeping the heating available for the customers at any time.

b) The expansion rate, assuming that new customers join the DH system in the years to come. The value of the expansion rate can be expressed as an average annual percentage value. Such a rate can be useful, if constant increase of the densely populated area relatively close to or within the existing DH system supports the plans to extend the customer base. Basically, the expansion rate may be negative in the case where demolishing of the existing blocks overruns the heat load of the new customers to be connected;

c) The DHW rate in cases where DHW will grow faster than the SH demand. Normally, the expansion rate includes both SH and DHW. In some countries, however, such as in Serbia and China, for instance, DHW does not belong to the usual service of DH but is organized in other ways. The DHW may be heated up by means of electricity, natural gas or solar energy to mention a few, even though the particular building is connected to the DH system. Adding DHW to DH service pattern based on the incremental costs and benefits offers interesting means to improve the economy of DH. Regarding DHW supply by means other than DH, while analyzing the economy of converting DHW supply from the existing separate ones to the DH the alternative energies must be taken in to account in the economic analysis; and,

d) The availability rate of heat network takes into account the undelivered heat energy caused by poor sectioning in the network. Typically the repair works of the network have to be carried out in the summer time when the entire system is shut down for a few weeks. The repair seasons collective to all customers had to be adopted, because the production driven heat supply has been radial and the old-type valves have not been tight enough to close the heat supply, neither effectively nor safely. No sales of DHW can be done during the repair break. The existing loops in the network can be commissioned by means of the improved network sectioning with modern valves, and therefore the incremental DHW sales may materialize as the repair breaks can be avoided, thus gaining profit to the DHE and comfort to the customers. Using the availability rate, the undelivered heat energy will be added to the actual heat demand resulting in the real heat demand, which should be supplied if the network availability were equal to 1.

6.2. Least-cost Analysis

In general, a least-cost analysis should be carried out to regions where

1. Relatively low heat load density prevails, which is indicated by long network branches and scarcely located small customers;
2. Alternative fuels are available and seem competitive on site; and,
3. CHP neither is available at present nor seems feasible in the future.

In general, DH has proved to be the least-cost option in areas with a high heat load and high population density. However, high fixed costs may make DH too expensive in poor ETs where households consume less heat than the DH systems are designed to supply, and the households have lower heat expenditures than required for cost recovery (Lampietti and Meyer, 2002).

The least-cost analysis may provide a set of indicators that can be used later on in any DH system to justify whether a network partially or entirely really is the least-cost case for rehabilitation, or should the network be disconnected from the DH system. Some case studies in ETs have indicated that heat can be produced at an average economic cost ranging from US$ 7 with CHP plant to US$ 20 per MWh with building level boilers provided that the remuneration of the generated electricity at the CHP plant is at least US$ 40 per MWh and that the gas fuel is based on the economic price. (ESMAP, 2000, Executive summary).

Based on the least-cost analysis, the sustainable and unsustainable parts will be separated. The further optimization will focus on the sustainable entity of the existing DH system, as a focus of this research.

7. Scope of Research

The scope of the research will focus on the DH system, which has been identified as the least-cost approach in the long term. The DH system is the least known part for the PSP in the DH/CHP chain, starting from the fuels and reaching the end user, since

1. The network is mainly underground, geographically large and invisible, and therefore, the technical condition cannot be directly assessed; and
2. Little measured data is available about the various losses of the network and the consumer equipment. Typically, the heat production and water consumption are measured only at the heat sources but neither in the network nor at the consumer side.

Therefore, DH rehabilitation planning at present is based on fuzzy or no information. In order to have a holistic optimization of the entire system, a computerized Model was considered useful for PSP. The Model would use existing data, reasonably reliable estimates of those parameters not measured, and other experiences on immaterial benefits achieved. The Model should produce a strategic plan for DH rehabilitation helpful for PSP.

All DHW is excluded as well, because most of the customers are equipped with DHW supply from the DH system and no major rehabilitation needs are indicated there, except elimination of the GSs.

Elimination of GSs and small boilers fueled with solid fuel have been excluded from the Model building due to their location specific features.

8. Methodology

Regarding the methodology, three approaches were used to design the tool, the Model, for rehabilitation strategy planning of the DH systems in the ETs as follows:

1. Economic and Environmental Analyses of Completed Projects

The outcome of the five Polish rehabilitation cases as summarized in Appendix 1,was analyzed from economic and environmental point of view. The final result of rehabilitation was verified to the alternative business as usual, in other words, the business was compared with and without rehabilitation. The analyzed benefits of the rehabilitation including other lessons learned, as summarized in Appendix 1, were further developed in the two other approaches described below.

2. Questionnaire Analysis on Immaterial Measures

The goal was to find a quantitative relation between the immaterial and material measures and related benefits in order to have a holistic prioritization of all major measures, both material and immaterial ones. Therefore, a questionnaire analysis was found necessary in order to evaluate the impacts of the immaterial measures comprising education, co-operation, small investments in IT systems and maintenance practices. By means of the questionnaire, the task was to find out benefits and lessons learned from the large projects already completed or being completed shortly. Two prioritizations were made: first, the immaterial versus the material set of measures, and second, the individual measures inside the immaterial set of measures. The priorities were then used to model the impact of the immaterial measures in the Model on general level. The questionnaire form is presented in Appendix 2 and the specialists who have filled in the questionnaire are listed in Appendix 3.

3. Model for Rehabilitation Strategy

Development of a Model was considered useful for planning a rehabilitation strategy. The task of the Model is to produce an optimal rehabilitation strategy for the case system, either from the financial or the economic point of view. On the strategic level, the Model aims at optimizing the measures and the scheduling to rehabilitate a DH system in any city in the ETs under some restrictions to be discussed later in the document. Eligible measures consist of various investments in frequency controlled pumping, large, medium and small pipelines, consumer substations with/without heat exchangers and temperature controllers, network sectioning valves, CHP development, heat metering and DSM as well as of immaterial measures. The measures are used to improve the DH system economy. Based on the measures to be implemented, the energy system economy will be improved by reduced thermal, electricity and water losses, reduced flue gas emissions, reduced need of heat production capacity and both HR and repair works under the prevailing financial constraints. Moreover, the system economy may be improved by means of additional sales of heat and electric energy as well as of extended lifetime of the fixed assets. The Model has been documented, adjusted to the analyzed experience and demonstrated in a fictive case in Appendices 4, 5 and 6 respectively.

9. Requirements of Model

9.1. Challenges of Model Design

A potential investor may consider the rehabilitation feasibility from the financial and the economic point of view. The first considers the costs and benefits of the investor, whereas the latter considers the costs and benefits of the national economy. The economic view offers the potential for the investor that the investor may target by means of revised institutional framework: tariff system structure and level, including externalities to costs and benefits, ownership of fixed assets, etc.

The main conditions in designing the rehabilitation strategy are:

1. Predicting the heat load by means of the expansion rate, connection rate and the availability rate. However the DHW rate that is specific for a few countries only has been left for later development of the Model;
2. Limited financing available at the local district heating enterprise (DHE) and its owner;

3. Requirements and restrictions of financing at any potential investor and financier;
4. Low affordability of the customers preferring a low heat tariff level;
5. Unknown optimal order and quantity of a variety of investment options;
6. Uncertain quantitative importance, design and timing of the immaterial measures; and,
7. In general, incomplete institutional framework for PSP, either foreign or domestic, as addressed separately in the Handbook (Author, 2002).

As presented in Fig. 3, the regulatory framework of DH in an ET is out of the influence of PSP. The local regulator stipulates the rights and responsibilities of the owner, PSP, the DHE and the customers. A financier may fund the measures of the investor but not the ones of the DHE, because the DHE cannot offer eligible guarantees for the financier. The investor shall enter in a contract with the owner of the DHE in order to carry out material measures in heat sources, network and the substations as well as immaterial measures to improve HR productivity of the DHE. The Model is aimed at improving the quality and focus of the measures and alleviating risks related to the contract.

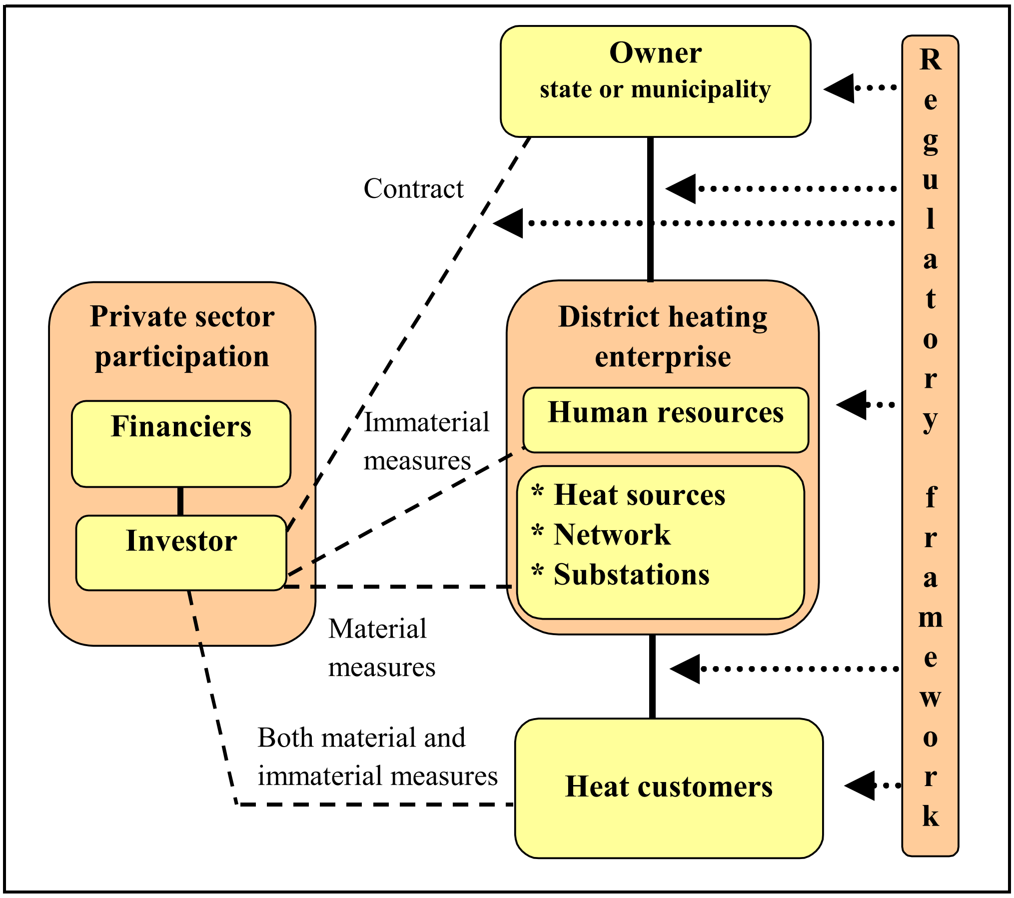


Figure 3. A typical regulatory framework of the DH in an ET.

The following two features have been excluded from the Model in detail, because a separate spread sheet is a more feasible approach to address the optimization need:

1. Group substations with four pipes: whether elimination or rehabilitation; and,
2. Heat only boilers: whether elimination, rehabilitation or fuel conversion.

Nevertheless, if the data has been prepared in a spreadsheet in a way appropriate to the structure of the Model, the Model offers assistance in optimizing the measures of the two issues above. Guidelines of data preparation are given in Appendix 5.

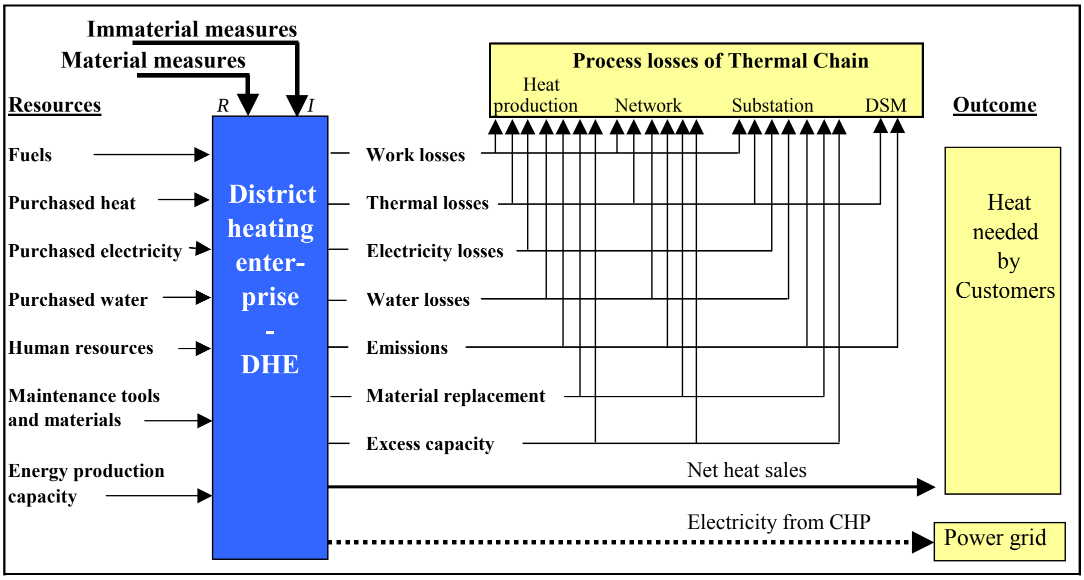


Figure 4. The loss flows of the resources in a district heating system.

9.2. Flows of Losses

Despite of offering an efficient infrastructure for energy supply, the DH system has a number of loss flows in operation, particularly in the ETs. Fig. 4 above lists the main resources, identifies the flows of lost resources and yields the final energy sales to the customers. The main flows of losses are as follows:

1. The work related losses are due to low productivity of using the HR in energy production, heat transmission and distribution;
2. Thermal transmission losses in pipelines are caused by the poor or missing thermal insulation of the pipelines, holes of insulation in valves, pumps and compensators, and in ventilation of chambers. High thermal losses at the heat sources are caused by poor combustion efficiency;
3. Electricity losses in DH pumping, despite being mainly used for compensation of the friction in pipelines, are due to poor efficiency of the pumps and couplings, low cooling, high roughness of pipes and excess pressure difference of the consumer equipment;
4. Water losses are caused by leaks in the network, heat exchangers and in control equipment, but mainly by illegal tapping at the consumer side;
5. The undesired environmental impacts (losses) are caused by the various emissions, mainly CO_2, SO_2, NO_x and dust;
6. Frequent replacement of materials – pipelines, heat exchangers, boilers – due to short lifetime causes maintenance costs; and,
7. Excess heat production capacity typically existing in the DH systems is a reason for excess maintenance costs.

9.3. *Lessons Learned from Completed Rehabilitation Projects*

In order to plan the optimal rehabilitation program for a case system under both financial and physical constraints, one has to have adequate information on how to economically and efficiently reduce the various losses described above. In general, such information is not directly available for the case, because the measured data recorded from the particular DHE is usually insufficient. Therefore, estimates will be generated to substitute for the lack of measured data. For creating such estimates the information collected and analyzed from the already completed large DH rehabilitation projects is essential.

During 1991-2001, comprehensive DH rehabilitation projects have been completed in Poland and the Baltic countries under co-financing of the World Bank loans. Experiences from the projects were analyzed, and the lessons learned are now available for design of new rehabilitation cases.

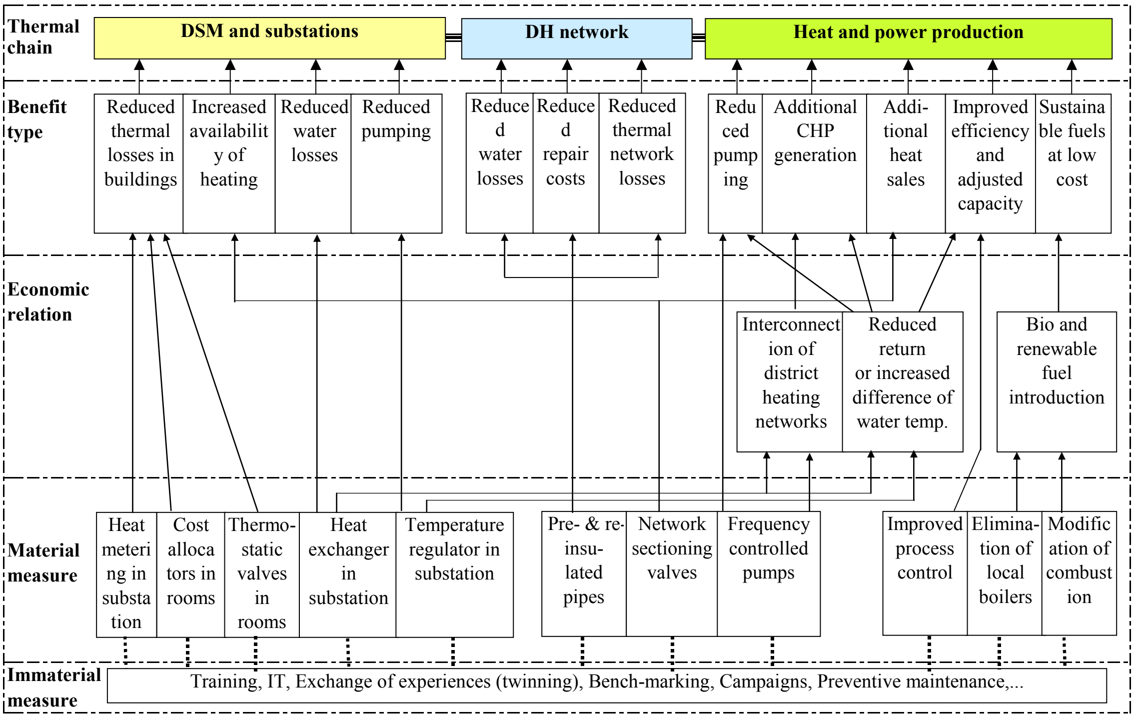


Figure 5. Relations between a variety of material (and immaterial) measures to the benefits of the components of the thermal chain.

Fig. 5 above illustrates the empiric relations between the major investments and the benefit categories. The immaterial measures, presented on the bottom of Fig. 5, have impacts on all the benefits. Education of HR reduces mistakes and speeds up processing tasks inside the DHE; new financial management tools will reveal a variety of matters causing financial losses, which, after recognized, may be promptly corrected; adopted preventive maintenance practices will reduce costs of maintenance, increase the system availability and extend the remaining life time of all the fixed assets, not only the assets having been rehabilitated.

The Model will give guidelines for the DH system development in the long term, for the period of 2-25 years ahead. The optimization will be based either on the economic or financial price estimates of the available resources such as fuel, water, electric power and HR, as well as sales revenues of heat and electricity.

10. Model Structure for Planning of Rehabilitation Strategy

The Model aims at optimizing the measures to rehabilitate a DH system in any city in the ETs on a robust level. Such measures consist of a variety of both material and immaterial measures. The material measures include rehabilitating large, medium, and small pipelines, consumer substations, network sectioning valves, CHP development, heat metering and DSM measures, as well as taking into account the total impact of the immaterial measures. The DH system economy will be improved by reducing thermal, electricity and water losses of the system as well as the need of HR and replacement investments by means of the measures under the financial and the physical constraints.

The documentation of the Model developed with GAMS with parameters, sets, scalars, tables and variables is presented in Appendix 4. The overall structure of the developed Model follows the general energy system modeling (Forsström and Tamminen, 1990, Goldstein at al, 2001).

The economic conclusions have been drawn from the case analyses (the World Bank, 2000 and 2001; Author, 2001). The conclusions have given the Model input data of the expected savings in use of the resources as functions of the completed measures.

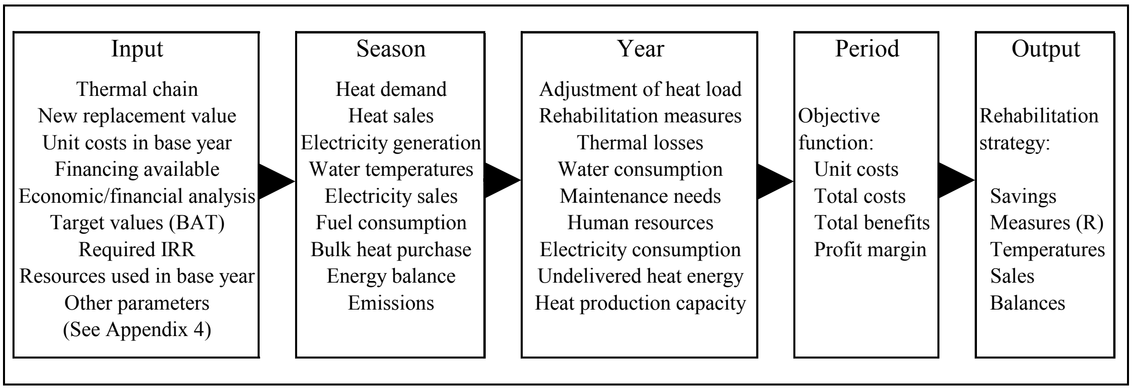


Figure 6. The timely structure of the Model.

The key definitions of the Model to start with are the input values of the base year and the unit prices of the resources, (ii) the features of the thermal chain, and (iii) the heat demand adjusted with the rates.

The Resource Input contains the unit prices and reference year consumption figures of resources such as a variety of fuels, water, electricity, HR and possible bulk heat purchase from an external source. The fuel prices and the unit costs of emissions, both from the economic and the financial point of view, are included in the Model. The operator has to choose whether the optimization is carried out from financial or economic point of view.

The energy sources in a CHP or a HoB plant will be specified by means of the heat production capacity, the annual energy efficiency, the annual energy availability and the annual cleaning rates for dust, SO_2 and NO_x emissions. The cleaning rates describe the environmental investments already done at the heat source. The rates are parameters, which may be changed in case direct investments in flue gas cleaning are under consideration.

For each type of fuel, the unit price in the economic and the financial analysis, the annual price escalation factor, the emission factors for CO_2, dust, SO_2 and NO_x based on normal combustion of such fuels without any flue gas cleaning available shall be inserted.

The unit costs shall be given for flue gas emissions for each type of emissions such as CO_2, dust, SO_2 and NO_x separately for financial and economic analysis, adding up to eight values altogether. The prices will be adopted for calculation depending on whether the economic or the financial case has been chosen and adjusted for the years to come according to the emission specific price escalators.

Aside from fuel, other types of resources are included in the Model, as presented in Fig. 4. For each such resource the volume of use on the base year shall be given. Moreover, for each such resource the unit cost shall be given separately for the economic and the financial analysis. The unit costs of resources can be raised/lowered in real terms from year to year by means of the inserted escalation factors. For each resource, a resource specific price escalation factor can be given, which calculates the annual increase/decrease of the particular unit price in the real terms during the entire period of planning. The escalation factors will be used in the Model both in the financial and in the economic analysis.

For water, heat, electricity and HR, the allocation of the particular resource both on the base year level and on the target level shall be allocated to the components of the thermal chain. For assessing the target level allocation, either benchmarking files possibly available or the individual target values of the investor/financier should be used.

The supply and return water temperature of the network shall be given collectively at the heat production level separately for each season of a year describing both the prevailing level before the rehabilitation and the minimum allowed level, adding up to eight values altogether. In calculation, the transfer from the prevailing to the target values is proportional to the temperature control system rehabilitation rate at the consumer substations.

The sales of heat and, in case a CHP plant is included, electric power are resources that help improve the system economy. In addition, the undelivered heat caused by poor network sectioning may be phased out, and additional heat sales will materialize. For heat and electricity sales as well as for undelivered heat energy the unit prices shall be given separately for the economic and the financial analysis. Moreover, escalation factor for the prices shall be given, which will change the price of the particular sales annually. The economic sales prices should be set according to the affordability of customers and the requirements of the electricity market.

The Heat Demand comprises an approximation of the annual heat load duration consisting of four seasons (winter, spring, summer and autumn) as well as of four values of seasonal duration hours allocating the annual heat demand to the seasons.

The heat demand on the base year will be calculated from the measured heat production by means of the chain of the estimated loss factors of the base year from the heat production until the room radiators and to the isolation valves of the BLS in the economic and in the financial analyses respectively. This is because the heat demand is usually unknown but the heat production is metered and recorded.

The rates of connection, expansion and availability are used in the Model to manipulate the heat demand as required. An increasing rate value indicates a proportional increase in the heat demand.

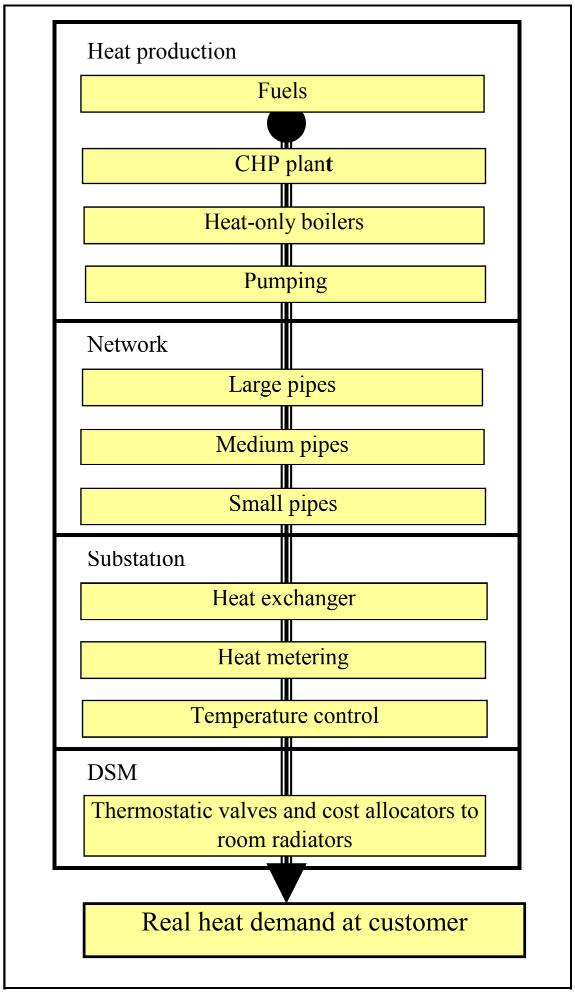


Figure 7. The thermal chain of components in the Model.

The Thermal Chain in the Model, as mentioned in Fig 6 and illustrated in Fig. 7, consists of consequential components. The components include (i) heat production with fuels, a CHP plant, HoBs and DH pumping, (ii) network with heat transmission in large and medium size pipelines and heat distribution with small pipelines, (iii) consumer substation with heat exchanger of the SH circuit, heat metering on building level, temperature controller at substations, and finally, (iv) the DSM measures with thermostatic valves and cost allocators in room radiators. In the financial analysis, however, the components beyond the heat meter have been neglected, as they are usually not owned by the DHE. The heat exchanger, however, is located before the heat meter in the chain, although physically being after it. The water savings, based on the heat exchanger installation, are financial savings for the DHE. The features of the thermal chain cover selected scalars describing the local DH system, briefly as follows:

1. The total heat supply of the heat production plants and the bulk-heat purchase sources in the base year shall be given. The total heat supply together with the

thermal loss factors of the thermal chain reflecting the base year will be used by the Model to determine the seldom measured and therefore unknown real heat demand of the system;

2. Both the power-to-heat ratio and the power generation sensitivity to return water temperature values shall be given specifically for the CHP plant. The capacity of the CHP plant shall be indicated by means of the heat supply capacity;
3. A switch for either financial (0) or economic analysis (1). The Model selects the components of the thermal chain and the unit costs of resources for the analysis according to the given value of the switch;
4. The expected lifetime of the new investments in average. The average expected lifetime will be used to linearly depreciate the investments. The depreciation will be used as investments of the selected period, whereas the remnant value of funds will remain unused in the analyses. The expected economic lifetime varies from 20 to 30 years, with the lower limit being more common for boilers and substations and the upper limit for pipelines;
5. The new replacement value – NRV shall be given to each component of the thermal chain. Rehabilitation of any of the components in the thermal chain up to its NRV corresponds to the rehabilitation rate R equal to 1 for the particular component;
6. The down-sizing factor for investments is needed, because typically some of the system components have initially been oversized. The pipelines, for instance, have initially been sized for a radial type of supply in the production driven mode and with excess reserves for possible expansion of the system later on. Therefore the rehabilitation of such pipelines with equal diameter may not be economically justified particularly when turning the system to variable flow. Replacing the old pipelines with often smaller pipelines should be used instead of the initial size of pipes. The re-sizing of the network depends on the heat load forecast and the separate hydraulic analysis of the network simulated in the demand driven mode. The systematic re-sizing of any component of the thermal chain can be done by means of a component specific down-sizing factor. The down-sizing factors shall be inserted to the Model specific to each component. In the Model, the down-sizing factor reduces the given value of the NRV of the component in order to down-size the needed investments;
7. Lifetime extension of the fixed assets is one of the main benefits in rehabilitation. This has been taken into account by means of the expected lifetime of the rehabilitated components and the remaining lifetime of the existing components in the base year;
8. Reduction of pumping power takes place in two stages. First, the variety of measures improving the economy of the thermal chain will reduce the electricity used for pumping. Second, a frequency controller may be installed to control DH pumping, thus directly reducing electricity consumption;
9. The commercial losses, caused by heating of the network water lost at the customer premises free of charge, may be turned to financial heat sales after the heat exchanger and the heat meter have been installed to the BLS. Such recovery of commercial losses reflecting the rehabilitation rate of both aforementioned components shall be given to the Model;
10. The connection rate of the existing heat customers prevailing in the base year shall be inserted to the Model. In course of the rehabilitation, investments in heat metering, temperature controllers and in DSM are assumed to linearly phase out the disconnection problem, thus adding the heat demand accordingly;

11. In order to assess the costs of maintaining the excess heat production capacity in the system, three parameters shall be inserted to the Model, namely (i) the peak load duration hours of the heat production in the base year, which shall be estimated by means of the operation diary, (ii) the percentage value of reserve capacity truly required, and (iii) the annual costs of maintaining the excess reserve capacity;
12. Efficiency of DH pumping in the base year shall be estimated;
13. Impact of the immaterial measures to the rehabilitation benefits is based on the results of the questionnaire analysis discussed later in this document. A switch should be inserted to the Model implying whether or not the immaterial measures will be taken into account in benefit calculation;
14. The financing available for the rehabilitation investments and the possible annual constraints have to be inserted into the Model in total and of a maximum percentage of the total financing per year respectively. The Model does not use the funds in case the measures do not gain sufficient benefits while maximizing the profit margin;
15. The investor always has a minimum requirement on the IRR regarding the funds invested in the rehabilitation. The required IRR value adjusting the annual benefits and investments in the cash flow of the objective function shall be inserted to the Model;
16. The total costs estimate for sufficient sectioning of the DH network should be inserted to the Model;
17. The undelivered heat energy caused by poor network sectioning shall be given in terms of a percentage value out of the total heat demand;
18. The unit price of the expected CO_2 savings based on Kioto Protocol shall be given. The Model assumes that the emission credits are available from the second year of the period on, thus simplifying the regulations of Kioto Protocol;
19. Simulating the Kioto Protocol, the electricity generated by the CHP process will reduce CO_2 emissions elsewhere, presumably at condensing power plants. However the value of generated CHP electricity depends on the ET of the case and shall be adjusted accordingly; and,
20. According to Kioto Protocol, a switch in the Model selects whether the baseline or the target level, after the rehabilitation measures completed, shall be calculated. In order to calculate the expected emission credits the emission level of the baseline case shall be given as an input value for the rehabilitation case.

The Benefit Potential, or the efficiency gap in other words, set by means of benchmarking gives the total potential in savings of the resources between the current inefficient system and the long-term optimal system. The potential can be achieved if all equipment and systems will be replaced, and the number of HR will be adjusted to the real need and educated to meet the modern requirements.

The existing level of the thermal losses may be estimated as follows:

1. In five Polish reference cases the thermal losses of the pipelines used to range from 3 to 4.5 times higher than the theoretical values of the corresponding new pipelines on average, while the average size of pipelines ranged from DN 216 to DN 333 equivalent.
2. In Bulgaria, where the DH systems represent a similar type as in Poland for a decade ago, the DSM measures together with controlling substations and heat metering have resulted in 25% savings in energy consumption on the building level. Heat metering alone does not provide any technical means of energy conservation, and therefore the impact on energy consumption is assumed at zero

or insignificant. Controlling properties of the substation are substantially larger than those of the DSM measures. Therefore, approximately two thirds of the consumer side energy saving potential is attributed to the substation control and the balance to the DSM measures in the Model.

The target level of heat transmission and distribution losses may be estimated according to the pipeline manufacturer brochures and/or to the experiences of similar companies with modern types of pipelines and with advanced maintenance procedures. The thermal losses of modern substations and DSM equipment have been estimated at zero. The HR requirement should be estimated according to experiences of the benchmarking or to the targets of the investor.

10.1. Benefits Depending on Rehabilitation Rate

The benefits accrue in a variety of ways depending on the type of the particular measure. The most essential investments comprise boilers at heat sources, pipelines in the network and control systems in the substations. Such investments comprise the bulk of the costs in any comprehensive rehabilitation project, typically more than 90% of the total costs. Due to their high volume, the dependence of the expected benefits on the rehabilitation rate deserves a closer focus.

The Benefits depending on the rehabilitation rate R indicate the impact of the investments on the benefits of any component. For instance, investments in the worst pipes have a higher IRR than replacing all the pipes of the system. On the contrary, replacing only a few substations may have a lower IRR than replacing the bulk of the substations, which finally would change the operation mode from the production to the demand driven one.

The benefits are assumed as functions of the rehabilitation rates. The functions of the LP Model consist of both truly linear and linearized ones, whereas non-linear functions are also included in the NLP Model.

The positive variable R(c,t) specific to any component c has a range from zero to one. The benefit depends on the value of R(c,t). In LP the dependence is a linear, whereas in NLP a non-linear benefit function of the type of either a trigonometric (1), a logarithmic (2) or an exponential (3) one has been selected. The selection is based on the author’s understanding and experience about the behavior of various ways of benefit accrual expressed in mathematical approximations, and not on any tests. Therefore, the approximations do not simulate the real behavior in an accurate manner but are assumed to be better than the linear approximations. The selected function types for such approximation are expressed below and illustrated in Fig. 8:

$$\Theta(c,t) = 1 - \cos(\tfrac{1}{2}\pi R(c,t)) \quad (1)$$

$$\Theta(c,t) = \lg(10 R(c,t) + 1) \quad (2)$$

$$\Theta(c,t) = 0.1/(0.1 + 10 e^{(-10 R(c,t))}) \quad (3)$$

With the conservative trigonometric function (1), the benefits of HR start accruing slowly and are delayed after the rehabilitation measures have been executed. The benefits lag behind the implemented measures but reach the final value when the R reaches the value 1. The trigonometric function simulates (i) the behavior of labor unions, since the HR reduction may not be allowed instantaneously following the investment measures, (ii) and moreover, may not be reasonable, because implementation of the investments requires temporarily more HR to install, supervise and tune the new equipment in the rehabilitation phase than to use them later in the O&M phase.

By means of the logarithmic function (2) the benefits start accruing fast, as the earlier rehabilitated pipes and boilers most likely have been in the worst condition. Therefore, the early rehabilitation of such worst equipment would yield higher relative benefits than those to be rehabilitated later on and, often being in a relatively good technical shape.

With the exponential function (3), the benefits start accruing slowly at first. The factor Θ lags behind the value of R until about 0.4, after which the values of Θ exceed the value of R. Such a benefit function is typical for the temperature controllers in substations: The R has to reach a critical mass before the system operation turns from the production to the demand driven mode.

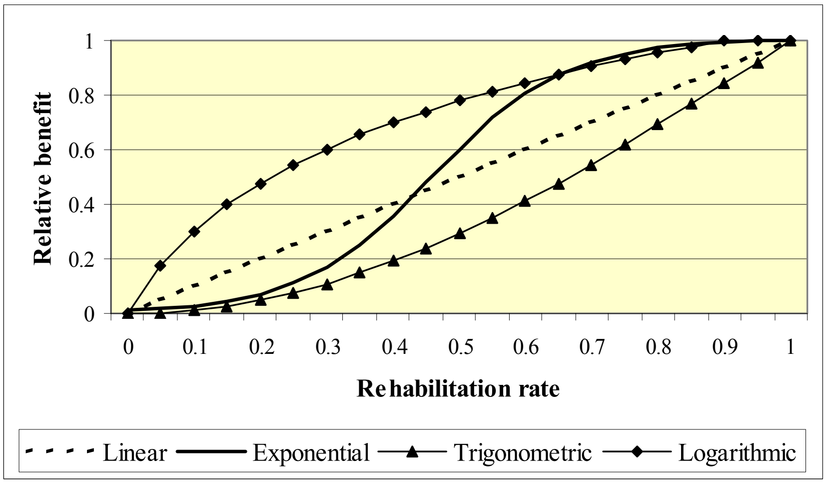


Figure 8. The relative benefit of the rehabilitation measures according to different types of benefit weighing functions.

The first investments on the substation control systems will yield little or no incremental benefits for the system. This is the case when the rehabilitation rate ranges from zero to some 0.3. These benefits are expected to be insignificant because:

1. In winter, the control valves of the new substations are mostly open and the substation takes heat energy from the network at full capacity. The pressure loss of the modern substations with heat exchangers and the control valve is about 40 kPa only, whereas more than 150 kPa is required by the old hydroelevators. Therefore, the modern substations effectively supply heat in any case but the hydroelevators may face problems, if either the supply capacity or the pressure level is not sufficient. Therefore, there are no substantial system level benefits identified in the winter.
2. In spring and fall, on the other hand, the control valves of the modern substations throttle the water flow according to heating needs of the particular building. The old hydroelevators, which typically provide their buildings with excess energy for the SH circuit in order to keep the DHW temperature on the required level, will face an even higher pressure difference than before the modern substations were connected to the network. Therefore, the modern substations may even worsen the situation by increasing the excess heating of the SH circuit in hydroelevator

systems. Thus, no considerable system level benefits can be identified in the spring and fall seasons either.

When the rehabilitation rate will be increased from some 30 to 70%, the system operation will change from the old constant to a new variable flow mode, in other words, from the production to the demand driven operation. The range from 30 to 70% represents the strongly progressing benefit function with a high incremental IRR.

In the Model, the above dependencies are modeled as linear and non-linear approximation patterns in the LP and the NLP options, respectively.

10.2. Model Components

In the Model, as presented in Fig. 6 before, the following features have been applied.

For each season, the seasonal heat demand has been created by means of the heat load duration approximation. The energy balance of the season including purchase, production and sales of energy as well as thermal losses of the thermal chain will be formed, based on the component efficiencies of the chain. Moreover, the flue gas emissions will be quantified and the DH water temperatures determined at the heat source for each season. The efficiency of each component and the water temperatures of the DH supply depends on the annual rehabilitation rate - specific for each of the material measures under consideration.

The fuels applied in the Model may consist of any possible type of fuel such as coal, gas, heavy or light fuel, peat, bio fuel or recycled waste. Each fuel will be characterized by means of the equivalent price per lower heating value and specific emission factors for sulfur, nitrogen and carbon oxides as well as particles (dust).

The CHP component is described by means of the constant power-to-heat ratio, α, and its sensitivity to water temperature changes. The component parameters include the total plant efficiency, the type of fuel and the annual energy availability. The CHP component in the Model is able to operate in the CHP mode only. Moreover, only one CHP plant can be included in the Model at the time, as is typical in the systems in the ETs.

The heat-only-boiler (HoB) component may include an unrestricted number of boilers connected to the same network. Each boiler is characterized by production capacity, boiler efficiency, type of fuel, emission cleaning rates and annual energy availability.

In the Model, the heating network is divided to three components according to the size of the pipes, such as large, medium and small pipes. Despite physically being in a grid form, they are described as a chain of components where the bulk of medium size pipelines follow the large pipelines, and similarly, the small pipelines follow the ones of the medium size. The small pipes physically connected to the large transmission pipes are usually small in number and, therefore, have been neglected in the Model. While transmitting hot water, the network components cause losses in thermal energy, water and maintenance material as well as unproductive use of HR. The length, size and age of the pipelines in the case system are always known at least in a reasonable accuracy, but not precisely. This may appear surprising; does the DHE not always know the technical data of the network that they operate? In many ETs, the local DHE is the operator of the system only. Typically, the municipality owns the fixed assets at least partly. The local design institute is often responsible for designing system repairs and extensions, and therefore, has the technical data of the system. Therefore, the DHE may not have all essential data of the network in disposal.

The substation component consists of three parts: (i) a water temperature controller, which controls SH water temperature according to the ambient temperature variations, (ii) heat metering, which comprises the heat meter measuring the heat consumption on the building level to be installed in the BLS, and (iii) a heat exchanger as water circuit isolator in the SH circuit. The water temperature control is based on the outdoor temperature and the estimated properties of the radiator network. The SH and the DHW temperatures, with a possible heat exchanger, determine the requirements of the primary water flow, supply temperature and results in a return temperature delivered to the DH network.

The DSM measures consist of both a thermostatic valve and a cost allocator installed in a room radiator.

There shall be a control system in the BLS before the benefits of the DSM measures become relevant, as is programmed in the Model. Another condition is set in the Model, not allowing a greater number of DSM measures and temperature than heat meters controllers installed in the buildings. The rationale of such conditions is that the customer is expected to save energy if both incentives (heat metering) and means (temperature controllers and DSM) are available.

Parallel to the chain described in Fig. 7, other measures/benefits are included in the Model as follows:

1. Modernization of a set of network valves will allow network looping and maintenance works during operation, not only during the long summer break as is the common practice. The new valves will cause additional sales of DHW due to shortened/avoided summer break. The new sectioning will also reduce water losses due to earlier repair of damages, which, however, is neglected in the Model as less significant.
2. The electric power used for pumping will be allocated to thermal losses and the friction heating of the circulation water. This separation will be done for all pumping in the network.
3. The amount of excess heat production capacity will be calculated and suggested for shut-down. The consecutive savings in HR and material maintenance are roughly taken into account in the Model. The excess capacity is one of the typical features of the systems in ETs.

10.3. Variables and Parameters of the Model

The detailed list of the variables and the parameters of the Model is presented in Appendix 4 and the input value tables, covering the parameter values in Table 6.1 of Appendix 6. A summary of the variables and parameters of the Model is presented here.

The variables are subject to optimization (i) on the seasonal level, or further (ii) on the annual and (iii) on the periodical level.

(i) Variables ranging from a season to the period

- Heat supply
- Electricity sales of CHP plant
- Fuel consumption
- Flue gas emissions
- Bulk heat purchase
- Supply and return water temperatures

(ii) Variables ranging from a year to the period

- Heat sales covering energy both for SH and DHW
- Investments and rehabilitation rates
- Thermal losses
- Water consumption

- Maintenance materials
- Electricity consumption
- HR
- Excess heat production capacity

(iii) Variables over the period

- Costs and benefits

The parameters of the Model consist of both (i) individual parameter values, referred to as scalars in GAMS terminology, and of (ii) a number of series of individual parameters, referred to as sets of parameters respectively. The summary of the parameters is as follows:

- Single parameters – scalars
- Parameters consisting of sets.

11. Seasonal Features

11.1. Energy Production and Fuels

The energy and emission balance of a year is the sum of the specific balances of the four seasons.

During a season, the sum of the produced heat energy and the purchased bulk heat energy is equal to that given for transmission at the gate of the heat sources:

$$\sum_{i=1}^{n} \eta_i \Phi_i + Q_b = Q_{de} \tag{4}$$

Typically only one heat purchase option is available in a DH system, as included in the Model.

11.2. Peak Load Duration Time

The peak load duration times **τ** for heat production, heat transmission and distribution losses and final heat consumption are different.

The peak load duration time of heat production, for instance, in five Polish systems has been about 2,300 hours. One may assume that the final consumption roughly meets the peak load duration of the Nordic modern systems, about 1,800 hours.

The peak load duration time of the heat distribution losses caused by poorly functioning substations is irrelevant, as the losses take place during the transition periods such as spring and fall and do not require any heat production capacity.

Based on the above, the peak load duration time estimate of the transmission losses amounts to about 3,100 hours.

Obviously, such estimates for **τ** depend on the climate conditions prevailing in the case location.

11.3. Heat Production Capacity

The DH system rehabilitation typically has some impact on the heat production capacity required in the system.

In the radial system typical for the ETs the reserve capacity has to be located at the same site, as the main (single) heat source amounting to 50-100% of the real heat load. If the critical transmission pipe is broken the reserve capacity may not be more helpful than the operative capacity. In an ET city typically a number of separate radial systems exist, each requiring their own heat source and related reserve capacity. Therefore, the construction and maintenance costs of such a large reserve production capacity are relatively high.

On the other hand, in the looped system typical for the Nordic EU countries, the heat sources can be located all over the city and connected to one united network, thus supporting each other. Therefore, little excess reserve capacity, only about 10% of the real heat load or the size of the largest boiler unit, is needed and the different locations are redundant to each other. In this way the cost of reserve capacity remain modest.

When an existing boiler plant is eliminated and the customers are connected to the DH network, the substation capacity should be sized according to the real heat load, not according to the total capacity of the boilers that used to be on site.

The Model estimates the amount of the excess heat supply capacity for possible elimination. The benefit of such elimination is valued by means of an input parameter expressing maintenance related savings per eliminated boiler capacity unit.

11.4. Water Temperatures

The water temperature controller of the SH circuit in the substation reduces excess heating of the building and changes the supply (t_s) and return water (t_r) temperature levels in the SH circuit, usually improving cooling of the DH network as well.

In the Model the water temperatures of the supply side will be calculated for each season depending on the rehabilitation rate of the thermal control of substations. Based on the experience in Poland, the fall in the supply temperature has been about a half of the temperature of the return temperature, thus increasing the cooling (Appendix 5). During a season the changes in water temperatures depending on the rehabilitation rate of the temperature control systems to be installed in the substations are as follows:

$$\Delta t_r(t) = -R_{co}(t)\ (t_{r,o} - t_{r,m}) \qquad (5)$$

$$\Delta t_s(t) = -0.5\ R_{co}(t)\ (t_{s,o} - t_{s,m}) \qquad (6)$$

Where R_{co} is the rehabilitation rate of temperature controllers in the BLSs, Δt_r and Δt_s are the expected changes in supply and return water temperature respectively, $t_{r,o}$ and $t_{s,o}$ are the initial values of supply and return water temperatures in the base year respectively, and finally, $t_{r,m}$ and $t_{s,m}$ are the minimum allowed values of the supply and return water temperatures in a season respectively.

11.5. Electricity Generation in CHP

The CHP production is used to gain electricity sales revenues for the DHE. From operation point of view, CHP production takes place if the market price of electricity exceeds the price of the CHP fuel divided by the efficiency of the CHP plant.

The focus here is more in DH than in CHP. Therefore, the Model does not optimize the existence or size of the CHP plants, but the CHP plant, whether existing or planned, shall be specified to the Model.

The power-to-heat ratio α defines the electric power production based on the relevant heat load, as follows:

$$\alpha\ \hat{Q}_{chp}(s)\ \tau(s) = P(s) \qquad (7)$$

Fuel consumption Φ of the CHP plant in a season is

$$(1+\alpha)\,\tau(s)\ \hat{Q}_{chp}(s) = \Phi_{chp}(s)\ \eta_{chp} \qquad (8)$$

Where α is the power-to-heat ratio of the CHP plant, $\hat{Q}_{chp}$ is the heat production capacity of the CHP plant used in the season, η_{chp} is the total efficiency of the CHP plant, Φ_{chp} is the fuel energy of the CHP plant in the season, τ is the duration time of the season, and P is the electric energy generated by the CHP plant in the season.

The electricity sales are considered at the main switch gear of the CHP plant as net energy supplied to the grid. The CHP production depends on either the actual average heat load or the capacity of the CHP plant, which ever is lower, and multiplied by the power-to-heat ratio of the plant. The CHP power supply of a season will be adjusted according to the return water temperatures and the rehabilitation rate of the substation control systems, as follows:

$$P(s) = \hat{Q}_{chp}(s)\ \tau(s)\ \alpha\,(1 + \xi\ \Delta t_r(s)) \qquad (9)$$

11.6. Flue Gas Emissions

In the Model, the flue gas emissions of a season are calculated according to the fuel specific emission factors as well as the plant and the emission specific cleaning rates.

At any energy source, an emission specific flue gas cleaning rate will reduce the emissions of SO_2, NO_x and dust accordingly.

In the financial analysis, the CO_2 benefits are calculated by means of the total emission difference between the baseline and the results of rehabilitation. For the electric energy generated by the CHP plant, the conversion factor inserted to the Model will convert the electric energy to reduced CO_2 emission equivalents.

In the economic analysis, all emissions are calculated for heat production only. The emissions of the electricity production at the CHP plant do not usually increase the emissions on the national level, but on the contrary, will reduce such emissions elsewhere. Therefore, all emissions of electricity generation have been conservatively neglected in the economic analysis of the Model.

No green house gases other than CO_2 are included in the Model.

12. Annual Investments and Benefits

12.1. Rehabilitation Investments

The typical investments as the material measures consist of:

1. New boilers, fuel conversions or boiler improvements;
2. Frequency controlled DH pumps
3. New preinsulated pipelines either for transmission or distribution lines;
4. Modernization of consumer substations, usually by means of prefabricated compact substations;
5. Replacement or installation of heat exchangers;
6. Installation of temperature control systems to existing substations;
7. Heat meters to substations;
8. Gate valves to the network for sectioning;
9. Thermostatic valves and costs allocators to radiators (DSM).

There are other investment candidates, of course, as well, for instance as follows:

1. Re-insulation of aboveground pipelines. Usually, the share of aboveground pipelines in a DHE amounts to about 10% of the total network length. Such pipelines and their physical conditions are visible and their re-insulation needs and costs can be assessed separately. There is no separate feature in the Model to take into account the re-insulation of the aboveground pipelines. Therefore, the impact shall be taken into account by reducing the NRV, for instance;
2. Installation of de-aeration valves, ventilation and drainage of the pipeline channels. Such a measure extends the lifetime of the pipelines by preventing external corrosion of the pipelines by keeping the channels dry. The investment costs of such a measure depend on the local conditions and is required only if the existing pipelines will be rehabilitated. No such experience was identified in the 14 DHEs participating in the research. Therefore, no cost estimates are available from the real world. Due to its absence such maintenance approach has been assumed to be covered by the other maintenance related benefits of the Model, such as the extension of the lifetime of the assets and the increased productivity of HR in the O&M functions.

In order to minimize the unavailability of the heating services the bulk of the investments will be carried out in the summer season. In the Model, the benefits of the investments start accrue in the next year after the investment has been executed. The obvious benefits of the first autumn after the investments have been completed have been neglected in the benefit accrual, since the first autumn is conservatively considered a commissioning and testing season without full-scale benefits.

12.2. Thermal Efficiency of District Heating

In the **thermal chain**, one has to insert two estimate sets of the thermal loss percentages, two estimates for each component of the Model. The first set of estimates reflects the loss percentage values in the base year and the second set reflects the ones expected in the target year. A parameter β_c will be calculated for each component as a difference between the base year and target year values in order to express the relative thermal saving potential related to rehabilitation of the particular component.

In NLP, the heat energy transfer in the thermal chain is characterized by means of the recursive formula as follows:

$$Q(c,t) = \eta_o(c)\, Q(c-1,t) + \beta_{dh}(c)\, \Theta(c,t)\, Q(c-1,t) \tag{10}$$

In the NLP, the benefit weighing function Θ has been used instead of the rehabilitation rate, because the benefits are assumed to accrue in different nonlinear ways depending on the component.

For LP, the above formula has been linearized in order to avoid the product of the two time dependent variables, Θ and Q, by means of the three first terms of the Taylor series method (Braun, 1978).

$$\begin{aligned} Q(c,t) = {} & \eta_o(c)\, Q(c-1,t) + \beta_{dh}(c)\, [R(c,t)\, Q(c-1,0) + \\ & R_o(c,t)\ (Q(c-1,t) - Q(c-1,0)) + (R(c,t) - R_o(c,t)\, Q(c-1,t))\,] \end{aligned} \tag{11}$$

Where $Q(c,t)$ means the heat energy at the output of component c during the year t, $\eta_o(c)$ the efficiency of the component c during the base year o, $\beta_{dh}(c)$ the potential of thermal energy savings at component c as inserted by means of the sets of estimates, and, $R(c,t)$ the rehabilitation rate of component c at the end of year t.

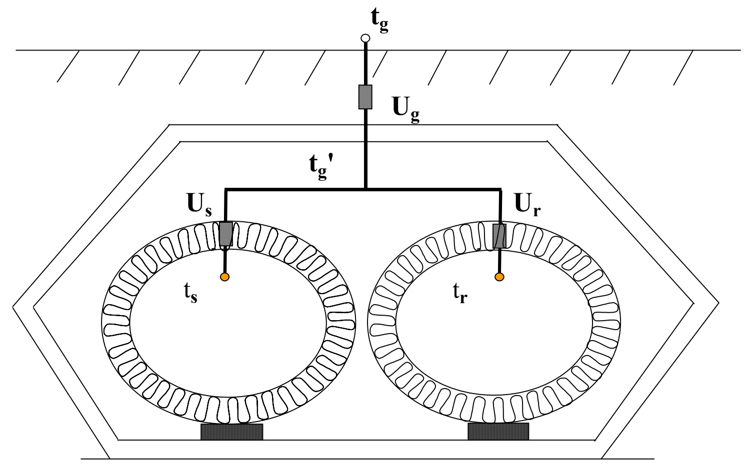
The formulas (10) and (11) indicate that the Model is dynamic; the achieved level of rehabilitation in a year creates the basic value for additional rehabilitation in the consecutive year throughout the selected period of years. In the Model, the level of the rehabilitation rate, as a variable ranging from 0 to 1, reflects the relative level of the investments in any component of the thermal chain.

Thermal losses of the thermal chain are assumed as the difference of the heat energy of the second component, heat production, and the last component, the heat sales, as follows:

$$Q_l(t) = Q_{pr}(t) - Q_{de}(t) \tag{12}$$

The thermal losses have been divided to three parts depending whether to relate to excess water temperature, heating up the make-up water or to the base losses (Appendix 4).

Theoretically, the **thermal transmission and distribution losses** per network length under steady-state conditions can be simplified as presented in Fig 9.



t_g and t_g': Undisturbed temperature in the soil and in the channel respectively
t_s and t_r: Supply and return water temperature respectively
U_g,U_s,U_r: Thermal loss coefficients of the ambient soil as well as the thermal insulation of the supply and the return pipe respectively

Figure 9. Thermal Conductivity in a Typical Cross-section of a DH Pipeline.

The thermal losses of the network, calculated separately for large, medium and small pipelines in the Model in a steady-state environment, depend on the thermal loss coefficients U and the temperatures t in general as follows:

$$Q_l = U_g\,(t_g - t_g') = U_s\,(t_g' - t_s) + U_r\,(t_g' - t_r) \tag{13}$$

Where Q_l is the thermal loss, U is the heat loss coefficient, t is the temperature and the subscripts a, s, r and l relate to ambient soil, supply and return water and the losses respectively.

The thermal network losses are known only when the heat energy is measured both at the heat sources and at the heat customers by means of heat energy meters. In the reference cases, the heat sources were usually equipped with heat meters, but the consumers became metered gradually during the course of the DH system rehabilitation, practically having had no consumer metering at all before the rehabilitation had started. This is a typical situation in the DH systems all over the ETs before rehabilitation.

Therefore, in the reference cases the thermal network losses of the early years have been estimated by the DHEs themselves by using different methods based on various conditions that have prevailed in early 1990's and in 2000's. The parameters used in estimation were as follows:

1. Levels of the water temperatures;
2. Length of the network;
3. Network rehabilitation rate; and,
4. Estimated real heat sales based on the connected building volume.

Heating up the make-up water, which has been lost in the consumer installation and partially in the network, does not necessarily belong to thermal transmission losses. Heating takes place at the heat sources, thus being an internal process loss of the heat source. On the other hand, the make-up water will be transferred to the customers where most of the water will be lost, thus indicating that the energy is a consumer related loss. The change in make-up water consumption does not have any significant impact on the thermal transmission losses, even though the water flow rate may decline but the water temperatures remain the same. Therefore, the thermal losses of make-up water heating are consumer related losses, mainly attributed to the direct substation structure.

At the heat source, the connection of heat meter and make-up water input has impacts on how the thermal make-up water losses should be considered. In Fig. 10, the heat meter does not recognize the make-up water flow if connected like A but does if connected like B. Nevertheless, the impact of the connection adds up to 0.7 to 2.2% of the thermal network losses in the reference cases, except in one of them having 6.7% of the network losses in year 1992.

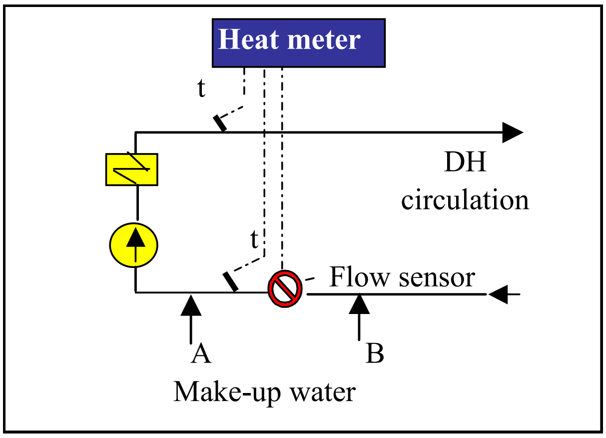


Figure 10. Locations A and B available for make-up water input affecting the heat metering at the heat source.

Simultaneously, the DHEs have managed to reduce water losses substantially. Heating of the make-up water used to be 18% and 13% of the estimated thermal network losses before and after rehabilitation, respectively. The thermal losses caused by make-up water heating were calculated according to the temperature difference of the average water temperature of the network deducted by the average temperature of the city water, presumably 8 ^{o}C. Thus, the temperature difference ranging from 51^{o}C to 62^{o}C depends on the DHE and the year.

Replacement of pipelines, and in few cases replacement of thermal insulation of the overhead pipelines has reduced the insulation related thermal transmission losses.

The Model allocates the thermal losses into three other categories as follows:

1. Water temperature related losses, which approach to zero while the water temperatures approach the set minimums;
2. Make-up water heating related losses, mainly commercial losses, which are proportional to the water losses of the system; and,
3. Base losses, mainly convective losses, due to the existing thermal insulation of the pipelines respective to the levels of minimum water temperatures and water losses.

In many ETs in systems where comprehensive **consumer substation** modernization has not started yet the excess heating of room space in spring and autumn used to be the dominant phenomenon during the early 1990's. Such seasonal excess heating is caused by poor temperature control. The domestic hot water system requires a minimum supply temperature not of 50°C. To provide such a temperature level together with simultaneous supply of SH, both the poor control system and the high temperature difference of the DHW heat exchanger require a relatively high supply temperature in the primary network, thus leading not only to high thermal transmission losses but high room temperatures in the buildings as well. The high room temperatures cause substantial open window losses in the heated buildings.

In early 1990's, various consultants estimated those losses at 15-20% out of the total heat supplied to the buildings. Afterwards, the DHEs have confirmed that such an estimate was justified and corresponded to the measured experience (The World Bank, 2000 and 2001).

Technically, the **heat metering** alone does not save energy. Despite of that some estimated energy savings are usually related to metering investments, because people may start paying more attention to their heat consumption, if metered and invoiced according to the meter readings. Thus, heat metering may reduce thermal losses at the building level and has been modeled by means of the specific metering rate.

In this analysis, only the **DSM measures** directly related to the heating equipment are discussed and all other measures improving the performance of the building envelope have been excluded. Such a restriction was made, because the building envelope is out of the scope of DH.

The DSM measures, such as the thermostatic valves and cost allocators to radiators, reduce thermal losses at the apartment level. Since the valve is the controlling, and the allocator is the recording device, their combined function offers a strong incentive and a tool for the customer to save heat energy.

In order to obtain full benefits of the DSM measures in a building, the substation shall be equipped with the temperature controller first. Such a condition is included in the Model.

Since the DSM measures take place in the customers' premises beyond the heat metering, the DSM benefit is considered as an economic but not a financial benefit. From the DHE's point of view, the DSM benefit will be seen as reduced (lost) heat sales, whereas from the national economic point of view as reduction of the DH system losses. Therefore, the switch in the Model selects whether the measures will be optimized from the financial or the economic point of view.

12.3. Water Economy in District Heating

Based on the recent experience, the water losses are caused by leaks in the network as well as leaks and illegal tapping at consumers. The bulk of the water losses are caused by the direct connections in the buildings in which the network water circulates in the radiator circuits as well, and by the distribution pipelines. Therefore, the impact of transmission lines on the water losses is assumed to be occasional and small.

The heat exchangers efficiently reduce water losses on the secondary side, either by eliminating illegal tapping of the customers and leaving the secondary make-up water system to the responsibility of the customer. The relation of water consumption has been modeled as follows:

$$W(t) = W_o - \sum_{c=1}^{n} \beta_{w,c} \; R_c(t) \qquad (14)$$

Where $R_c(t)$ is the rehabilitation rate and $\beta_{w,c}$ refers to the relative savings of water consumption of component c in the thermal chain. W_o and $W(t)$ refer to the initial water consumption of the base year and the water consumption in the case year respectively.

The experience discussed in Appendix 5 implies that 84% of the initial water consumption is lost in consumer equipment and only 6% in the network, out of which two thirds in heat distribution and one third in heat transmission. Conclusively, the substation modernization with heat exchangers is the main factor to reduce water losses in the system.

Despite of heat metering, the customer may tap water from the system in such a way that neither the water nor the energy flow is metered. Such a tapping possibility, of course, depends on the type of the substation as well as on the possibly existing metering of water and heat. The heat energy used for heating up the make-up water tapped by the customers causes *commercial* losses to the DHE, in other words, heat sales without financial return.

The commercial losses can be eliminated at the substation by means of installing either (i) the flow sensor of the heat meter to the supply side, or, (ii) the heat exchanger to the BLS hydraulically separating the DH network from the SH circuit of the building.

The first option alone would be a sufficient measure to convert the commercial losses to normal heat sales, but is rarely used in practice. Usually, the flow sensor is located in the return side where the temperature varies less than in the supply side, thus providing a slightly more accurate flow rate measurement. In the Nordic countries, for instance, where neither commercial nor water losses are any issue, the sensor location in the return side is well justified. In the ETs, however, the location should be in the supply side in order to catch the commercial and water losses of the system that usually comprises a considerable financial problem to the DHE.

The Model assumes that both the rehabilitation rates of heat metering and heat exchangers are the ways to eliminate the commercial losses. A rough assumption exists, stating that a certain portion of the commercial losses can be converted to heat sales revenues. The portion shall be estimated by the Model user.

12.4. Improved Network Availability

One of the problems in the DH systems in ETs is the poor availability of heating services. Short breaks in supply may not cause problems for SH circuits, because a lot of heat energy is constantly stored to the network water and to the building structures. The customer may not notice, if the break lasts a few hours only, of course, depending on the ambient temperature. Therefore, little or no statistics is available regarding the impacts of such short supply breaks on the customers. For DHW supply, however, the availability problem prevails.

Typically, in the old-type DH system the gate valves in the network are of poor quality. Therefore, the entire system is taken out of operation for a couple of weeks (break-off period) in summer for pressure tests (network tightness test) and for the necessary repairs identified by the test. Therefore, there is no DHW supply to the customers during the break-off period.

In addition, in case a serious damage had taken place somewhere in the network, the entire network will be out of use until the damage is identified and finally repaired. This has caused a relatively long break-off period, as the network is a radial one with a few back-up loops, and the poor valves are not reliable for complete isolation of the damaged area.

Installation of appropriate gate valves to allow sectioning of the network when needed will practically eliminate the break-off period of the network. Therefore, effective sectioning increases heat sales, mainly during summer time.

For the Model, based on the discussion in Appendix 5, the approximation for the incremental heat sales was determined as follows:

$$Q_{de}(t) = Q_{de,o}\,(1 + (d_{bo}/d_y)\,\varsigma\, R_v(t) \qquad (15)$$

Where $Q_{de}(t)$ and $Q_{de,o}$ mean the heat sales of the case and the base year respectively, d_{bo} the number of break-off days in a year, d_y the number of total days in a year, ς the input parameter setting the desired availability level, 98% of the break-off time, for instance, and $R_v(t)$ the network sectioning rate ranging from 0 to 1 reflecting the desired availability level.

The real case may need some new looping connections in order for the sectioning to work effectively. Assessment of such possible looping requirements, however, depends on the geographical layout of the particular network, and therefore has been excluded in the general discussion at hand.

If the availability requirement would be increased from 98 to 99%, the number of the sectioning valves, for instance, would triple. Moreover, the likelihood of additional looping branches needed in the network will increase very fast, and the network investment much faster than those of the valves. Therefore, from the theoretical point of view, the availability values higher than 98% cannot be used on the general level without loosing reasonable accuracy on the investment side.

Such a robust simulation of the network sectioning is considered justified, because the impact of the incremental sales is about 2% of the total heat demand only, and a more accurate simulation would not yield any significant added value. Despite of the small impact on the heat sales, however, the sectioning will have a substantial positive impact on the customer satisfaction, as the DHW will be available all year round and practically no regular break-off period with only cold domestic water available will occur.

12.5. Quality of Circulation Water

The appropriate quality of the circulation water is crucially important for both extending the lifetime of the fixed assets and for ensuring proper operation of the rehabilitated equipment. Poor water quality would stimulate internal corrosion of the pipelines and substations and may block and deteriorate functioning of the controlling and metering devices in the entire DH system. (FDHA, 1988).

In initial project design in the early 1990’s, before the rehabilitation experiences became available, a problem on how and why to improve the performance of the existing water treatment facilities used to emerge. This is because the water losses might have been several times higher than the existing water treatment capacity, and perhaps even ten-folds higher than the real need to be faced after the system rehabilitation is completed. The problem was to avoid excess investments that may become obsolete in a few years after the system rehabilitation initiated.

Later on, the experience has shown that simultaneous investments in indirectly connected substations and in modern water treatment facilities is the least-cost way to improve the circulation water quality in the DH system. Neither way solely is sufficient. Rehabilitation of the water treatment system only at the existing capacity may be wasting of funds, usually because the existing capacity is insufficient to clean up the circulation water quality to the satisfactory level. The water losses substantially exceeding the treatment capacity account for this. So far the capacity is insufficient, the excess oxygen content and the usually low pH value of water cause corrosion of the pipelines, heat exchangers and armatures.

Since the water quality improvement obviously yields benefits to the entire system operation and lifetime extension, the quantitative impact will be discussed in the next Chapter.

12.6. Extension of Lifetime of Fixed Assets

One considerable benefit in DH system rehabilitation is the extension of the expected lifetime of the system. Until a comprehensive rehabilitation had started, the lifetime of the pipelines used to be relatively short, only about 10 years for the underground DHW pipelines compared with the design lifetime ranging from 30 to 50 years for the modern preinsulated pipelines. Therefore, for example, the old pipelines had to be replaced up to five times during 50 years compared with the estimated one time for the modern pipelines. Therefore, extension of the lifetime of the fixed assets will substantially reduce replacement investments in the future, and thus the extension may become the major benefit of rehabilitation of the heating network and the water treatment.

In Fig. 11, the damage frequency of various sizes of pipes in the FSU has been estimated. The damage frequency of the small pipes rapidly increases when the lifetime exceeds 15 years.

The extended lifetime means that the need for annual replacement investment will substantially decline. Such an extended lifetime is not caused by the modern pipelines alone but also by the improved water quality, adopted preventive maintenance practices and used modern installation technologies. The good quality of circulation water effectively prevents internal corrosion of the pipes. The quality of water can be improved both due to reduced water consumption, thanks to heat exchangers at consumer substations and more effective water treatment facilities. The DHEs have also adopted preventive maintenance practices with leak detection devices, network monitoring programs and computerized maintenance databases. Moreover, advanced pipeline installation technologies will create watertight joints to pipelines, thus preventing external corrosion.

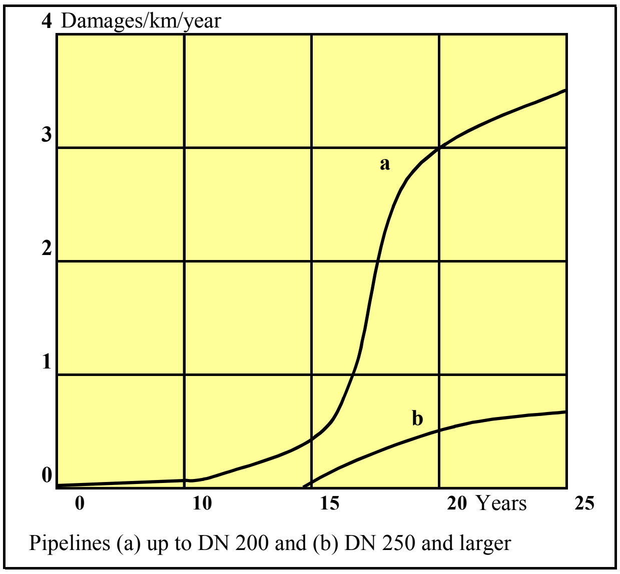


Figure 11. Damage frequency of small and large pipes in the FSU (Ljuza et al, 1989).

The same phenomenon applies to the other components of the thermal chain.

The achieved extended lifetime, t_{ex}, after the rehabilitation of the fixed assets of any component has been completed can be estimated by means of the rehabilitation rate of the particular fixed assets:

$$t_{ex}(c,t) = R(c,t)\, t_{el,n}(c) + (1-R(c,t))\, t_{el,o}(c) \qquad (16)$$

Thus, the lifetime extension Δt_{ex} is as follows:

$$\Delta t_{ex}(c,t) = t_{ex}(c,t) - t_{el,o}(c) = R(c,t)\, (t_{el,n}(c) - t_{el,o}(c)) \qquad (17)$$

In general, the rehabilitation rate R here is different for each component of the thermal chain. Moreover, the remaining lifetimes of the existing assets of the chain vary.

Let us now introduce the new replacement value (NRV and here only N) of the DH system, which is the value of the existing DH system if built today using BAT. In monetary terms, the benefit of the extended lifetime can be expressed by means of the N in a non-linear form as follows:

$$B_{ex} = N(c)/\, t_{el,o}(c) - N(c)/(t_{el,o}(c) + \Delta t_{ex}(c,t)) \qquad (18)$$

For modeling, the above function shall be expressed in a general form:

$$B_{ex} = f(R)\, N(c) \qquad (19)$$

Where B_{ex} is the benefit of the lifetime extension of a component, N is the new replacement value of the assets of a component, $t_{el,n}$ is the expected lifetime of the rehabilitated assets of a component, $t_{el,o}$ is the estimated remaining lifetime of the existing assets of a component, Δt_{ex} is the expected extension to the lifetime of a component by means of rehabilitation, and R is the rehabilitation rate of a component.

Fig. 12 describes the function f(R) by means of a variety of ratios of the expected lifetime of the new assets per the remaining lifetime of the old assets ranging from 30/20 to 50/10. Based on the variation, which is used in NLP, a linear approximation for LP common to all components was formed as follows:

$$B_{ex} = 0.05 \text{ N R} \qquad (20)$$

The factor 0.05 conservatively corresponds to the expected lifetime of the new fixed assets of 20 years on average.

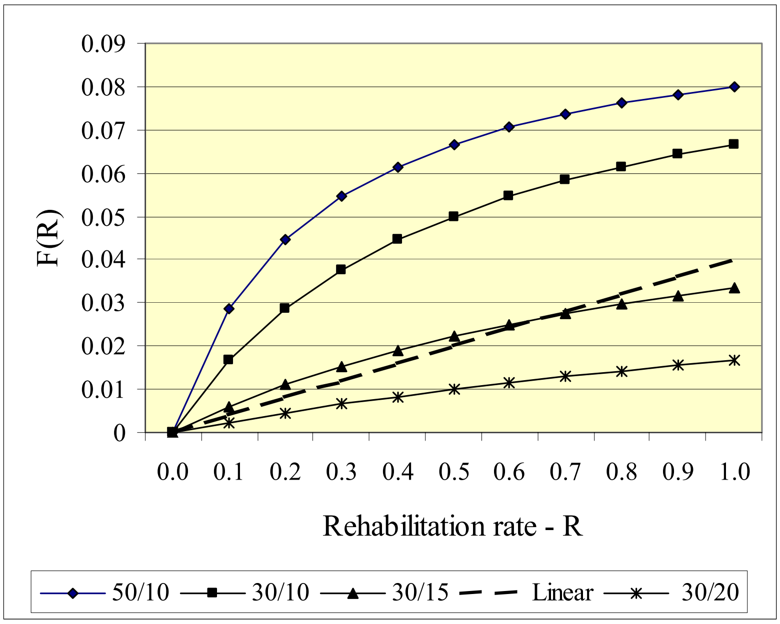


Figure 12. Non-linear and linear approximations of the factors used to estimate the lifetime extension in the Model, designed/remaining lifetime pairs as parameters.

In order to avoid exaggerating the benefit of the lifetime extension with the linear form, the denominator factor $t_{el,o}$ should be equal to or higher than 10 (years). In theory, one may always extend the lifetime of the current assets despite of poor quality by means of more frequent and comprehensive repairs, thus justifying the minimum of ten years.

The general rehabilitation rate R here is different for large, medium and small pipes, boilers, substation elements and the DSM, as are the lifetimes of the new and old assets, as well.

The annual investment costs, equal to the depreciation, are estimated at the N divided by the expected lifetime of the system. Thus, the annual investment requirements will decline, while the rehabilitation proceeds and the expected lifetime expands.

12.7. Electricity Savings in Pumps

Since the focus here is more in DH than in CHP, especially excluding large CHP plants, the main consumer of electricity in the system is DH pumping, which in general can be expressed as follows:

$$P_{pu} = \frac{\rho V h g}{\eta_{pu}} \qquad (21)$$

Where P_{pu} is the electric energy used for pumping, ρ is the density of water, V is the volume of water, h is the height of the water column over the pump, g is the gravity constant and η_{pu} is the efficiency of the pump set including the pump, motor and the possible clutch.

The need of pumping for the circulation water will substantially decline after the DH system has been modernized, because:

1. Switching the operation from the production driven mode to the demand driven one will reduce the water flow rate;
2. Energy savings in heat transmission and distribution will reduce the need of circulated water and its pumping;
3. Modern substations will improve the cooling, i.e. the difference of the supply and the return water temperatures, thus reducing the need of circulated water and its pumping;
4. Modern substations require lower pressure difference for operation, usually lower than 40 kPa, whereas the old hydroelevators require more, about 150 kPa (Olsson, 2001);
5. The demand driven mode enables network looping, offering alternative ways for the water flow to proceed. Thus, the piping resistance will be reduced due to looping and so is the electricity needed for pumping; and finally,
6. Frequency controlled pumps will reduce electricity consumption of any pumping substantially.

Based on the above, the electric energy used for DH pumping is estimated in the Model. The frequency controller for the pumping is considered as a linear pattern instead of an on/off element in order to avoid extending the optimization problem to the mixed integer programming. The investment in the frequency controlled pumping is relatively small compared with the bulk of investments in pipelines and substations. Therefore, the linear approximation does not cause significant inaccuracy to optimization.

Based on the number of arguments, the water circulation in the system will substantially decline in course of the rehabilitation measures. Therefore, one may consider that reduction of the pipeline diameters would become eligible, thus providing cost savings in investment and in thermal transmission, both of which together represent more than half of the lifecycle costs of the pipelines. In course of the rehabilitation, in order to downsize the diameters of the new pipelines, for instance, a downsizing factor of the NRV specific for each component of the chain is available in the input values of the Model.

For assessment of the electric consumption, the affinity rules do not apply for two reasons: (i) the expected fall of the water flow rate will most likely be substantial, about 20% or more, and (ii) booster pumps usually run in the network depending on the operation of the main pumps.

In pumping, a part of the electric energy is converted to friction losses in the pipelines, thus heating up the circulation water. Therefore, not all the electric energy is considered as losses but only the part that has been either ventilated from the pump motor or led to drainage together with cooling water.

The electricity consumption of the reduced pumping mainly depends on the rehabilitation rate of the temperature controllers and the large pipelines, but is in general as follows:

$$P_{pu}(t) = \left(1 - \sum_{c} R(c,t)\,\beta_{pu}(c)\right) P_{pu,o} \qquad (22)$$

Where $P_{pu}(t)$ and $P_{pu,o}$ are the electricity consumptions for DH pumping in the current and the base year respectively and $\beta_{pu}(c)$ is the potential for electricity savings in a component.

12.8. Productivity of Human Resources

In early 1990's, the number of HR in the case DHEs used to be more than three times as much as in the modern reference DH systems in the Nordic EU countries (Author, 2002). The reasons for large amount of HR were:

1. Low level of automation if any at all;
2. High number of small heat production units scattered all over the city in the regional or building level heating systems;
3. Frequent and comprehensive repairs of worn-out equipment;
4. Centralized and authoritarian organizations; and,
5. Normative: in a country a norm may have existed according to which the maximum number of HR for a certain type and size of an enterprise was set. Moreover, the salary level of the management has been dependent on the number of HR employed. Therefore, the management has had an incentive to employ as much HR at low salary level as allowed by the norm regardless of the real need.

The experience from the completed projects gives the total reduction of HR achieved in the DHEs, but does not indicate how and in which functions the reduction was done. In other words, any direct physical relation with HR depending on the individual rehabilitation measures could not be identified. Therefore, the user has to create a similar table, as described already in context of the thermal energy, allocating the number of the HR working with O&M to the components of the thermal chain both for the base year and the target year separately.

The Model uses the HR reduction potential at any component of the thermal chain according to the rehabilitation rate of the particular component. The benefits in reduced HR typically accrue slowly, because the rehabilitation of a component will require a substantial contribution of HR to implement and supervise the rehabilitation process. Moreover, the labor organizations may slow down the plans of human resource adjustment.

Therefore, the benefit of the HR has been modeled by means of the conservative benefit function, as follows:

$$M(t) = M_o - \sum_{c=1}^{n} ß_{hr}(c)\,\Theta(c,t) \qquad (23)$$

Where Σ sums the impacts over all the components in year t on the total reduction of the HR. The parameter $ß_{c,hr}$ reflects the potential of the HR reduction and Θ is the delay function, which is used in NLP only. In LP, the value of variable R substitutes the delay function Θ.

13. Immaterial Measures and Benefits

13.1. Approach to Quantify Benefits

The immaterial measures covering IT, training and experience exchange have had a substantial impact on the success of the completed DH rehabilitation projects, as indicated by the DHEs (The World Bank, 2000 and 2001). In order to convert the impact of the immaterial measures to the quantitative benefits and to have experience in designing new projects, the immaterial impacts were taken to a closer view.

By means of a questionnaire (Appendix 2) a personal assessment of a sample of 141 key specialists in 14 DHEs (Appendix 3) regarding the benefits and the sources of such benefits was requested. In each company the key specialists that have been centrally involved with the rehabilitation were selected to the sample together with the management. The selected specialists used to work in key positions to implement a comprehensive DH rehabilitation project in their DHE. While selecting the sample of specialists, the quality of HR in terms of experience and involvement in the project was preferred to the quantity in order to expect the response as qualified as possible. On average, the selected specialists have worked with the DHE 86% of the duration of the project and have used more than half, 53%, of their working time with the project. Moreover, the specialists have worked 7.8 years with the company until the date of questionnaire. The rehabilitation projects have lasted from three to eight years depending on the DHE.

There were some 40 females out of the sample of 141, about 28% of the total, which may well represent the average level of the females in the technical oriented DHEs. Therefore, no gender bias is assumed in the results.

Before filling in the questionnaire forms, the specialists were invited to participate in a short briefing session, where the background of the questionnaire was explained, the questionnaire was reviewed and possible clarifications were given if requested. Each specialist was given 1-3 days time to fill in the questionnaire. Such a period of consideration was regarded useful in order to have qualified response. After filled in, the questionnaires were collected for statistical analysis.

The number of large completed DH rehabilitation cases worldwide is limited. Due to their limited number, practically all DH systems that had undergone a comprehensive rehabilitation before year 2000 have been covered by the questionnaire analysis.

The share of TA out of the loan financing has varied city by city from 1.2% to 12%. No correlation was identified with the type or size of the DHE .

The specialists and the filled-in questionnaires collected from them were allocated to four groups depending on their specific area of business:

1. Top management (member of the Board)
2. Finance and economy
3. Technology, operation and maintenance
4. General administration.

The number of HR in the categories working in the DHEs was used to unbias the results in such a way that the weight of any group of responses was weighted by the number of the particular HR in the company.

The results were weighted also by means of the size of the DH system in order to balance (unbias) the different numbers of the responses per DHE.

Only the time the specialists have worked with the Project was taken into account in the analysis.

13.2. Questionnaire Analysis

The immaterial measures covered by the questionnaire were allocated to three groups: (i) maintenance facilities, (ii) IT systems and (iii) training and twinning.

The maintenance group concerns tools and facilities for advanced maintenance practices as follows:

1. Maintenance vehicles
2. Leak detection device
3. Thermo camera
4. Laboratory equipment

The group of IT systems consists of items as follows:

1. Financial accounting
2. Financial planning
3. Customer database with billing and collecting
4. Geographical information system - GIS
5. Hydraulic network analysis
6. Maintenance database
7. Remote monitoring and control

The investments in maintenance tools and IT systems were included in the questionnaire and the corresponding analysis due to their immaterial, knowledge-management related nature. IT and maintenance tools are considered here as immaterial measures even though a part of the investments have been included in the material measures. This causes inaccuracy in the results. However, this inaccuracy is considered insignificant.

The group of training and twinning consists of items as follows:

1. Preparation of master plans and feasibility studies
2. Preventive maintenance versus repairing damages afterwards
3. Quality Assurance (ISO 9000)
4. Environmental management (ISO14000)
5. Marketing & public relations with computerized customer database
6. Economic analysis of investments
7. Personnel assessment and development
8. Technical advice
9. Optimization of operation.

The questionnaire was designed to request the personal assessment of the economic impact of the items listed above. Later on, a statistical analysis was carried out based on the responses of the 141 specialists.

Assumingly, the Gauss-Markov conditions will apply to the sample (Dougherty, 1992), because,

1. The expected value of the disturbance term in any observation is zero. No systematic tendency of the disturbance term to deviate from zero is assumed;
2. The variance of the disturbance term is assumed constant for all observations. There is no reason to assume that some of the observations may be more erratic than the other ones, because only subjective assessments were asked from the specialists;
3. There are no systematic associations between the values of the disturbance term in any of the observations. The order of the observations is arbitrary and the correctness of each observation is assumed equal;
4. The disturbance terms are assumed to be distributed independently of the explanatory variables, because the order of the observations is arbitrary; and,
5. One may assume that the disturbance term is normally distributed.

Table 1. Statistical analysis of the quantitative impacts of the immaterial measures on the economic benefits of the completed district heating rehabilitation projects.

Source of benefits	All together	Top management	Finance & economy	Operation & maintenance	General administration
Material measures	74 %	73 %	72 %	75 %	71 %
Immaterial measures	26 %	27 %	28 %	25 %	29 %
Sample	141	23	18	87	13
Standard deviation	0,08	0,11	0,13	0,10	0,08
Variance	0,01	0,01	0,02	0,01	0,01
Confidence (95%)	0,013	0,045	0,060	0,021	0,043
Immaterial, upper 95%	27,3 %	31 %	34 %	27 %	33 %
Immaterial, lower 95%	24,7 %	23 %	22 %	23 %	25 %

The average values of the filled questionnaires are presented in Table 1 above and in Appendix 2 as well. Based on the outcome of the questionnaire analysis, some 74% of the benefits have accrued from material measures, whereas the balance, 26%, from the immaterial measures. For the entire sample, the standard deviation was 8% units and the variance 1% units. Therefore, on the confidence level of 95%, the share ranging from 24.7% to 27.3% of the economic benefits of the completed DH rehabilitation has been caused by the immaterial measures. The specialists working in technical and O&M functions have ranked the immaterial benefits slightly lower, at 25%, whereas the other specialist groups ranked them higher, ranging from 27% to 29%. The specialists other than the technical and O&M have received more education and tools during the project, which may explain their slightly higher rating of the immaterial benefits.

On the other hand, only 1.5 % of the total rehabilitation funds in the case projects have been used for the “services”, immaterial measures, which cover consulting, training and most of IT. Since the weighted average ERR of the completed projects has been high, ranging from 12% to 53%, as summarized in Appendix 5, covering both material and immaterial measures but excluding the environmental benefits, one may easily realize that the indicative ERR of the immaterial measures has been huge.

The questionnaire form, as presented in Appendix 2, may attract the replier to allocate benefits more than justified to the immaterial than to the material measures as the list of the immaterial measures is larger and more specific than the list for the material measures. Therefore, the real quantitative impact of the immaterial measures may be somewhat lower than indicated by the questionnaire analysis. On the other hand, however, a U.S. Department of Energy study has revealed that in an effective energy management program up to 80% of the saving could be attributed to the energy efficiency practices of the O&M personnel. This means that the equipment may provide as little as 20% of the savings. Operating the equipment near the design requires the equipment to be well maintained and operated, which in turn requires that the O&M personnel have the training, motivation and oversight to be sure it happens (Hansen, 2003). Therefore, the result of the questionnaire analysis here, 26% of the total benefits obtained from the immaterial measures compared with the above estimate of 80% for energy efficiency performance may not be exaggerated.

Separation of the immaterial from the material measures is partly artificial, because much of the training, for instance, is bound to the selected investment goods. Without investing in goods, the benefits of the training related immaterial measures would remain low or even none.

The statistical results presented above were used to quantify the impact of the immaterial measures while adjusting the Model.

13.3. Education of Human Resources

The immaterial measures have an impact on the performance of the administrative HR consisting of finance, economy, and other office employees not categorized to technical or operational tasks. Adoption of IT technology drastically reduces the need of HR in financial management, billing & collecting and in personnel administration.

Due to education, modern IT tools and improved motivation, the HR of the reference DHEs have managed to improve O&M of the other assets, which were not touched by the rehabilitation program. Such assets comprise more than 70% of the network and about half of the substation related assets. Due to such immaterial measures to improve the HR productivity and quality, the overall ERR of the completed projects in Poland have exceeded the one estimated in the project preparation phase about 15 years ago.

Introduction of IT technology in technical design, planning and monitoring of operation as well as in preventive maintenance will substantially improve the technical and economical quality of service, provided that the modern tools are used appropriately. Such benefits may comprise, for instance, accurate down-sizing of the investments according to the need, improved optimization of operation, reduced maintenance costs and improved availability of the energy services.

By means of the adopted modern maintenance practices, the raised level of motivation and the revised operation policies the DHEs have managed both to extend the lifetime and to reduce the damage rate of the remaining old assets not touched by the rehabilitation project at all. (Appendix 5).

Appropriate linking of the individual immaterial measures to a certain benefit is difficult and could not be done in this research. Therefore, the benefit factor of the immaterial measures is considered to cover the unidentified material benefits, achieved in the completed projects. On the other hand, most of the achieved quantitative benefits that have been recorded and used for tuning the Model have been caused both by the material and the immaterial measures.

Therefore, in the Model the benefits have been quantified as a result of implementation of either material measures only (74% of benefit potential) or of joint material and immaterial measures (100%).

13.4. Days of Receivables

In addition to the improved labor productivity, the immaterial measures have had impact on the reduced *days of receivables*. A new consumer database and/or strong efforts to speed-up billing and strengthen collecting functions have resulted in substantial benefits in terms of released capital. In the five Polish cases, for instance, based on the more effective billing & collecting the number of *days of receivables* has reduced from the previous level of some 90 days to about 60 days (The World Bank, 2000). Such a benefit can be quantified in monetary terms as follows:

Benefit = Turnover * Interest rate* [(90-60) days/364 days]

In the Model assumptions the reducing *days of receivables* is included implicitly in the benefit coefficient of the immaterial measures.

13.5. Priority of Immaterial Measures

The share of the impact of the immaterial measures has been 26% of the total benefits of the completed rehabilitation, as presented in Table 1.

Understandably, the priorities of the specialists have depended on their background area: for example, financial HR prefers financial and technical HR technical education and tools. Therefore, the priority of the sources of such measures differs slightly according to the business area of the specialist category. One of the four HR categories, the top management, might be considered to have the most objective understanding of the problems and the requirements of the DHE. However, usually most of the representatives of the top management category are technicians, and their neutrality may be a little questionable.

Apart the software, the items such as leak detection, laboratory equipment, remote monitoring and control and technical advice appeared more important than the others. The top management alone prioritized the master plans and feasibility studies, which is understandable, because the top management is most responsible for strategic thinking in a DHE.

The manufacturers and the consultants are the most important sources of information, about 32% each, whereas less help was experienced from other DHEs - both from domestic and foreign DHEs - and from other organizations. Both the top management and the economic/financial specialists have appreciated more the consultants than the manufacturers as information sources, whereas the other two categories have considered the sources equal. The most desired output from the consultant consists of the master plans and the feasibility studies, whereas little was received regarding personnel assessment and environmental management. The most desired output from the manufacturers was all kind of technical advice and know-how on optimization of operation.

Based on the results of the analysis, the immaterial measures have been allocated to three groups of priority (A, B and C) from the DHE's point of view and to an assessment (D) taking the investor's point of view in to account, as follows:

A. High Priority Measures

A remote monitoring and control system was needed as early as possible in order to optimize the system operation and to identify/locate possible problems in heat delivery. The priority of remotely controlled heating system seems justified as the system can be used for minimizing the thermal and pumping losses as well as improving the system availability. The fuel-related costs typically cover three quarters of the DHE's turnover.

Optimization of Operation is justified by control of the thermal network losses (supply water temperature) and heat production (flue gas losses), which both cover about one tenth of the DHE's turnover each.

Laboratory equipment is needed for analysis of circulation water quality and the fuel quality. The controlled water quality is of crucial importance to the reliable operation and low maintenance costs, whereas the controlled fuel quality increases accuracy in estimating the fuel costs and combustion efficiency.

Leak detection devices are needed to locate the numerous damages and water leaks in the underground network. The implemented network sectioning with modern valves has enabled pipeline repairs during the heating season. Therefore, leak detection had become real. Before the sectioning, all major repairs had to be postponed to the summer to come, simultaneously with the system break-off period.

Master plans and feasibility studies are important in defining the development needs under the prevailing circumstances. In designing the strategic plan for a DHE, the Model and the master plan support each other, thus aiming at improving the feasibility of the strategy.

B. Medium Priority Measures

Maintenance vehicles with a set of advanced tools, four-wheel drive, and lighted space for minor repairs are useful for maintaining the performance of the network and the substations regardless of material rehabilitation.

A customer database and billing & collecting systems are needed in order to know how much each customer is responsible for paying, has already paid and still needs to pay for the delivered heating services. In many DHEs, the ledger has been computerized in course of the project.

An economic analysis of investments is an analytic way to present the profitability of a variety of investment options to the management in monetary terms for decision taking.

Personnel assessment and development, from the HR' point of view, understandably belongs to the medium priority at least if not higher. Regardless the medium priority, the productivity of HR has substantially improved in four out of five DHEs in Poland during the project implementation.

C. Lower Priority Measures

A financial management system including financial planning as well as internal and external cost accounting was rated at lower priority. Even the top management has rated the importance of such management low. This seems strange, since the accounting problems used to be frequent when the World Bank supervision mission paid the annual visit to any of the DHEs. Problems with inaccurate financial data were still experienced at the late stages of the projects.

On the other hand, inaccurate data was obtained on the technical side as well, throughout the years of the project and at every DHE. Such an experience also hampers the Model adjustment discussed in Appendix 5 in detail.

Marketing & public relations is a way to keep the existing customers connected to the DH system and to attract new ones to join. In course of the project, all five DHEs have established such functions and have managed to increase the volume of the customers. Perhaps the new customers would have joined even without substantial effort in marketing.

Preventive maintenance procedures and systems is an approach to prevent damages and repair them soon after they occur, thus aimed at improving the system availability and reducing the costs of repairs. DHEs seem to feel that the main problem with maintenance used to be the quality of circulation water. By means of new equipment in the laboratory and heat exchangers in BLSs, the improved water quality and reduced water losses, respectively, have been rather sufficient to address the maintenance problem.

Quality assurance systems according to the ISO 9000 standard were established and certified in four out of five DHEs in Poland by the time of the questionnaires. The task of such systems is to streamline the functions inside the DHE and to improve the quality of the heating product served to the customers. The systems were commissioned in the last years of the project. Due to their late commissioning, perhaps the improvements in the organizational performance had not been experienced yet, which may have reduced the priority of quality assurance.

Introduction of environmental management systems has emerged in the DHEs just after the quality assurance systems have almost been commissioned. Moreover, the environmental management is more customer than DHE oriented compared with the quality assurance. Therefore, the low rating of the environmental systems seems understandable.

The geographic information system used to be one of the priorities in some of the DHEs in the early years of the project. Later on, its attractiveness has declined to the level indicated by the analysis.

Hydraulic network analysis tool is unavoidable for the network designer, because otherwise, simulating the water flows in a densely looped network operated in the demand driven mode would be rather impossible. Since the designer is the sole user of such a tool, the priority of such a tool for the DHE seems low among all specialists.

D. Investor’s assessment

The Investor’s priorities, however, likely differ from those of the DHEs as analyzed by means of the questionnaire. Any investment on the DH system rehabilitation is ultimately a financial transaction. Therefore, from the investor’s point of view, the financing related systems of customer database and cost accounting, for instance, might have a substantially higher priority than was rated by the specialists of the DHEs. The investor’s point of view was excluded in the questionnaire analysis, because the investors are assumed to recognize their own priorities by themselves.

13.6. Example of Economy of an Individual Measure

The percentage keys presented in Appendix 2 may be used to create indicative ERR estimates for individual immaterial measures. Let us consider an example as follows: Based on the economic analysis of the completed five projects in Poland the total annual benefit of the rehabilitation project in one of the DHEs has been about € 20 million equivalent, starting from zero in year 1991 and gradually increasing to the aforementioned amount in year 1999, conservatively excluding the environmental benefits. Due to such a high annual benefit, the indicative ERR of the entire project has been estimated at 44% during 1991-2015 (The World Bank, 2000).

Using the keys from Appendix 2:

1. The share of immaterial benefits out of the total benefits: 26%;
2. The share of the IT out of total immaterial benefits: 37%; and,
3. The share of the customer database, billing and collecting system out of the IT related benefits: 19%.

Based on the percentage keys above, the annual economic benefit of introducing such a system in the DHE amounts to EUR 0.37 million a year.

On the other hand, let us assume that the estimated investment costs of a complete billing and collecting system including a customer database amount to EUR 0.50 million for the DHE.

Based on the estimated investment cost and the annual benefit, the indicative ERR of the billing and collecting system amounts to 73% during the expected 10 years of operation, substantially higher than the ERR of 44% of the entire project is assumed to be. The expected operation time of such an IT system is assumed at 10 years, substantially shorter than 20-30 years that is typical for the material measures.

14. Objective Function of Model

The optimal rehabilitation strategy will be a result of either the LP or the NLP, whichever selected for analysis, as well as based on the given data, parameters, features and financial constraints. The strategy will offer a basis for the potential investor to create an implementation plan for a new rehabilitation project.

The objective of the Model is to maximize the value of the objective function during a given period of time, as presented in Appendix 4 in detail. The objective function is the difference of the expected benefits and the accrued costs during the consecutive years to come, the period.

The following cost items have been used in the Model:

1. Investment costs based on the average unit costs and quantities optimized under the financial constraints, but deducted by the non-depreciated residual value prevailing at the end of the period;
2. Fuel costs based on either economic or financial unit costs of the particular year as chosen;
3. Bulk heat purchase costs based on the optimized heat energy multiplied by the unit cost of the particular year;
4. Cost of the undelivered heat energy due to low availability, which is a share of the total heat demand multiplied by the given unit cost;
5. Cost of flue gas emissions depending on whether economic or financial unit costs of the particular year will be used;
6. Commercial losses caused by the water lost at the customer premises but heated by the DHE; and,
7. Base costs of the HR, water and electricity in the particular DHE in the base year.

The following benefit items have been used in the Model:

1. Heat sales revenues as a product of the sales energy and the unit price of each particular year;
2. Electricity sales revenues as product of the sales energy and the unit price of each particular year;
3. Electricity savings in DH pumping in terms of saved electric energy multiplied by the electricity purchase price of the particular year;
4. Water savings in the network and consumer equipment in terms of water volume multiplied by the unit price of treated water of the particular year;
5. Material maintenance benefits due to the extended lifetime of the fixed assets;
6. Improved productivity of the HR in terms of the product of the reduced number of the HR multiplied by the unit cost of the particular year;
7. Reduced maintenance costs of the excess heat production capacity suggested for elimination; and,
8. In the financial analysis, the benefits of CO_2 emission reduction regarding emission trading.

In the objective function, the benefits and the investments will be adjusted annually according to the required level of IRR. The positive value of the function indicates that the required profitability has been met.

In case only the benefits of the material measures are needed, the benefits will be multiplied by the factor 0.74, thus neglecting the impacts of the immaterial measures.

The following constraints apply for maximizing the object function value:

1. The rehabilitation rate R is a positive variable ranging from 0 to 1;
2. Investment costs are restricted by the given annual maximum and the total maximum of the financial constraints;

3. Electricity generation of the CHP plant is limited to consist of the real CHP process only. Therefore, no power generation based either on condensing or on extra cooling is allowed at the plant, even though it may be physically possible. Feasibility of such extra generation depends on the actual situation on the market, and therefore, has been left for operative and tactical decision taking;
4. The Model does not allocate investments in the DSM and temperature controllers more than in the heat metering. Moreover, the controllers need to installed before the DSM measures are taken; and,
5. The optimized water temperature levels may not decline below the season-specific limits.

The number of the years in a period may range from two to the expected lifetime of the newly invested fixed assets, typically 25 years. Therefore, the periods longer than 25 years are not relevant for any analysis. Depending on the selected number of years included in the period, the remnant value of the fixed assets at the end of the period has been taken into account in the Model.

The benefits accrue cumulatively from year to year with linear and non-linear relationships depending on the completed measures of the previous year.

Either the linear or the non-linear solver, whichever selected from the commercial MINOR solver package, will maximize the value of the objective function.

The NLP differs from the LP only in the few features mentioned below:

1. The benefit functions for the investments regarding thermal losses in the pipelines and in the BLSs;
2. The assessment of the extended lifetime of the fixed assets;
3. The accrual of the benefits of the HR productivity;
4. Electricity production of the CHP plant depending on the actual heat demand and the actual return temperature, and finally,
5. Year-to-year calculation of the thermal efficiencies of the components in the thermal chain.

In other words, in the NLP the benefits of the investments - the increases of the rehabilitation rates - accrue either according to a trigonometric, logarithmic or an exponential function depending on the type of the measure and the benefit.

15. Model Implementation and Testing

The Model was implemented by means of the GAMS programming tool and with the MINOS solver, which is designed to use both LP and NLP. GAMS – the General Algebraic Modeling System has been developed by the World Bank since 1978 and later on outsourced to GAMS Development Corporation, Washington, D.C., for further development and commercial distribution. MINOS is one of the commercially available and widely used solver packages linked with GAMS. In general, GAMS has been widely used for planning of energy systems (Goldstein et al, 2001; McCarl et al, www.gams.com).

The Model performance has been demonstrated by means of a fictive case as presented in Appendix 6. Fig. 13 below is an example of the Model demonstration.

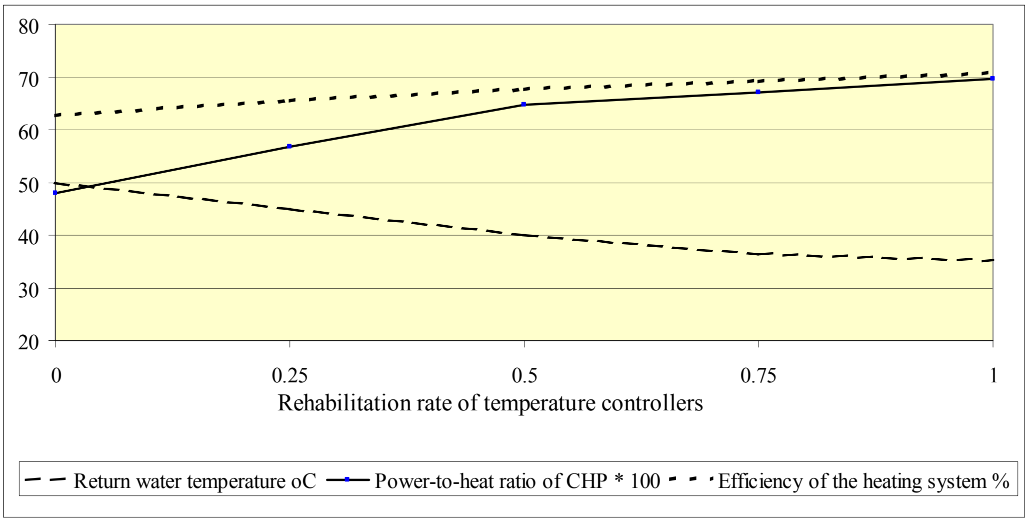


Figure 13. Temperature control rehabilitation rate in the substations improves the total efficiency of the chain, reduces the return temperature and thus improves the power-to-heat ratio of CHP.

In Fig. 13, the system efficiency covering the chain from heat production down to consumer equipment has improved, because the temperature controllers that were installed to the consumer substations have reduced both the supply and the return water temperatures in the system.

The power–to-heat ratio, α, of the CHP plant has increased due to the reduced water temperatures. The amount of increase depends on the type of the CHP plant.

16. Constraints of Model

The Model, merely being a simulation of the real world, cannot be exact and accurate. The Model structure has been designed and the parameters adjusted in order to reflect the real world rehabilitation process in a reasonable extent and accuracy. However, the Model has been compressed to contain the most essential features of the rehabilitation, which should be sufficient to analyze most rehabilitation cases in a reasonable accuracy.

The Model can be used in most of DH systems in the ETs with the exceptions as follows:

1. The heat load pattern is simple dividing the annual heat demand to four seasons. Such a simplification creates inaccuracy to real fuel consumption, but may be sufficient when comparing alternative investment strategies;
2. The Model expects that both DHW and SH are supplied by the DH system. In some countries such as China and Serbia, the DHW is usually not supplied by the DH system but either by individual solutions in apartments or not at all. Such DH systems without including the DHW services are rather rare in the ETs, thus not necessarily requiring the DHW rate to be included in the Model;
3. The energy sources are modeled in a rather simple way. Only one fuel per source is possible. The annual maintenance planning is excluded from the scope of the Model. Such deficits in the Model do not have any significant impact on the rehabilitation planning in the strategic time frame;

4. The Model contains the most simplified pattern of a CHP process, because the focus has been in the network and the substations rather than in energy production. Therefore, any investments aside from the DH circulation pumps and entire CHP plants should be planned separately. Only one CHP plant at the time can be included in the Model, which is typical in the smaller systems, presumably more attractive to Finnish financiers than the large systems;
5. The Model does not have any link to hydraulic analysis of the heating network. The large, medium and small pipelines in the Model are connected to each other in the order of the size without any link to the real network topography. Therefore, the sizing and location of the pipelines for rehabilitation must be designed separately;
6. The water losses and water temperatures do not have direct relation to thermal transmission and distribution losses in the Model, even though such relation physically exists. The water temperatures are used for quantifying the electricity generation at the CHP plant. The thermal losses of the chain, however, are allocated to (i) the temperature related, (ii) the water loss related and (iii) to the base losses as a result of the optimization, thus compensating the neglected physical relation; and,
7. The Model is idealistic in a number of respects, which however, is typical for the planning tools designed for the strategic level.

Regardless the obvious benefits of using such Model some restrictions prevail, which cannot be included into the Model, for instance, as follows:

1. An elimination program for small polluting boilers should be developed separately by means of a spreadsheet tool;
2. A transition program for heat distribution from the 4-pipe to the 2-pipe system should be developed separately by means of spreadsheet tool; and,
3. A program for interconnecting a variety of local heating networks needs to be designed by means of hydraulic simulation.

17. Conclusions

Heating of room space and domestic hot water is a necessity in most northern countries in the world. DH is a largely adopted practice and recognized as the least-cost solution to serve more than 100 million people Europe, but too often with poor performance. In general, the objectives of DH rehabilitation are to provide the customers with heating services that meet the requirements of economy, affordability, technical performance and environmental sustainability. In order to meet the objectives PSP is considered necessary. The PSP, however, faces a number of barriers. Some of the barriers can be addressed by means of more accurate strategic planning of the rehabilitation projects.

In this research, a Model was developed and demonstrated to assist potential investors and financiers in strategic planning of the DH system rehabilitation in the ETs. The need of such assistance is both urgent and crucial, because, first, the existing systems deteriorate fast as they have been maintained at necessary annual repair level only, but lack any considerable upgrading for a decade or longer, second, on the northern globe the availability of heating is an even more important necessity facilitating the human life than the availability of electric energy, and third, involvement of the PSP is necessary to foster rehabilitation but requires new means in order to manage a variety of risks related to such rehabilitation.

The Model is aimed at addressing a number of barriers that the investor faces while considering a DH system rehabilitation, for instance, as follows:

1. Improving accuracy and focus in planning of material measures taking the impacts of the immaterial ones into account, which improves the feasibility of rehabilitation;
2. Assisting in the least costs analysis of the existing system while suggesting a sustainable rehabilitation strategy;
3. Managing the financial risk of investments, because the materialized experiences from the completed comprehensive rehabilitation projects have been incorporated to the Model;
4. Reducing the costs of financing, because the Model will assist in risk mitigation; and,
5. Sizing the rehabilitation measures according to the affordability and quality requirements of the heat customers.

The Model in its current status of development has been designed to focus on the core needs of the investors to improve rehabilitation economy. In the future, the Model may be developed to the a more detailed level and be extended to cover new features as follows:

1. Heat load duration: the heat load part may be extended from the current four-seasonal block pattern to a more detailed one by means of connecting the Model to a separate heat load model;
2. Energy Production: Expansion of the Model to cover more features in the heat production. Such features, as mentioned before already, consist of issues such as double fuel, several CHP units and maintenance planning;
3. DHW rate. The DH system does not usually supply DHW services in a few countries such as Serbia & Montenegro and China. Possible extension of the DH services to cover DHW as well offers interesting business opportunities;
4. DC rate: Similarly, district cooling could be a business opportunity in the future, when expanding CHP business becomes actual; and,
5. Steam rate: Analysis of steam network, usually operated with the DH systems in parallel, may become possible in the Model in some extent. Usually, the objective in Europe has been to get rid of the steam systems and either convert the customers to water system to provide them with customer-specific steam generators whichever more economic. In China, however, comprehensive steam networks have been built to provide steam to industry, to absorption chillers and DHW in the commercial and public buildings as the water type DH is used for 3-4 months a year for SH alone.

Improved optimization of the investment operations on the strategic level will improve the economy of the investments, thus likely improving opportunities for economic CHP expansion and CO_2 emission reduction, as was aimed at with the research work.

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Appendix 1

Summary of Polish District Heating Rehabilitation Projects During 1991-2000[1]

1. Background

District heating (DH) is the governing heating mode in Northern and Central Europe, mainly because of the extensive use of highly efficient co-generation of heat and electric power. In some countries, however, DH systems are still inefficient due to obsolete technologies and years of only minor investments. Such a poor efficiency combined with the low level of co-generation has negatively affected the competitiveness of DH on the local heating markets, thus causing customers to switch to gas heating. Several Central European countries have started optimization of widely spread DH systems, with assistance of the World Bank. Especially Estonia and Poland have achieved encouraging results in terms of improved economy, ecology and competitiveness of DH. DH customers in these countries have benefited the most from the optimization investments, because the costs of heating of one square meter of living floor area have dropped, in Poland, for instance, about 60% from 1991 to 1999 in the real terms corresponding to the cost level of the year 1999. In Poland, the World Bank has recently completed DH rehabilitation programs in five large cities covering about 20% of the DH market in the country, as presented in Table 1.1. The program completion costs amounted to US$530 million, of which US$328 million was financed by the five Polish DHEs and the balance by the World Bank loans. The DH system rehabilitation as a way to a greener future in Europe was successfully demonstrated in Gdansk, Gdynia, Katowice, Krakow and Warsaw.

The Polish energy sector was brought to the forefront of the World Bank-Poland dialogue in the late 1980's. The district heating DH sector was at the core of these inefficiency problems. For a considerable period of time, the district heating enterprises (DHEs) suffered from a lack of funds to effectively operate, maintain and renew their infrastructure. This resulted in major heat and hot water losses because of serious corrosion caused by poor water quality and water leakage, and lack of insulation. The decentralization of ownership combined with the phasing out of investment subsidies and the lack of long-term financing for infrastructure exacerbated the financial

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[1] *The Paper is based on the Implementation Completion Reports (World Bank, 2000 and 2001) and the presentation given by Mr. Nuorkivi at Euroheat&Power Conference in Gdynia, Poland, in June 2001. The World Bank's key team members in project supervision have been as follows:* ***Mr. Rachid Benmessaoud,*** *Senior Energy Specialist and Team Leader, has been responsible for the energy program assistance in Poland, covering preparation of the five Polish programs and implementation supervision of the programs in Gdansk, Gdynia, Krakow and Warsaw;* ***Mr. Enar Wennerstrom****, Financial Analyst, who has been responsible for program implementation supervision and financial analysis in Katowice.* ***Mr. Arto Nuorkivi,*** *District Heating & Power Specialist, has supervised the technical implementation of the projects and has carried out the environmental and economic analyses in all the aforementioned cities.*

problems of the DHEs. The local authorities did not have the technical or financial resources to address these problems.

Table 1.1. Background data of district heating in Poland.

	Gdansk	Gdynia1)	Katowice2)	Krakow	Warsaw	5 Cities	Poland	5 Cities
Population (million)	0.5	0.3	0.7	0.7	1.7	3.9	38	10 %
Market								
Heat Sales (TWh)	2.3	1.5	2.4	2.9	10.6	19.7	90.0	22 %
Sales Revenues (M$	57	38	50	77	257	479	2 334	21 %
Implementation Costs	75	46	60	72	278	470	M$	
Investments	74	45	59	71	276	467	M$	
Technical Assistanc	1.4	0.7	0.8	0.5	1.2	3.8	M$	
Financing								
Five DHEs	35	21	23	47	203	328	M$	
World Bank	40	25	37	25	75	202	M$	
Total financing	75	46	60	72	278	530	M$	

1) Gdynia heating covers Rumia, Wejherowo and a part of Sopot.
2) Katowice heating covers five towns such as Swietochowice, Siemianowice, Chorzow, Myslowice and Katowice.

2. What Was Done

During the program period, 24% of the total network length, consisting of 972 km of poorly insulated and leaking pipes, was replaced with preinsulated pipes. About 50% of all substations were fully modernized and an additional 20% were partially modernized, through the installation of 35,000 new heat exchangers and 3,000 compact substations. Network sectioning, automation and remote metering systems were installed, and all heat supply sources and consumer substations were equipped with heat meters. In addition, 561 coal-fired heat-only-boilers (HoBs) with a capacity of 517 MW were eliminated and the customers connected to the DH networks. A further 185 HoBs with a capacity of 103 MW were converted to natural gas or oil fuel. Foreign consultants, manufacturers and other DHEs provided substantially training for institutional building of the five DHEs in Poland. The topics of training covered marketing and customer care, financial planning, economic analysis, quality assurance, environmental management, preventive maintenance, technical design and economic operation, thus changing the organizational attitude and behavior towards customer oriented and more efficient operation.

3. Achievements Met Objectives

The key results related to competitiveness and environment protection of DH are highly satisfactory and surpass early expectations as summarized below:

Substantial Subsidies Were Phased Out Fast: Investment subsidies were eliminated, and household subsidies phased out gradually from a nationwide average of 78% of the heating bill in 1991 to zero in 1998.

Consumers Benefited in Reduced Heating Costs in Real Terms: The efficiency gains resulting from the Government's energy pricing policy and achieved by both the DHEs and the combined heat and power plants greatly benefited the DH customers through a 56% lower price for heating one square meter (m^2) of floor area (from

54.5 PLN/m^2 in 1991 to 24.0 PLN/ m^2 in 1999, at 1999 prices), as presented in Fig. 1.1.

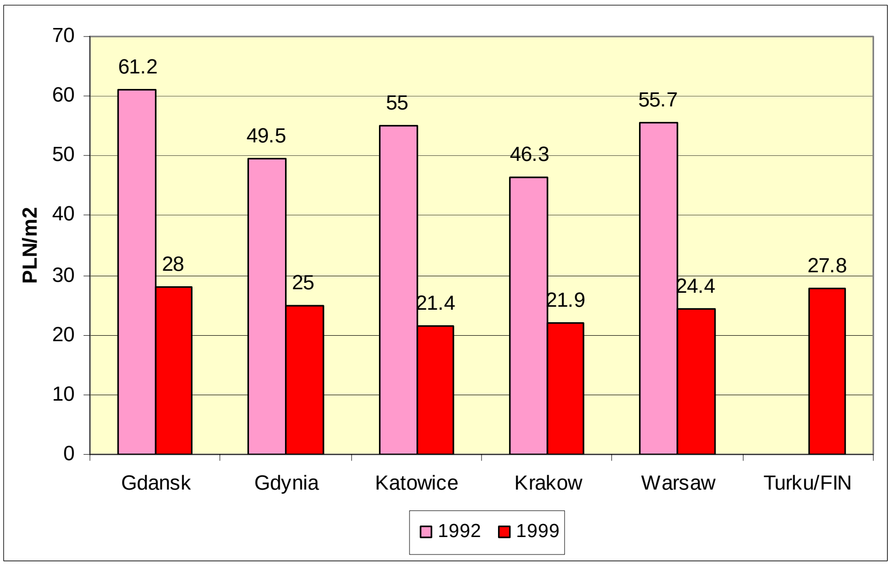

Figure 1.1. Heating costs per floor area in real terms (1999 price level).

The customers didn't see the price drop in full because the VAT was added to the heat price in the course of the program.

Practically most of the economic benefits of the program were given to the customers in terms of low heat tariffs, as demonstrated above. This was the reason that little economic benefits remained in the DHEs. Therefore, some of the DHE's had to operate under extremely tight financial circumstances during the years of program implementation and still be able to finance at least 30% of the total costs of the program.

Efficiency Gains Provided Energy Savings: 22% energy savings in the five cities amounting to 1,200 Gg of coal a year was achieved and valued at US$60 million per year. The achieved savings were 35% more than 900 Gg expected in 1990 when the program was started. The Bank-financed investments were focused on sustaining the least-cost heat solution, with significant benefits for the environment.

Competitiveness To Gas Improved: due to DH system rehabilitation, competitiveness of DH has improved in terms of lower costs and higher quality of service. Therefore, customers who used to escape to gas are now returning to DH.

The DHEs Started to Generate Own Funds for Investments: Despite the reduction in their profit margins due to real tariff decreases, the enterprises were able to generate cash internally of 62% of capital investments, exceeding the minimum level of 30% required under the financial covenants of the World Bank loans.

Technical Rehabilitation Enabled Customers to Control and Meter Their Heat Consumption: Control of the district heating systems was automated and changed from production control to demand control, thus giving the customer the possibility to regulate their heat consumption.

Environmental Benefits Gained from Rehabilitation: The citizens benefited from improved air quality through reduction in gaseous and dust emissions. Due to both HoB elimination and energy savings achieved in the DH system, the annual emissions were reduced substantially as follows:

1. Reduction of 26 Gg of SO_2 out of the initial 102 Gg in 1992 was based on the energy savings of coal of 0.7% S-content on average and having no desulphurization plant available at any plant during the program;
2. Reduction of 9.5 Gg of NO_x of the initial 37.7 Gg was based on the reduced coal consumption and having no low-NO_x burners available at any plant, even though some burners of such type may have been installed on the later years of the program to the CHP sources but not being financed by the program on hand;
3. Reduction of 3.2 Tg of CO_2 out of the initial 12.7 Tg is based on reduced coal consumption (below); and
4. Reduction of 6.7 Gg of dust out of the initial 15.5 Gg is based on HoB elimination program only (below). The CHP sources have had electric precipitators all time long and possible changes in their efficiency were excluded from the analysis.

The DHE of Krakow was officially eliminated from the list of heavy air polluters, thanks to the boiler elimination and coal-to-gas conversion programs. The Polish economy also reduced its contribution to greenhouse gases (mainly from carbon dioxide emissions).

The DHE of Gdansk started to implement a modern Environmental Management System in their organization, according to the international ISO 14000 standard, to better serve their customers in environmental improvement. The Environmental Management System was later being integrated to the Quality Assurance System, that was initiated in 1995 and certified according to the ISO 9002 standard by year 1999, likely as the first certified Quality Assurance System at any DHE in the Central and Eastern Europe. Later on, other DHEs in Poland have started implementing such systems.

Water consumption in the five DHEs dropped substantially, as presented in Fig. 1.2, thus saving both energy and raw water.

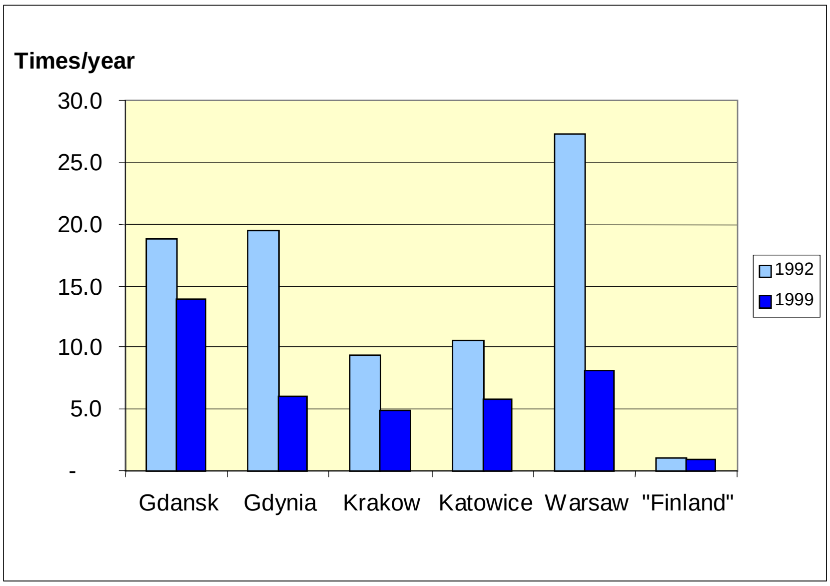

Figure 1.2. Replacement of network water.

Due to DH system modernization, the share of CHP generated heat out of total heat supply increased during the years, as shown in Fig. 1.3 below. In Gdansk and Katowice, new CHP capacity was implemented during the course of the program but not financed by the program. The share of CHP in Helsinki is given as reference.

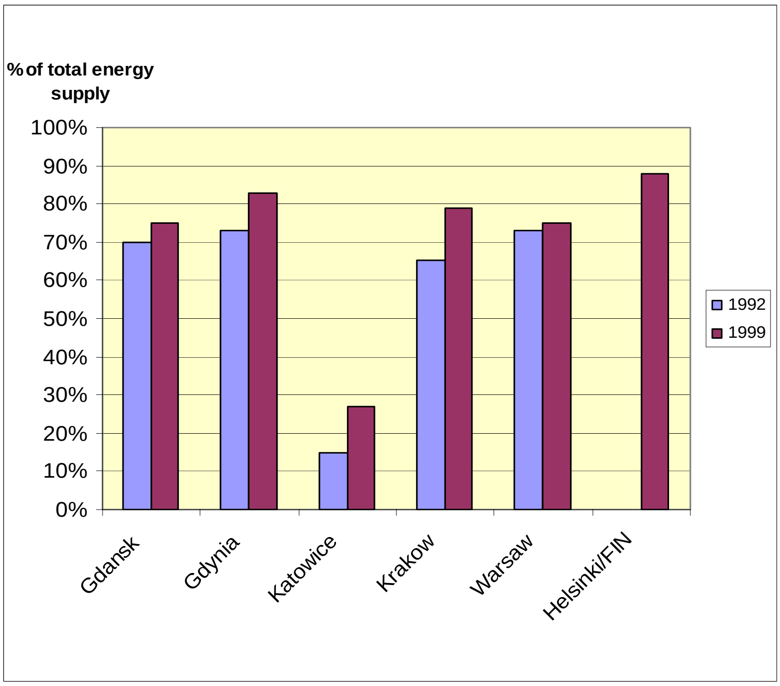

Figure 1.3. Heat energy supplied by CHP sources as percentage of the total heat supply.

A summary of the obtained benefits is presented in Table 1.2.

Table 1.2. Key performance indicators of the DH rehabilitation program.

Indicators		Gdansk	Gdynia(3	Katowice(3	Krakow	Warsaw	Total
Coal Savings	(Gg)	125	125	118	215	630	1,213
	% reduction	23%	25%	24%	25%	21%	22%
Metering of sales	Before	14%	15%	30%	16%	24%	21%
	After	100%	100%	100%	100%	100%	100%
Reduction in Water Losses		26%(2	69%	45%	48%	69%	65%
Reduction in Number of Staff		30%	33%	3%	35%	30%	32%
Increase in Productivity (MWh sales/employee)		11%	60%	-7%	21%	38%	34%
Reduction in Air Pollution (various emissions)		26-52%	30-42%	21%-31%	27-53%	25-42%	26%-45%
Internal Cash Generation as % of Investments		49%	52%	46%	74%	64%	62%
Technical Assistance (man weeks)		295	225	230	170	330	1,250

2) Average of 1998 and 1999 values

3) the DH systems in Gdynia and Katowice cover also some neighboring cities and towns.

4. Conclusion

In 1999, the five DHEs of Poland in Gdansk, Gdynia, Katowice, Krakow and Warsaw have sold about 20 TWh of heat to their customers, representing about 20% of the entire DH market in Poland. Rehabilitation of their DH systems was demonstrated in full scale and with achievements exceeding early expectations in improved economy, energy savings, environmental protection, financial performance and in customer orientation. Therefore, the Polish example offers a considerable solution to rehabilitate the DH systems in the Central and Eastern Europe, where the DH is the governing heating mode and most often the least cost solution in the long term, but simultaneously suffers from inefficiency, deterioration and poor competitiveness on heating market.

Appendix 2

Questionnaire and Results

about experiences and lessons learned in the comprehensive DH rehabilitation projects

The questions are given in four groups: A, B, C and D as follows:

A. Five questions in "A" about your professional background and involvement with the completed DH Rehabilitation Program;

B. The questions in "B" are to indicate how do you think the DH customers and the citizens of your town have benefitted from the DH Rehabilitation Program;

C. The questions in "C" reflect the usefullness of the various know-how sources such as the consultants, the other DH companies and the equipment manufacturers (advice and training but excluding the equipment delivered). You should assess how much the DH customers may have benefitted from the various know-how sources (through your company and staff) and the know-how areas listed in the Questionnaire.

D. The questions in "D" are related to the IT (Information Technology) systems of your company. First, what are the important arguments for you to select a new IT system product and the supplier; and, second, how satisfied you are with the software you are possibly using regularly.

A. Five questions about You…

1. Question about your profession: please mark the business area which is closest to you:

> Top management (member of the Board)	16 %
> Finance and Economy	13 %
> Technology, Operation and Maintenance	62 %
> General Administration	9 %

2. How much out of your working time you have worked for the DH Rehabilitation Program (from 0 up to 100%) during the years the Program has been under implementation?

53 %

3. How much you feel you know about the various improvements in your company compared with the other staff on average?

	Much	Some	Little	None	Σ
> Technical matters like boilers, pipes, etc.	85	32	19	2	138
> Maintenance tools and practices	65	55	14	7	141
> IT (information technology), programs and sys	34	63	40	3	140
> Received training, education and information	58	46	29	6	139

4. Are you female of male?

female	40
male	101

5. How many years you have been with the company? 16 years

B. Qualitative Benefits

Based on your personal asseement, please assess how much from the improved economy in energy, water and electricity consumption was caused by either the material "hardware" or the immaterial "software" as follows:

Instruction: B1+B2 = 100% and a+b+c=100%	Σ=100%		
B1: "Hardware"	74 %		Σ=100%
1 New Boilers			20 %
2 New Substations			27 %
3 New Pipelines			25 %
4 Water Treatment Rehabilitation			8 %
5 Heat Metering of Customers			20 %
B2: "Software"	26 %	Σ=100%	
a. Maintenance Tools		28 %	Σ=100%
1 Maintenance Cars			24 %
2 Leak Detection Device			29 %
3 Thermocameras			17 %
4 Laboratory Equipment			30 %
b. IT systems		37 %	Σ=100%
1 Financial Accounting			8 %
2 Financial Planning			9 %
3 Customer Database, Billing & Collection			20 %
4 Geographical Information System (electr maps)			7 %
5 Hydraulical Network Analysis			15 %
6 Maintenenance System			13 %
7 Remote Monitoring & Control			23 %
8 Other			5 %
c. Training and Twinning		35 %	Σ=100%
1 Master Plans and Feasibility Studies			13 %
2 Preventive Maintenance			9 %
3 Quality Assurance (ISO 9000)			10 %
4 Environmental Management (ISO 14000)			5 %
5 Financial Management (Accounting)			7 %
6 Marketing & Public Relations			8 %
7 Economic Analysis of Investments			10 %
8 Personnel Assessment and Development			8 %
9 Technical Advice			16 %
10 Optimization of Operation			14 %

C. Sources of obtained Training and Education

Based on your personal assessment, how much the DH customers may have benefitted from the various knowhow sources (through your company and staff) and the know-how areas listed below?

Instruction: C1+C2+C3+C4+C5 = 100% and a+b+c+d+e+f+g+h+i+j = 100%

Σ=100%

C1.	**From Consultants**	34 %	Σ=100%
a	Master Plans and Feasibility Studies		17 %
b	Preventive Maintenance		8 %
c	Quality Assurance (ISO 9000)		10 %
d	Environmental Management (ISO 14000)		4 %
e	Financial management (Accounting)		8 %
f	Marketing & Public Relations		7 %
g	Economic Analysis of Investments		11 %
h	Personnel Assessment and Development		7 %
i	Technical Advice		19 %
j	Optimization of Operation		10 %

C2.	**From Manufacturers**	29 %	Σ=100%
b	Preventive Maintenance		12 %
c	Quality Assurance (ISO 9000)		10 %
d	Environmental Management (ISO 14000)		5 %
e	Financial management (Accounting)		4 %
f	Marketing & Public Relations		11 %
g	Economic Analysis of Investments		8 %
h	Personnel Assessment and Development		8 %
i	Technical Advice		23 %
j	Optimization of Operation		19 %

C3.	**From Domestic DHEs**	15 %	Σ=100%
b	Preventive Maintenance		14 %
c	Quality Assurance (ISO 9000)		10 %
d	Environmental Management (ISO 14000)		5 %
e	Financial management (Accounting)		7 %
f	Marketing & Public Relations		12 %
g	Economic Analysis of Investments		10 %
h	Personnel Assessment and Development		6 %
i	Technical Advice		20 %
j	Optimization of Operation		15 %

C4.	**From Foreign DHEs**	12 %	Σ=100%
b	Preventive Maintenance		11 %
c	Quality Assurance (ISO 9000)		10 %
d	Environmental Management (ISO 14000)		5 %
e	Financial management (Accounting)		7 %
f	Marketing & Public Relations		11 %
g	Economic Analysis of Investments		12 %
h	Personnel Assessment and Development		8 %
i	Technical Advice		19 %
j	Optimization of Operation		18 %

C5.	**From Other Organizations**	10 %	Σ=100%
b	Preventive Maintenance		10 %
c	Quality Assurance (ISO 9000)		13 %
d	Environmental Management (ISO 14000)		7 %
e	Financial management (Accounting)		7 %
f	Marketing & Public Relations		12 %
g	Economic Analysis of Investments		14 %
h	Personnel Assessment and Development		9 %
i	Technical Advice		15 %
j	Optimization of Operation		13 %

D. Experiences from the existing IT systems

D1. Which are the professional software packages that you are either using personally or being the major benefiaciary of the software output, mark those with "x"

1	Customer database with billing and collecting	94 %
2	Equipment database with maintenance system	87 %
3	DH network analysis	91 %
4	Storage database (ware house inventory)	78 %
5	Financial management (accounting)	85 %

Based on your personal opinion, please mark with one "x" in each of the rows corresponding colums 5 (very much), 4 (much), 3 (cannot say or neutral), 2 (little) or 1 (very little or not at all).

D2. While procuring a professional software package, how important for your decision making is that the IT company:

	5	4	3	2	1
1 is well known		3.6			
2 is local		2.8			
3 has a large market share in your country		3.3			
4 has a good reputation		4.4			
5 offers after sales services		4.3			

D3. As a user of the professional software, are you satisfied with

	5	4	3	2	1
1 the software in general		3.7			
2 with the user interface			3.4		
3 changing the outlook of the screens			2.8		
4 tayloring			3.5		

D4. In case you were able to tailor the software in accordance with your particular needs,

	5	4	3	2	1
1 we have tailored the software			3.5		
2 tailoring has created problems			2.5		
3 tailoring has yeilded benefit		3.6			

Appendix 3

Specialists Replied to Questionnaire

Nr	DHE	Name	Title
1	Buzau	Victor Busuioc	General manager
2	Fagaras	Viorel Enuica	Technical manager
3	Gdansk	Leszek Wegrzyn	Marketing director
4	Gdansk	Krzysztof Rozanski	IT specialist
5	Gdansk	Renata Krasowska	Financial director
6	Gdansk	Miroslawa Frasunkiewicz	Manager
7	Gdansk	Ireneusz Stykiel	Specialist of DH network
8	Gdansk	Andrzej Krawzyck	Specialist of financial department
9	Gdansk	Marek Kozikowski	Specialist on business control
10	Gdansk	Stefan Hnatiuk	President
11	Gdansk	Arleta Ruszel	Specialist in PMU
12	Gdansk	Piotr Czabaj	Manager of PMU
13	Gdansk	Henryk Piontek	Main technical specialist
14	Gdansk	Janusz Jankowski	Manager of operation department
15	Gdansk	Petros Atanasiu	Manager of tech development
16	Gdansk	Kasimierz Kwiatkowski	Expert on Quality Assurance
17	Gdansk	Lucjan Stachowski	Technical director
18	Gdansk	Jaroslaw Miesikowski	Manager of network department
19	Gdansk	Tomasz Wroblewicz	Technical specialist in PMU
20	Gdansk	Maryla Mackowska	Specialist in PMU
21	Gdansk	Mr. Kmiecinski	Manager of boiler units
22	Gdansk	Marec Dec	Director of marketing
23	Gdynia	Tadeusz Gaizewski	Manager
24	Gdynia	Andrzej Mirolajski	Investment manager
25	Gdynia	Roman Prill	Specialist
26	Gdynia	Janina Kreft-Piotrowska	Specialist
27	Gdynia	Ewa Pyszna	Investment manager
28	Gdynia	Janusz Rozalski	Vice director, technology
29	Gdynia	Joanna Wotkowska-Panaz	Tech specialist
30	Gdynia	Marian Kochanowski	Manager
31	Gdynia	Alexander Wellenger	President of Board
32	Gdynia	Marian Wojtkowski	Director of technical affairs
33	Gdynia	Wojciech Ostrowski	Deputy manager
34	Gdynia	Tadeusz Listkowski	Chief specialist for automatics & telemetry
35	Gdynia	*Name missing*	
36	Gdynia	*Name missing*	
37	Jelgava	Irina Kuznechova	Engineer
38	Jelgava	Mihails Bragins	Manager of production laboratory
39	Jelgava	Irina Ivanova	Engineer
40	Jelgava	Lucija Truksane	Engineer

41	Jelgava	Peteris Kazulis	Tech director
42	Jelgava	Olga Kulchenko	manager of electricity departnment
43	Jelgava	Nikolajs Samsonovs	Manager of boiler plant
44	Jelgava	Aleksejs Djukarevs	Manager of DH distribution department
45	Jelgava	Svetlana Stepanenko	Manager of boiler plant
46	Jelgava	Aleksandrs Gura	manager of damage department
47	Jelgava	Aigars Upelnieks	DH equipment engineer
48	Jelgava	Aleksandrs Volkovs	Manager of DH transmission department
49	Jelgava	Ruslans Gribanovs	Administrator of IT systems
50	Jelgava	Gennadijs Dupusz	Managing director
51	Jelgava	Jelena Grohowska	Engineer
52	Jelgava	Meta Reine	Engineer
53	Jelgava	Astrida Bandina	Engineer
54	Jelgava	Gennadijs Bragins	Ass. manager of boiler plant
55	Jelgava	Marite redisone	Secretary, staff manager
56	Jelgava	Oksana Burkovska	Sales engineer
57	Jelgava	Maija Uldrika	Manager of technoical depoartment
58	Jelgava	Larisa Pilipenko	Sales engineer
59	Jelgava	Juris Strods	Executive director of city administration
60	Jelgava	Vera Brauna	Manager of financial department (city)
61	Katowice	Jerzy Swider	Director of investments
62	Katowice	Wanda Kobula	Chief investment implementation
63	Katowice	Janina Adamiec	QA specialist
64	Katowice	Tadeusz Turek	Director of marketing
65	Katowice	Ryszard Bialy	Manager of technical documentation
66	Katowice	Andrzej Tryba	Manager of marketing
67	Katowice	Witold Orszulski	Manager of energy planning
68	Katowice	Marius Krolikowski	Chief of DH section
69	Krakow	Janusz Miechowicz	Manager of PMU
70	Krakow	Renata Smolik	Specialist in PMU
71	Krakow	Marek Jaglarz	President
72	Krakow	Adam Swierz	Vice president, investments
73	Krakow	Katarzyna Firlit	Technical specialist
74	Krakow	Ryszard Gitis	Financial director
75	Krakow	Miroslaw Wroblewski	Main technical specialist
76	Krakow	Piotr Malysa	Specialist in DH
77	Krakow	Janusz Mazur	Manager of planning department
78	Krakow	Krzysztof Marendziuk	Manager of tariff department
79	Krakow	Darius Pitala	Manager of IT departmentr
80	Krakow	Michal Ramza	Specialist in PMU

81	Oltenita	Marin Craciun	Director, technical project manager
82	Oltenita	Claudian Popa	Project officer
83	Oltenita	Niculae Iudifta	Economist of Project
84	Oltenita	Veronica Mereuta	Specialist Licitatii
85	Oltenita	Violeta Craciun	Secretar of PMU
86	Ploiesti	Ion Ocneanu	General manager
87	Ploiesti	Sorina Barabas	Financial manager
88	Ploiesti	Christina Gheorghiu	Chief of technical department
89	Pärnu	Hillar Nuut	Sales Manager
90	Pärnu	Velvo Jöger	Network manager
91	Pärnu	Ivi Martens	Chief accountant
92	Pärnu	Mare Karotamm	Chief economist
93	Pärnu	Meelis Ilp	Master of maintenance
94	Sarajevo	Mirzo Hadzialic	Director of PMU
95	Sarajevo	Sanela Islamovic	Mechanical engineer
96	Sarajevo	Darko Repovic	IT assistant manager
97	Sarajevo	Azra Glisic	Civil engineer
98	Sarajevo	Nirha Kozica	Mechanical engineer
99	Sarajevo	Sanela Muhovic	Mechanical engineer
100	Sarajevo	Nihad Kurtalic	Mechanical engineer
101	Sarajevo	Anesa Libric	Mechanical engineer
102	Sarajevo	Ferduhin Islamovic	Mechanical engineer
103	Sarajevo	Milada Simic	Chief civil engineer
104	Tallinn	Olaf Saar	Network manager
105	Tallinn	Aare Leis	Head of network area
106	Tallinn	Valeri Dounits	Head of network area
107	Tallinn	Igor Vassilsuo	Head of network operation department
108	Tallinn	Vitali Moskalenko	Production director
109	Tallinn	Toivo makke	Manager,electrical & automation departm
110	Tallinn	Juri Soojärv	Project manager, automation department
111	Tallinn	Leonid Lipavski	Ex general manager
112	Tallinn	Sergei Trifonov	Ex development manager
113	Tallinn	Rein Tivas	Manager of automation
114	Tallinn	Vello Kaarlop	Head of network maintenance department
115	Tartu	Helle Proosa	Main economist
116	Tartu	Marcus Land	Director
117	Tartu	Mart Alver	Engineer
118	Warsaw	J. Wiktorko	Manager of Operation department
119	Warsaw	T. Lipiec	Vice manager of Operation department
120	Warsaw	M. Wojdan	Vice manager of labor department

121	Warsaw	A. Micor	Main specialist
122	Warsaw	A. Telakowiec	Main specialist in cost analysis
123	Warsaw	A. Wisniewska	Deputy of main specialist
124	Warsaw	T. Szymanski	Manager of operation department
125	Warsaw	Z. Plaszewski	Vice manager of operation department
126	Warsaw	A. Daszkowski	Manager of operation department
127	Warsaw	S. Sikora	Director, research & development institut
128	Warsaw	M. Bednarkiewicz	Vice manager,scientific research departm
129	Warsaw	A. Smyk	Manager of IT technology
130	Warsaw	Z. Pietrzyk	Manager of heat regulation department
131	Warsaw	J. Bojek	Manager of automation
132	Warsaw	E. Horbowiec	Main technical specialist
133	Warsaw	M. Sienniki	Specialis,heating design & modernization
134	Warsaw	J. Cieslik	Verificator of technical documentation
135	Warsaw	A. Dlugosz	Main specialist
136	Warsaw	K. Wesolowska	Specialist in technical modernization
137	Warsaw	J. Gecow	Main specialist,investment implementation
138	Warsaw	B. Niemiec	Manager, investment planning
139	Warsaw	E. Owczarczyk	Manager, investment preparation
140	Warsaw	P. Grzeszkowiak	Main specilist in technical affairs
141	Warsaw	E. Jaroskiewicz	Main specialist in system control

PMU means project management unit

Appendix 4

Model Documentation

1. General

All parameters and variables below are assumed positive except the variables of water temperature changes and the profit margin, which may be positive or negative. The summarizing operator Σ is over the years if not otherwise indicated.

2. Variables Ranging from a Season to the Period

2.1 Heat Supply

$Q(i,t,s)$	Heat produced by an energy source in a season (MW)
$Q(c,t)$	Heat energy input to a component (GWh)
$Q(i,t)$	Heat energy produced by an energy source in a year (GWh)

2.2 Electricity Sales of CHP Plant

$Q_{chp}(i,t,s)$	Heat energy consumption of the CHP plant in a season (GWh)
$P_{de}(t,s)$	Electricity sales to the grid in a season (GWh)
$P_{de}(t)$	Electricity (generation) sales to the grid in a year (GWh)
P_{de}	Electricity sales to the grid during the period (GWh)

2.3 Fuel Consumption

$\Phi(i,t,s)$	Fuel demand of an energy source in a season (GWh)
$\Phi(i,t)$	Fuel demand of an energy source in a year (GWh)
$\Phi(i)$	Fuel demand of an energy source during the period (GWh)
$\Phi(i,t,s)$	Fuel demand of an energy source in a season (GWh)
$\Phi(f,t,s)$	Total demand of a particular fuel in a season (GWh)
$\Phi(f,t)$	Fuel demand of a particular fuel in a year (GWh)
$\Phi(f)$	Total demand of a particular fuel during the period (GWh)
$\Phi(t,s)$	Fuel energy demand in total in a season (GWh)
$\Phi(t)$	Fuel energy demand in a year in total (GWh)
Φ	Fuel energy demand during the period in total (GWh)

2.4 Flue Gas Emissions

$\Delta\Psi(m=CO_2)$	Benefit in CO_2 reduction relative to Baseline case (Gg)
$\Psi(m,i,t,s)$	Emissions of an energy source (Mg)
$\Psi(m,t,s)$	Emissions in a season (Mg)
$\Psi(m,t)$	Emissions in a year (Mg)
$\Psi(m)$	Emissions during Period (Gg)
$C_{em}(t)$	Costs of SO_2, NO_x, CO_2 and dust emissions in a year (M€)

2.5 Bulk Heat Purchase

$Q_b(t,s)$	Bulk heat purchase in a season (GWh)
$Q_b(t)$	Bulk heat purchase in a year (GWh)

2.6 Supply and Return Water Temperatures of DH at the Main Heat Source

$t_s(t,s)$	Supply water temperature in a season (^oC)

$t_r(t,s)$	Return water temperature in a season (^oC)
$\Delta t_s(t,s)$	Reduction in supply temperature in a season (^oC)
$\Delta t_r(t,s)$	Reduction in return temperature in a season (^oC)
$t_{av}(t)$	Average water temperature in a year (^oC)

3. Variables Ranging from a Year to the Period

3.1 Heat Sales Covering Energy both for SH and DHW

$\Delta Q(\rho,t)$	Heat energy related to the actual connection rate of the heat demand (GWh)
$Q_o(t)$	Heat energy ideally demanded by the customers per year (GWh)
$Q_{de}(t)$	Heat sales as a basis of the DHE's cash flow in a year (GWh)
$Q_u(t)$	Undelivered heat energy (GWh)

3.2 Investments and Rehabilitation Rates

$C_{in}(c,t)$	Annual investment in a component of the Thermal Chain (M€)
$C_{in}(t)$	Total investment costs in a year (M€)
$C_v(t)$	Investments in network sectioning valves, part of the total investments (M€)
$D(t)$	Depreciation of the investments implemented in the previous years (M€)
N_{re}	Residual value of the Thermal Chain at end of the period (M€)
$R(c,t)$	Rehabilitation rate in the Thermal Chain (#)
$R_v(t)$	Network sectioning rate (#)

3.3 Thermal Losses

$Q_l(t)$	Thermal losses of the Thermal Chain (GWh)
$Q_{l,t}(t)$	Excess water temperature related thermal losses, a part of Q_l (GWh)
$Q_{l,w}(t)$	Water consumption related thermal losses, a part of Q_l (GWh)
$Q_{l,b}(t)$	Base thermal losses of the Thermal Chain, a part of Q_l (GWh)
$\Delta Q_l(R)$	Effect of investments on heat loss reduction (GWh)
$\Theta(R)$	Trigonometric or logarithmic benefit weighing function for material benefits in NLP (#)

3.4 Water Consumption

$W(t)$	Total reduction of water losses in a year (km^3)
$\Delta W(R)$	Reduction of water losses in a component in a year (km^3)
$W_{cm}(c,t)$	Commercial losses of water due to tapping (km^3)
$Q_{cm}(c,t)$	Commercial losses in a year (GWh)

3.5 Maintenance Materials

$B_{ex}(t)$	Benefit of extending lifetime of fixed assets of the Thermal Chain in a year (M€)

3.6 Electricity Consumption

$P_{pu}(R)$	Electricity savings in DH pumps (GWh)

3.7 Human Resources

$M(c,t)$	Reduction of HR in component in year (man year)
$M(t)$	Status of HR reduction at the end of year (man year)

$\Theta(R)$	Exponential benefit weighing function for HR benefits in NLP (#)

3.8 Excess Heat Production Capacity

$\Pi(t)$	Excess heat production capacity for phase-out (MW)

4. Variables over the Period

4.1 Costs and Benefits

B_{tot}	Benefits of investments (M€)
C_{tot}	Costs of operation and investments (M€)
$B_{em}(m=CO_2)$	Benefits of CO2 emission reduction (M€)
B_{ca}	Benefit of phasing out excess heat supply capacity (M€)
$B_{dh,de}$	Benefit of heat sales (M€)
B_{hr}	Benefit of reduced need of HR (M€)
B_w	Benefit of reduced water consumption (M€)
$B_{e,pu}$	Benefit of reduced consumption of pumping power (M€)
$B_{e,de}$	Benefit of CHP electricity sales (M€)
B_{ex}	Benefit of lifetime extension of the fixed assets (M€)
C_{in}	Costs of investments (M€)
C_f	Costs of fuels (M€)
C_o	Base costs of the DHE including fuels, electricity, water and HR in the base year but heat purchase costs excluded (M€)
C_u	Costs of undelivered heat in economic analysis (M€)
C_{em}	Costs of flue gas emissions (M€)
C_{cm}	Costs of commercial losses (M€)
PROFIT	Profit margin to be maximized during the period (M€)

5. Parameters

5.1 Single Parameters - Scalars

Selection I: financial (0) or economic (1) analysis to be done
Selection II: baseline (0) or rehabilitation (1) case to be analyzed
Selection III: impact of immaterial measures to benefits (1) or not (0)

a_1	Excess capacity needed over the real heat load (%)
a_2	Electricity from CHP converted to CO_2 reduction elsewhere (g/kWh)
a_3	Commercial losses recovery rate to convert part of water losses to sales of treated water (%)
a_4	Required IRR level (%)
a_5	Expected lifetime of the new fixed assets on average (a)
a_6	Heat demand escalation rate without measures (%/a)
a_7	Investment financing available, $\hat{C}_{in}$, in the period (%/a)
a_8	Peak load duration time in heat production (h)
a_9	Undelivered heat energy in base year summer as a share of total demand (%)
a_{10}	Recorded heat supply from the energy sources in the base year (GWh)
a_{11}	= 1 if immaterial measures included in benefits, but = 0.74 if not

a_{12}	Energy content of make up water (kWh/m^3)
a_{13}	Capacity of bulk heat purchase (MW)
a_{14}	Maximum network rehabilitation rate of small, medium and large pipes on average (%)
$\hat{C}_{in}$	Investment financing available (M€)
$\hat{C}_{v}$	Investment available for in network sectioning (M€)
$K_{em}(CO_2)$	Financial analysis: price of CO_2 savings in emission trading (€/Mg)
K_{ca}	Unit cost of not needed capacity a year (k€/MW)
$Q_o(t=0)$	Heat demand on room (economic analysis) and substation level (financial analysis) will be calculated according to the selected analysis
α	Power-to-heat ratio of CHP (MW/MW)
ξ	Sensitivity of power-to-heat ratio to return temp (%/^{o}C)
$\Psi_o(CO_2)$	Financial analysis: CO_2 emissions corresponding the Baseline (Gg)
η	Efficiency of a component in the Thermal Chain (%)
κ	Connection rate of radiators out of all radiators in the base year (%)

5.2 Parameters Consisting of Sets

$b_1(f)$	Type of fuels
$b_2(i)$	Names of energy sources
$b_3(i)$	Identification of CHP in the Names of energy sources
$b_{4a}(i)$	Properties of energy sources [capacity of heat production (MW)]
$b_{4b}(i)$	Properties of energy sources [efficiency of energy production (%)]
$b_{4c}(i)$	Properties of energy sources [annual energy availability (%)]
$b_{4d}(i,m)$	Properties of energy sources [flue gas cleaning rate for dust (%), flue gas cleaning rate for NO_x (%), flue gas cleaning rate for SO_2 (%)]
$b_5(k)$	Types of resources other than fuel [water, electricity, HR, heat purchase]
$b_6(-)$	Energy sales [heat (GWh), electricity (GWh), additional DHW sales in summer (GWh)]
$b_7(-)$	Sales prices [financial price (€/MWh), economic price (€/MWh), price escalation (%/a)] for Energy sales
$b_8(-)$	Volume and unit prices of resources other than fuel [volume([2]), financial price (€/unit), economic price (€/unit), price escalation (%/a)]
$b_9(s)$	Names of seasons [winter, spring, summer, autumn]
$b_{10}(s)$	Duration of each season (h)
$b_{11}(m)$	Types of emissions [SO_2, NO_x, Dust, CO_2]
$b_{12a}(f)$	Properties of fuel [economic price (€/MWh), financial price (€/MWh), price escalation (%/a)]
$b_{12a}(f,m)$	Properties of fuel [SO_2, emission coefficient (g/kWh), NO_x emission coefficient (g/kWh), Dust emission coefficient (g/kWh), CO_2 emission coefficient(g/kWh)]
$b_{13}(t)$	Water temperatures on the base year (^{o}C) [actual supply temperature, actual return temperature, minimum allowed for supply temperature, minimum allowed for return temperature]
$b_{14}(t)$	Selected number of years covered by the Period [base year, final year]
$b_{15}(c)$	The Thermal Chain of components of heat delivery (GWh) [heat

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[2] Unit for water: k m3, electricity: GWh, HR: man-year, and heat purchase: GWh

	production, pumping, heat transmission with large pipes, heat transmission with medium pipes, heat transmission with small pipes, heat metering, heat exchangers, temperature controller for SH, DSM measures in rooms]
$b_{16}(c)$	Benefit weighing function, linear [pumping, heat metering, heat exchangers, DSM measures in rooms]
$b_{17}(c)$	Benefit weighing function, logarithmic [heat production, heat transmission with large pipes, heat transmission with medium pipes, heat transmission with small pipes]
$b_{18}(c)$	Benefit weighing function, trigonometric [temperature controller for SH]
$b_{19}(c)$	Expected lifetime of the existing fixed assets per component of the Thermal Chain (a)
$b_{20}(c)$	Expected lifetime of the new fixed assets per component of the Thermal Chain (a)
$b_{21}(c)$	NRV of new fixed assets after rehabilitation per component of the Thermal Chain (M€)
$b_{22}(c)$	Physical investment downsizing factor per component of the Thermal Chain (%)
$b_{23}(c)$	Reduction potential of pumping power (%) in the Thermal Chain [pumping, heat transmission with large pipes, temperature controller for SH]
$b_{24}(c)$	Thermal loss coefficient of components of the Thermal Chain in base year (#)
$b_{25}(c)$	Thermal loss coefficient of components of the Thermal Chain in target year (#)
$b_{26}(c)$	Water consumption of components of the Thermal Chain in base year (km^3)
$b_{27}(c)$	Water consumption of components of the Thermal Chain in target year (km^3)
$b_{28}(c)$	HR allocated to components of the Thermal Chain in base year (man-year)
$b_{29}(c)$	HR allocated to components of the Thermal Chain in target year (man-year)
$b_{30}(m)$	Type of emission [SO_2, NOx, dust, CO_2]

For each heat source, the type of fuel has been appointed by means of the parameter sets, as follows:

$b_1(f)$ & $b_2(i)$

6. Equations and Inequalities

6.1 Objective Function of the Period

The objective function to be maximized is valued at PROFIT as follows:

$$\mathrm{PROFIT} = B_{tot} - C_{tot} \tag{4.1}$$

Where the total benefits and costs of the period are respectively:

$$B_{tot} = B_{em}(m=CO_2) + B_{ca} + B_{dh,de} + B_{hr} + B_{e,pu} + B_{e,de} + B_{ex} \quad (4.2)$$

$$C_{tot} = C_{in} + C_f + C_u + C_{em} + C_{cm} + C_o \quad (4.3)$$

The benefits and the costs of the period are summarized over the years of the period:

$$B_{ca} \leq \Sigma\ \Pi(t)\ (1+a_4)^{-(t-1)}\ a_{11}\ K_{ca} \quad (4.4)$$

$$B_{q,de} \leq \Sigma\ K_{dh}(t)\ Q_{de}(t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.5)$$

$$B_{hr} \leq \Sigma\ K_{hr}(t)\ M(t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.6)$$

$$B_w \leq \Sigma\ K_w(t)\ W(t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.7)$$

$$B_{e,pu} \leq \Sigma\ (P_{pu,o} - P_{pu}(t))\ (K_e(t) - \eta_{pu}\ K_{dh}(t))\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.8)$$

$$B_{e,de} \leq \Sigma\ K_e(t)\ P_{de}(t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.9)$$

$$B_{ex} \leq \Sigma\ B_{ex}(t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.10)$$

Benefits of CO_2 trading are taken into account only in the financial analysis, in which the obtained reduction of emissions compared with the emissions representing the Baseline can be traded.

$$B_{em}(m=CO_2) \leq \Sigma\ B_{em}(m=CO_2,t)\ (1+a_4)^{-(t-1)}\ a_{11} \quad (4.11)$$

The costs of the period are summarized over the years of the period for investments and fuels as follows:

$$C_{in} \geq \Sigma\ D(t)\ (1+a_4)^{-(t-1)} \quad (4.12)$$

$$C_f \geq \Sigma \sum_f K(f,t)\ \Phi(f,t)\ (1+a_4)^{-(t-1)} \quad (4.13)$$

The benefits of reduced consumption of fuel, electricity, water and HR above are from the initial level of such costs. The costs of the initial level of resource consumption would increase as the prices of resources increase in the real terms, if no rehabilitation program would be implemented. Therefore, at the end of the period, the base costs of the DHE are the costs of the initial resources added by the heat purchase costs.

$$C_o \geq \Sigma\ (K_b(t)\ Q_b(t) + C_o(t))\ (1+a_4)^{-(t-1)} \quad (4.14)$$

$$C_u \geq \Sigma\ K_u(t)\ Q_u(t)\ (1+a_4)^{-(t-1)} \quad (4.15)$$

$$C_{em} \geq \Sigma \sum_m K_{em}(m,t)\ \Psi(m,t)\ (1+a_4)^{-(t-1)} \quad (4.16)$$

$$C_{cm} \geq \Sigma\ K_{dh}(t)\ (1-R(c,t))\ ß(c)\ a_3\ a_{12}\ (1+a_4)^{-(t-1)} \quad (4.17)$$

The Model will adjust the inserted unit prices of resources and sales, K of the base year for the consecutive years by means of the inserted price escalation coefficients (ε_k) as follows:

$$K(t+1) = K(t)\ (1+\varepsilon_k) \qquad (4.18)$$

The unit price adjustments will be based on costs changes in real terms only, thus excluding the nominal price changes. The year-specific unit prices will be used in the Model both for quantifying the savings in use of resources as well as in sales revenues of heat and electricity (CHP).

6.2 Heat Sales

The increase of the rehabilitation rate of three components such as DSM, heat metering and the temperature controllers is assumed to increase the actual heat demand by ΔQ, which, due to prevailing disconnections, could not be supplied in the base year.

$$\Delta Q(\kappa,t) = Q_o(t)\ R_{av}(c,t)\ (1 - \kappa) \qquad (4.19)$$

The undelivered heat energy will decline when the rehabilitation the DH network sectioning rate will increase.

$$Q_u(t) = (1-R_v(t))\ Q_o(t)\ a_9 \qquad (4.20)$$

Therefore, heat sales of a year are as follows:

$$Q_{de}(t) = Q_o(t)\ (1 + 0.01\ a_6)^t + \Delta Q(\kappa,t) - Q_u(t) \qquad (4.21)$$

6.3 Investments and Rehabilitation Rates

Depreciation of the investment is calculated based on the performed investments and the average lifetime of the implemented assets:

$$D(t) = C_{in}(t)/a_5 + D(t-1) \qquad (4.22)$$

The residual value of the performed investments at the end of the period is:

$$N_{re} = \Sigma\ (C_{in}(t) - D(t)) \qquad (4.23)$$

The annual investments may not exceed the given percentage of the total funds available for investments.

$$C_{in}(t) \leq a_7\ \hat{C}_{in} \qquad (4.24)$$

The total funds available shall not be less that the sum of the allocated annual investment costs.

$$\hat{C}_{in} \geq \Sigma\ C_{in}(t) \qquad (4.25)$$

The rehabilitation rate of the network components - the small, medium and large pipelines - has been restricted to a_{14} on average, since the experience indicates that energy efficiency benefits do not accrue when exceeding the value of a_{14}.

$$R_{di}(t) + R_{tl}(t) + R_{tm}(t) \leq 3\ a_{14} \tag{4.26}$$

For any rehabilitation rate the eligible values range from zero to one.

$$R(c,t) \leq 1 \tag{4.27}$$

6.4 Thermal Losses

In NLP, the heat energy transfer in the Thermal Chain is characterized by means of the recursive formula as follows:

$$Q(c,t) = \eta_o(c)\ Q(c-1,t) + \text{ß}_{dh}(c)\ \Theta(c,t)\ Q(c-1,t)\ \Theta(R) \tag{4.28}$$

For LP, the above formula has been linearized in order to avoid the product of the two time dependent variables, R and Q, by means of the three first terms of the Taylor series method [Braun, 1978].

$$\begin{aligned} Q(c,t) = \ & \eta_o(c)\ Q(c-1,t) + \text{ß}_{dh}(c)\ [R(c,t)\ Q(c-1,0) + \\ & + R_o(c,t)\ \ (Q(c-1,t) - Q(c-1,0)) + (R(c,t) - R_o(c,t)\ Q(c-1,t))\ ] \end{aligned} \tag{4.29}$$

Where $Q(c,t)$ means the heat energy at the output of a component during a year, η_o the efficiency of the component during the base year, $\text{ß}_{dh,c}$ the potential of thermal energy savings at a component as inserted by means of the sets of estimates (%), and, $R(c,t)$ the rehabilitation rate of a component at the end of a year. R_o is a guessed rate of 0.2 for starting iteration.

The thermal losses of the Thermal Chain are

$$Q_l(t) = Q_{pr}(t) - Q_{de}(t) \tag{4.30}$$

The excess water temperature related thermal losses as part of the total thermal losses of the Thermal Chain are estimated on the annual level by assuming that the average annual ambient temperature is 10 ^{o}C as follows:

$$Q_{l,t}(t) \quad = Q_l(t)\ ((t_{av}(t) - 10)/(t_{m,av} - 10) - 1) \tag{4.31}$$

where $t_{av}(t)$ and $t_{m,av}$ are average annual water temperatures corresponding to the case year and the minimum allowed respectively.

The thermal losses caused by the make-up water consumption over the Thermal Chain are as follows:

$$Q_{l,w}(t) = W_o \sum_{c} (1-R(c,t))\ \text{ß}(c)\ a_{12} \tag{4.32}$$

The basic thermal losses of the Thermal Chain, after excluding the excess temperature related and the water loss related ones, which can be expressed as:

$$Q_{l,b}(t) \ = Q_l(t) - Q_{l,t}(t) - Q_{l,w}(t) \tag{4.33}$$

Rehabilitation of the pipelines, for instance, influences mainly on the basic part the thermal losses, the temperature controllers mainly to the excess temperature related and the heat exchangers mainly to the water consumption related thermal losses.

6.5 Water Consumption

The water losses in a year are:

$$W(t) = W_o - \sum_{c} \beta_w(c)\ R(c,t) \tag{4.34}$$

6.6 Maintenance Materials

The achieved extended lifetime, t_{ex}, after the rehabilitation of the fixed assets of any component has been completed, can be estimated by means of the rehabilitation rate of the particular fixed assets:

$$t_{ex}(c,t) = R(c,t)\ t_{el,n}(c) + (1-R(c,t))\ t_{el,o}(c) \tag{4.35}$$

Thus, the lifetime extension Δt_{ex} is as follows:

$$\Delta t_{ex}(c,t) = t_{ex}(c,t) - t_{el,o}(c) = R(c,t)\ (t_{el,n}(c) - t_{el,o}(c)) \tag{4.36}$$

In general, the rehabilitation rate R here is different for each component of the Thermal Chain. Moreover, the remaining lifetime of the existing assets of the Chain vary as well.

Let us now introduce the New Replacement Value (NRV and here only N) of the DH system, which is the value of the existing DH system if built today using BAT. In monetary terms, the benefit of the extended lifetime can be expressed by means of the N in a non-linear form as follows:

$$B_{ex} = N(c)/\ t_{el,o}(c) - N(c)/(t_{el,o}(c) + \Delta t_{ex}(c,t)) \tag{4.37}$$

In order to model, the above function shall be expressed in a general form:

$$B_{ex} = f(R)\ N(c) \tag{4.38}$$

Where B_{ex} is the benefit of the lifetime extension of a component, N is the new replacement value of the assets of a component, $t_{el,new}$ is the expected lifetime of the rehabilitated assets of a component, $t_{el,o}$ is the estimated remaining lifetime of the existing assets of a component, Δt_{ex} is the expected extension to the lifetime of a component by means of rehabilitation, and R is the rehabilitation rate of a component.

In the LP, a linear approximation for LP common to all components was formed as follows:

$$B_{ex} = 0.04\ N(c)\ R\ (c,t) \tag{4.39}$$

The factor 0.04 corresponds to the expected lifetime of the new fixed assets of 25 years on average.

6.7 Electricity Consumption

Electricity used for pumping in a year is as follows:

$$P_{pu}(t) = (1 - \sum_{c} R(c,t)\, \beta_{pu}(c))\, P_{pu,o} \quad (4.40)$$

6.8 Emissions

The flue gas emissions of a season in an energy source are based on (i) heat source specific fuel consumption, (ii) fuel specific factors for emissions, and (iii) both heat source and emission specific cleaning rates.

$$\Psi(m,i,t,s) = \Phi(i,t,s)\, b_{12a}(f,m)\, b_{4d}(i,m) \quad (4.41)$$

For each energy source (i), one type of fuel (f) only is specified, as given in the parameters.

6.9 Human Resources

The reduced number of HR is expressed below, where R(c,t) is the rehabilitation rate and Θ(c,t) is exponential benefit weighing function causing delay to the accrual of the benefits.

$$M(t) = M_o - \sum_{c} \beta_{hr}(c)\, \Theta(c,t) \quad (4.42)$$

6.10 Excess Heat Production Capacity

The excess heat production capacity, which should be eliminated, is estimated by the equation below:

$$\Pi(t) = \sum_{i} b_{4a}(i) + a_{13} - (1+ 0.01\, a_1)\, Q_{pr}(t) / a_8 \quad (4.43)$$

6.11 Other Restrictions

The water temperatures shall not be lower than the set minimums for each season

$$t_r(t,s) \geq t_{r,m}(s) \quad \text{and} \quad t_s(t,s) \geq t_{s,m}(s) \quad (4.44)$$

The energy production of each energy source shall be in the range of availability and physical capacity (α=0 to other sources than CHP)

$$Q(i,t,s) \leq (1+\alpha)\, b_{4a}(i)\, b_{4c}(i)\, b_{10}(s) \quad (4.45)$$

6.12 Accrual of Benefits

The below functions substitute the rehabilitation rates in the benefit functions

$$\Theta(c,t) = 1-\cos(\tfrac{1}{2} \pi\, R(c,t)) \quad (4.46)$$

The trigonometric function above is used in HR related benefits.

$$\Theta(c,t) = \lg(10\,R(c,t) + 1) \qquad (4.47)$$

The logarithmic function above is used for benefits related to the pipelines.

$$\Theta(c,t) = 0.1/\left(0.1 + 10\,e^{(-10\,R(c,t))}\right) \qquad (4.48)$$

The exponential function above is used for benefits related to the temperature controllers in substations.

Appendix 5

Model Adjustment

1. Background Information and Data

In general, the rehabilitation of the DH systems in the ETs has been carried out by using two different approaches, as presented in Table 5.1 and described as follows:

1. In Poland and the Baltic countries the rehabilitation started in early 90's with eliminating small polluting boilers, replacing pipelines in the network and with installing modern substations to buildings; and,
2. In Bulgaria, the rehabilitation started in late 90's with DSM measures. At first, heat meters and a little later the temperature controllers were installed to the substations countrywide. In parallel to the temperature controller installation, the PSP was given the opportunity to install DSM measures to the apartments and to organize billing and collection on apartment level.

Table 5.1. Contents of completed rehabilitation projects (x = included).

	DSM	Heat metering	Sub-stations	Network	Heat sources	
					HoBs	CHP
Poland		x	x	x	x	
Estonia		x	x	x	x	x
Latvia		x	x	x	x	
Bosnia		x	x	x	x	
Bulgaria	x	x	x			

The scope of all completed rehabilitation projects are summarized above. In all the aforementioned countries, heat metering of the customers was completed and invoicing was transferred from the fixed floor area based on the metering based billing, after the bulk of substations, the key component of the modern DH system, had been equipped with temperature control systems and heat meters.

The best sample of data has been available from the five DHEs in Poland, with which the author has had the opportunity to work for a number of years from the implementation to the completion phase. From the Baltic DHE, the data is based on the Implementation Completion Reports and the DHEs have been not willing/capable in providing with additional data in more detail.

The data for adjusting the Model to reality have been adopted from the reports on the completed projects (The World Bank, 2000 and 2001; Salminen, 2003).

The questionnaire analysis regarding the immaterial measures and the Model adjustment with real data were carried out in co-operation with 14 DHEs, where comprehensive DH rehabilitation projects, co-financed by the IFIs, have been completed already. The basic information of the DHEs and the related cities is summarized in Table 5.2.

Table 5.2. Summary of 14 DHEs having participated in the research project.

DHE	Network length km	Heat energy GWh	Staff	Turnover Local million	 M€	IRR	Project costs M US$
POLAND							
GPEC, Gdansk	339	2 300	728	57 US$	51	28 %	75
OPEC Gdynia	274	1 500	614	38 US$	34	40 %	46
SPEC Warsaw	1 429	10 600	2 460	257 US$	231	53 %	278
PEC Katowice	471	2 400	1 099	50 US$	45	26 %	60
MPEC Krakow	640	2 900	698	77 US$	69	44 %	72
BOSNIA&HERZEGOVINA							
Toplane Sarajevo	62	1 000	360	45 KM	23	19 %	45
LATVIA							
Jelgavas Siltumstikli	42	200	202	4 LVL	7	24 %	20
ESTONIA							
Tallinn Kute	490	1 904	617	692 EEK	22	24 %	21
Pärnu	41	142	76	42 EEK	1	12 %	5
Tarto	80	370	127	102 EEK	3	28 %	14
ROMANIA							
TermoficarePloiesti	92	686	537	104995 Lei	4	n.a.	32
Termoficare Fagaras	20	79	140	86740 Lei	4	n.a.	19
Termoficare Buzau	81	251	301	411225 Lei	18	n.a.	37
Termoficare Oltenita	35	43	160	45232 Lei	2	n.a.	32
Total	**4 095**	**24 375**	**8 119**		**515**		**756**

n.a.: not available

1.1 Poland

During 1992-2000 the WB has co-financed the DH rehabilitation in Gdansk, Gdynia, Katowice, Krakow and Warsaw. The rehabilitation mainly covered (i) elimination of 561 polluting coal/coke fired small boilers, 517 MW in total, by connecting the customers to the DH system or by installing a modern gas/oil boiler instead, (ii) replacement of 24% of the network pipelines, (iii) installation control systems to 80% of the substations, and installation of heat metering in all substations of the cities. As major benefits, the energy savings were 22% in terms of fuel consumption, the expected lifetime of the fixed assets was extended from 10 to 16 years, the water losses dropped 63% and, finally, the heat tariff level dropped more than 50% in the real terms of PLN/m^2 of floor area. Therefore, the heat customers were the main beneficiaries of the rehabilitation project. In Poland, the CHP plants remained rather untouched, as they did not belong to the borrowers' property. The five cities, with 20 TWh heat sales in total, cover 22% of the DH market in Poland, thus demonstrating the largest completed rehabilitation case not only in Poland but worldwide.

One significant benefit was the phase-out of consumer subsidies in early years of the project, from a nationwide average of 78% of the heating bill in 1991. This phenomenon has taken place in parallel, but has not been caused by the project. The WB, however, had issued certain conditions for approving the loan, one of them having been the phase-out of the heating related subsidies.

The total loan amounted to US$ 202 million and the total project costs to US$ 530 million. Despite poor financial resources in the early years, the five companies finally managed to cover 62% of the total investment costs.

The information available from the Implementation Completion Reports of the WB and the files collected by the author consist of the following time series and data:

Time series from year 1992 till 2000

- Inflation (%)
- Exchange rate (PLN/US$)
- Funds used for rehabilitation by the DHE (PLN)
- Fund used by the WB (PLN)
- Sold heat energy (GWh)
- Heat sales revenues (PLN/year)
- Number of customers (#)
- Connected floor areas of customers (m^2)
- Heat load ordered by the customers (MW)
- Metered heat sales per total sales (%)
- Purchased heat energy (GWh)
- Fuel (coal) consumption per year (Gg and GWh)
- DH network length in three size categories of pipelines (km)
- Heat transmission losses out of the supplied annual heat energy (%)
- Heat distribution losses of the sold annual heat energy (%)
- Small HoBs per fuel (# and MW)
- Small HoBs converted to gas/oil fuel (MW)
- Small HoBs eliminated and the customers connected to DH (MW)
- Water losses (m^3/a)
- Water volume of the system (m^3)
- Water quality: pH, total hardness, O_2, Ammoniac, Fe, Phosphate, conductivity
- Water temperatures, T_s and T_r (^oC)
- Electricity used for DH pumping at the CHP plant (GWh)
- Electricity used for DH pumping at the DHE with booster pumps and HoBs (GWh)
- HR allocated to O&M, Administration, Economy and finance and Management (#)
- Wages (kPLN)
- Unavailability of the heating services (number of days)
- Rehabilitated network length in three size categories (km)
- Rehabilitated substations with control systems (#)
- Rehabilitated substations with heat exchangers (#)
- Heat metering rate as metered substations of the total substations (%)

Single data

- Estimated remaining lifetime of the network in the base year (a)
- Estimated remaining lifetime of the substations in the base year (a)
- Man weeks used for training during the Project (man week)
- Man weeks used by the foreign consultants during the Project (man week)

1.2 Estonia

During 1994-1999 the WB has co-financed the DH rehabilitation in Tallinn, Pärnu and Tarto. The rehabilitation covered conversion/replacement of 36 polluting small boilers to bio fuels (wood, peat), 21.9 MW in total, improvement of the CHP plant IRU, replacement of only 4% of the network pipelines and installation control systems to all of the substations. As major benefits, the energy savings amounted to 31.6% in terms of fuel consumption, the water losses declined 84% and, finally, the heat was reduced in the real terms. Therefore, the heat customers were the main beneficiary of the rehabilitation project. The three cities cover about 50% of the DH market in Estonia, thus demonstrating a major rehabilitation case nationwide.

The total loan amounted to US$ 36.3 million and the total project cost to US$ 59.8 million. Co-financing from EIB, SIDA and some donors covered 18.0 million and the DHEs the balance, 5.5 million.

The information available from the Implementation Completion Reports of the WB and the files collected by the Author consist of the following time series and data:

Time series from year 1992 till 2000

- Funds used for rehabilitation by the DHE (US$)
- Funds used by the WB (US$)
- Sold heat energy (GWh)
- Heat sales (EEK/year)
- DH network length (km)
- Heat distribution losses of the sold annual heat energy (%)
- Water losses (m^3/a)
- Rehabilitated network length (km)
- Rehabilitated substations with control systems and heat exchangers (#)

Single data

- Small HoBs (# and MW)
- Small HoBs converted (#).

1.3 Latvia

During 1995-1999 the WB has co-financed the DH rehabilitation in Jelgava, Latvia. The rehabilitation has covered improvement of boiler efficiency from 75% (Jan 96) to 91% (Jun 00), replacement of 58% of the network pipelines and installation of temperature control systems to 100% of the substations. As major benefits, the energy savings were 26%, the expected lifetime of the fixed assets was extended from 5 to 30 years, and the water losses declined 87%. Despite the heat tariff being the fifth highest among 23 DHEs in Latvia, the estimated cost of heating a flat in Jelgava became the fourth lowest in Latvia. Therefore, the heat customers were the main beneficiaries of the rehabilitation project. The local CHP plant, owned by the sugar refinery, remained untouched, because the plant did not belong to the borrowers' property, unfortunately. Exclusion of the sugar factory from the rehabilitation scope has caused various problems later on. The price of heat sold by the CHP plant to the DHE exceeded the heat price of the boiler plants of the DHE. The DHE was obliged to buy heat from the CHP plant, because the plant was the only source on the right riverbank network.

The total loan amounted to US$ 11.8 million and the total project costs to US$ 16.9 million. SIDA co-financed US$ 4.2 million and the DHE of Jelgava financed the balance, US$ 0.9 million.

The information available from the Implementation Completion Reports of the WB and the files collected by the Author consist of the following time series and data:

Time series from year 1992 till 2000

- Funds used for rehabilitation by the DHE (US$)
- Fund used by the WB (US$)
- Number of customers (#)
- Metered heat sales per total sales (%)
- Fuel (coal) consumption per year (Gg and GWh)
- DH network length (km)
- Heat transmission losses of the supplied annual heat energy (%)
- Heat distribution losses of the sold annual heat energy (%)
- Water losses (m^3/a)
- Electricity used for DH pumping at the DHE with booster pumps and HoBs (GWh)
- HR (#)
- Rehabilitated network length (km)
- Rehabilitated substations with control systems and heat exchangers (#)
- Heat metering rate (%)
- Estimated remaining lifetime of the network in the base year and in target year (a).

1.4 Bosnia & Herzegovina

In Sarajevo, an emergency DH rehabilitation covering boiler rehabilitation, pipe replacement, and heat metering on building level was implemented during 1995-98 in a number of separate networks. After the project completed, no comparison about the situation before and after the project is available, largely because the war had interrupted the heat supply for several years and many documents from the pre-war times had vanished.

1.5 Bulgaria

Bulgaria is the first case where the DH system rehabilitation has started with metering all customers on the building level nationwide in all 18 cities, where DH systems exist. In addition, thermostatic radiator valves and cost allocators have been installed to most customers before any other rehabilitation was implemented in the DH/CHP system or in buildings. Therefore, the impacts of heat metering and thermostatic valves on the customers' behaviour can be measured in large scale and the obtained energy conservation level can be quantified and the lasting of the savings in course of the first years can be monitored. The first indicative results in obtained energy savings have been encouraging.

The WB loan of US$ 12 million was allocated for the above metering and substation control nationwide, but the DSM measures (thermostatic valves and cost allocators) were financed and implemented by the PSP. Based on the early experience from such measures, the energy conservation rate has been about 25% in 18 cities.

At the time of research, another and more comprehensive rehabilitation is going on in Sofia and Pernik, co-financed by the WB, EBRD and EU, but no results are available so far.

1.6 Romania

The DH system rehabilitation cases in Romania co-financed by EBRD were reviewed and the lessons were collected for the questionnaire analysis. The cities, where the DH systems were rehabilitated, are Buzau, Ploiesti, Pascani, Oltenita and Fagaras.

1.7 Nordic EU Countries

In many aspects, the Nordic (Finnish and Swedish) DH systems can be considered as best practice for the ETs. This is because:

1. The technology has been developed for harsh weather conditions, which exceed the requirements in most of the ETs and the EU countries;
2. The systems were developed under market conditions, thus being in line with the market requirements;
3. The efficiencies of the systems in terms of energy, water and electricity are high;
4. The heat price is competitive on the market, which makes DH attractive to the customers in most cities. The prices vary in ratio of two to one among the cities in Finland, for instance, thus making the DH rather expensive in some few locations, where typically solid fuels are used at small plants; and finally,
5. In general, the Nordic DH/CHP systems have been internationally acknowledged as bench marking targets for a desired system level performance. For instance, in year 1991 already, the United Nations has awarded the CHP/DH system of Helsinki for its high level of integration, high efficiency and good environmental performance. Thereafter, the system performance in Helsinki has improved further (Author, 2002).

2. Electricity Generation in CHP

The economic/financial viability of new CHP strongly depends on the operation costs and electricity sales revenues being a function of :

1. Power-to-heat ratio α varying from 0.2 up to 1.0 depending on the type and the actual loading of the CHP plant;
2. Sensitivity of α to the return temperature reduction, % of electricity production capacity per return temperature change (%/^{o}C)
3. The peak load duration time τ varying from 3,000 up to 8,000 h/a;
4. Variations of heat load on daily and weekly basis during the seasons of the year;
5. Price, quality and availability of fuels;
6. Price of electricity for sale to either the low, medium or high voltage grid and depending on the time (day, night, summer, winter) of the sales;
7. Price of heat for sale to heat customers;
8. Costs of various emissions, either in economic or financial analysis;
9. Investment costs including connections to fuel supply, water and heat networks and the electric grid; and,
10. Financial parameters including taxes.

3. Thermal Losses in Network

The thermal transmission losses depend on the length of the network. An approximation about the level of losses can be obtained by means of assuming the losses according to poor insulation in Fig. 5.1 below.

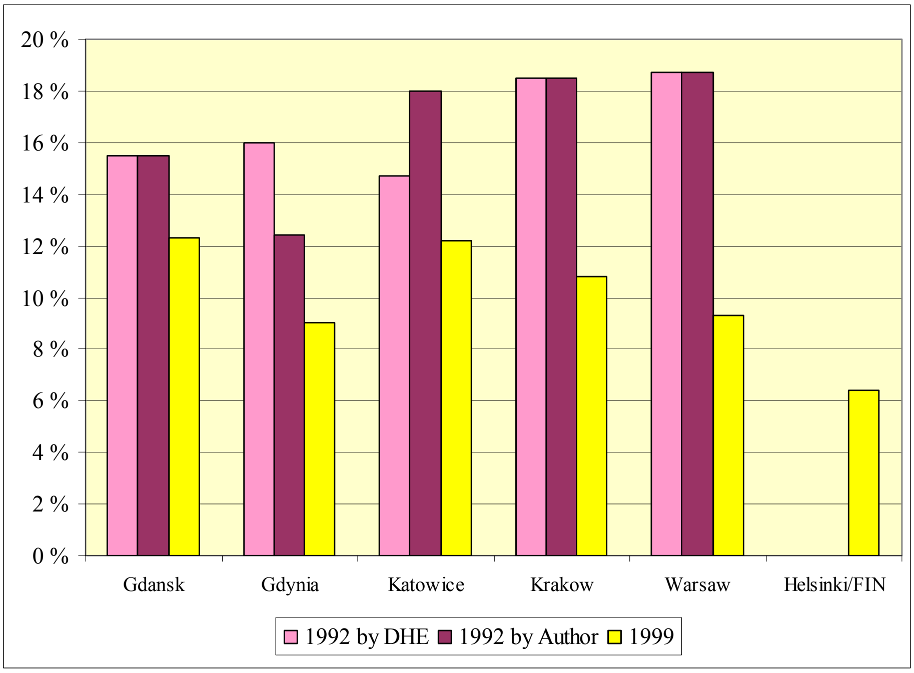


Figure 5.1. Indicative thermal losses in the network before and after rehabilitation, year 1992 estimated by the district heating enterprise (DHE) and the author, and year 1999 as measured (The World Bank 2000 and 2001; Helsinki, 1999).

In five Polish systems and in one from Bulgaria, the initial thermal losses of the network appeared to be four times higher on average, ranging from 3.3 to 4.6, than in a modern network, which is mainly caused by high conductivity of the thermal insulation. The same applies with Russia, where the thermal losses of the DH networks are assumed at the same level 19.2%, equal to 442 out of 2,300 mill Gcal (2.7 PWh) of produced heat (Bashmakov, 2004).

The thermal conductance of the pipeline is proportional to the overall heat transfer coefficient and the mantle area of the pipelines**.** The relation to mantle area, however, has been neglected in this discussion, because the mantle area of the pipelines in a DH system before and after rehabilitation has not changed significantly, but the new pipelines usually have replaced the old ones with the same dimension.

In the Nordic countries and in Germany, the thermal losses are about 10% of the supplied heat energy on average. The lowest values at 5% only are typical for large networks in these countries, such as the size of the five reference networks in Poland. In Poland the thermal losses have ranged from 15.5 to 18.7% before rehabilitation, and from 9.0 till 12.3% after the partial rehabilitation of the network had been completed.

Re-insulation of the usually aboveground pipelines improves the thermal efficiency according to the same benefit formula as for underground pipelines but with substantially lower investments. Typically 10% of the DH pipelines are installed aboveground and the balance underground. The main problem of such aboveground pipelines is theft of insulation materials. In order to avoid theft, the re-insulation may be done by a variety of technologies, for instance, such as with polyurethane foam, which is bound to the cover plates in a way which makes re-use of stolen insulation and the metal cover plates impossible, and by means of bitumen injection with Lebit methodology (Maxtherm, 2001; Förster et al, 2001).

For Model adjustment, the thermal transmission losses were obtained from six reference cities as presented in Table 5.3 below.

Table 5.3. The level of the thermal network losses of the network on the case year ($Q_{l,ne}$) and on the base year ($Q_{l,ne,o}$) depending on the network rehabilitation rate (R_{ne}).

DHE	$Q_{l,ne}/Q_{l,ne,o}$	R_{ne}
a	100 %	0 %
b	20 %	100 %
c	49.7 %	30 %
d	58.4 %	18 %
e	56.3 %	12 %
f	79.4 %	10 %
g	83.0 %	18 %
h	44.8 %	58 %

The linear regression formula based on the values given in Table 5.3 above with correlation of 0.89 is as follows:

$$Q_{l,ne}(t) / Q_{l,ne,o} = 0.93 - 0.84\, R_{ne}(t) \tag{5.1}$$

In creating the above formula, the weighing of the first row (a) in Table 5.3 is five times more than the consecutive rows down. The weighing is necessary as the thermal losses are 100% of the value of the base year while the rehabilitation rate is zero.

Another reference point, row b in Table 5.3, is assumed as an ideal situation when the entire network is rehabilitated (rehabilitation rate 100%). The network losses in large modern networks (Helsinki, for instance are about 5% of the produced heat energy, thus about a quarter of the initial level of the rehabilitated cases. In the system of Helsinki, however, there are still both preinsulated and mineral wool insulated pipelines, thus not yet being completely ideal. Therefore, the ideal target level of thermal losses is set at 20% of the initial thermal losses, when 100% of the network is rehabilitated.

In early 1990's, usually the heat consumed by the customers was not measured, because only relatively few customers were equipped with heat meters, the metering rate ranging from 14% (Gdansk) to 30% (Katowice), for instance. Despite of some heat metering having existed, the heat tariff for residential customers was not based on the meter readings but on the heated floor area. Therefore, the thermal transmission losses were unknown until all consumers were equipped with heat meters, thus having reached the metering rate of 1.

The metering rate in the reference DH systems has increased during the Project and by year 2000 all customers were metered and, thus the thermal transmission losses could be determined. Based on the development of the metering rate, the connected floor area and other energy conservation measures, that may have taken place in the buildings, the DHEs have estimated the level of the thermal transmission losses corresponding to the year 1992, the time before the rehabilitation started. The estimates regarding the initial thermal loss level of the DHEs vary from 14.7% up to 18.7% of the produced heat energy in the five cities of Poland.

In 2000, the measured transmission losses have ranged from 9.0% to 12.3% of produced heat energy in the five Polish cities.

In year 1992, the insulation related losses in the whole network used to be 3.4 times the heat losses of a modern network (all pipes new) on average and the factor ranging from 2.6 up to 3.9. During the Project, the pipelines worse than on average usually were replaced. Understandably, the thermal losses per network length of the worst pipes, that were replaced during the Project, were more than the thermal losses on average. Using the real insulation losses of year 2000 and the estimated ones for the year before rehabilitation, year 1992 or 1995 depending on the case, the change in insulation losses was caused by replacing a number of pipes. Thus, old pipelines, that were replaced, had the insulation losses about 1.4 times the insulation losses of the entire network before rehabilitation.

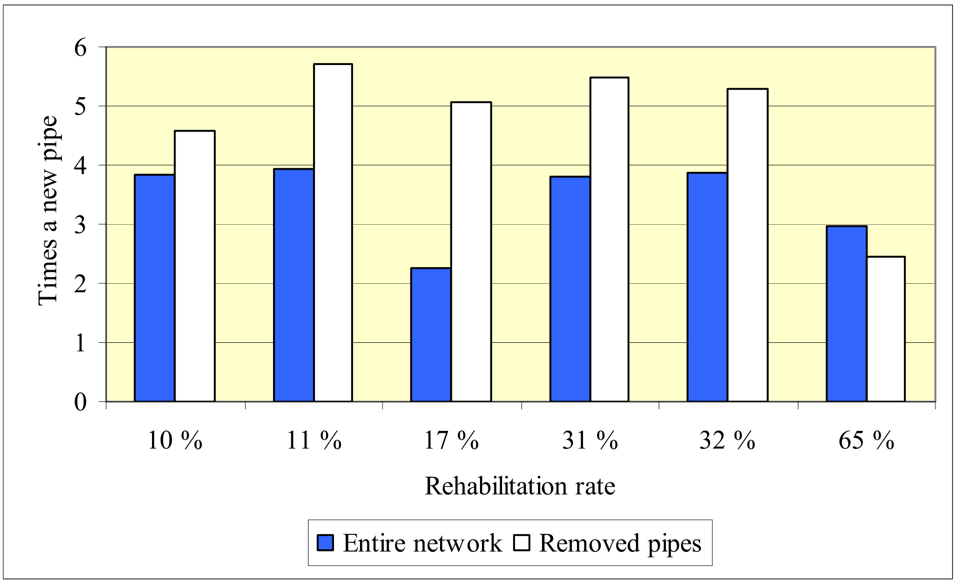


Figure 5.2. Thermal condition of pipelines in the network before rehabilitation and those that had been removed with indicated network rehabilitation rate, relative to brand new pipelines.

Fig. 5.2 above was created in four phases as follows:

1. The level of the basic thermal insulation (convective and conductive) losses was estimated by extracting the losses of make-up water heating regarding the water lost in the network pipelines and filtering out the impact of the different network water temperature levels in years 1992 and 2000, in a way presented in Appendix 4. Thus, the resulted basic thermal losses were caused only by poor insulation material and neither by high temperatures nor water losses;
2. For the year 1992, the relative thermal resistance of the existing network was estimated for the five DH networks in 1992 relative to the ideal network with brand new pipes. Thus the relative resistance appeared to be 3.4 times the resistance of a new network with same size and length of pipelines;
3. For year 2000, the unknown thermal resistance of the old pipes that still existed in the network, was estimated by using the ideal resistance values of the recently replaced pipes and the measured insulation losses of year 2000. This yielded the relative resistance of the old pipelines that were not replaced during the project; and,

4. Finally, the initial thermal resistance of the pipelines that were replaced during the Project, was estimated by using the thermal resistance of the not replaced pipelines to the old pipes and the estimated thermal insulation losses of the year 1992. The relative thermal conductance of the replaced pipes used to be 4.8 times the resistance of the new pipelines, thus 1.4 times the average of the entire network in year 1992.

In one DHE out of six, 50% or more of the network length was replaced. The insulation losses of the removed pipelines have been about the same or even less than those of the entire network before rehabilitation. This offers a reason to believe, that among the 50% replaced length relatively good pipelines were replaced as well. This may also indicate that (i) either the portion of the really poor pipelines in the network has been relatively small and all those had been replaced with the rehabilitation rate around 10% or so, (ii) or both DHEs did not know well the locations of the problematic pipelines before rehabilitation. Both indications may be true. The latter reason is understandable too, because the pipelines mainly are buried underground and are not visible in order to show their condition.

Data from five cities show that the pipes that were replaced the earliest, have had the highest incremental economic benefit compared to the later ones having lower incremental benefits.

While producing Fig 5.2 above, three probable inaccuracies (A, B and C) were identified in the thermal efficiency values in case Gdynia and Katowice estimated by the particular DHEs in Fig. 5.1 as follows:

A. In the year 1992, the network losses of Katowice have been 18% instead of 14.7 % as indicated by the DHE for two reasons as follows:

(i) The network of Katowice is relatively large (the load density of 3.9 MWh/m) compared with the other four cases (the density ranging from 4.7 to 7.4 MWh/m). Therefore, the thermal network losses are relatively high while the transmitted heat energy remains low, as in Katowice.

(ii) The average pipeline size is large DN 330 in Katowice ranging from DN 200 to DN 250 in the other four cases. A large pipe has more surface to produce thermal losses to the environment than the smaller ones.

B. In the year 1992, the transmission losses in Gdynia have been 12.4% instead of 16%, because the transmission network is relatively short compared with the other four cases. The DH system of Gdynia is characterized by group substations (GSs) separating the transmission and distribution networks, whereas the other cases are with individual building level substations (BLSs) and with relatively long transmission networks.

C. In year 1992, the efficiency of the GSs in five DHEs has been 91% instead of 95%, because the temperature control systems seem to have been poorer in quality than was estimated in the project completion phase in the year 2000. The efficiency of the GSs at 91% also fits better with the efficiency of the smaller BLSs than the estimated 95%, in which the efficiency has been about 84%. The technologies in the GSs and in the BLSs have been rather similar regardless the different size.

Based on Fig. 5.2, the network rehabilitation rate larger than 0.5 may not be economically prioritized, compared with other rehabilitation options available, because:

1. If the pipelines in poorest condition have been replaced first and the water quality has been improved simultaneously, the expected lifetime of the remaining pipeline is longer than the already replaced ones would have been and has even extended due to improved water quality;

2. The replacement costs of the entire network usually exceed the amount of funds available. Probably, a part of the network of the network still is in a relatively good technical shape; and,
3. Poor level of thermal insulation, as typical in the old DH systems, usually is not a sufficient economic argument alone to replace the pipeline section since other reasons must exist.

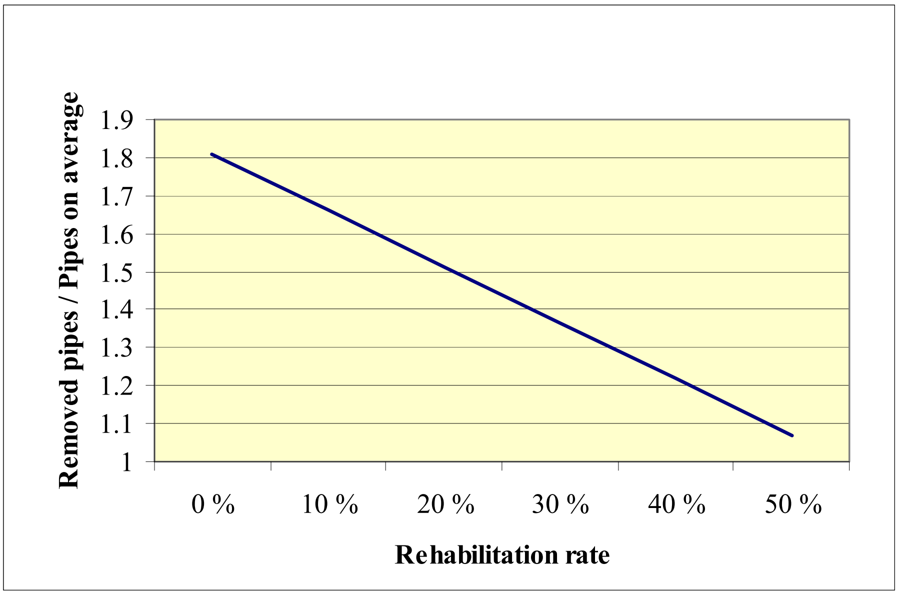


Figure 5.3. Level of thermal losses of the pipes to be replaced compared to all pipes in the network on average before rehabilitation.

In Fig. 5.3, the level of thermal losses of the pipes to be replaced compared to all pipes in the network on average before rehabilitation has been estimated. The line has been constructed by means of the data presented in Fig 5.2. The correlation, however, has remained low 0.56 for six cases. Therefore, the line can be considered as robust approximation only.

4. Thermal Control Losses in Buildings

In the DHW circuit of the buildings, the existing tube heat exchanger and the water temperature controller have required a relatively high water temperature in the DH network in order to deliver DHW at about 55^{o}C to the customers. Due to poor or missing control of SH at the consumer substations, the customers typically receive excess heating in spring and autumn. The heat sources are obliged to deliver excess heat in order to have simultaneous supply of DHW and SH at low heat load in spring and autumn. Such thermal losses related to poor thermal control of the SH circuit, which are acute in spring and autumn, here named as the thermal control losses in buildings, are presented in Fig. 5.4 below. Such losses do not exist in modern systems.

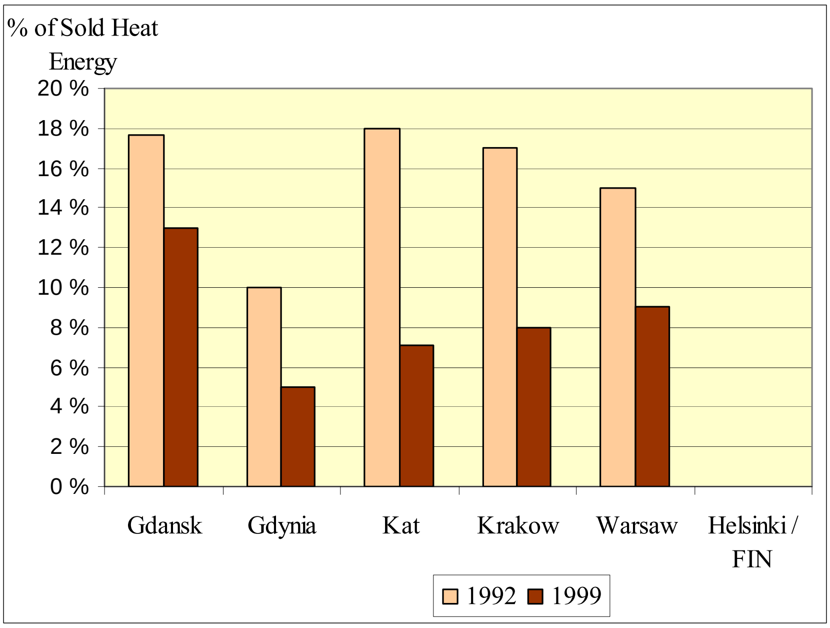


Figure 5.4. Thermal control losses in buildings caused by poor or missing control of space heating (SH) in the substation (The World Bank, 2000 and 2001).

Before rehabilitation, such control losses typically range from 10 to 20% of the delivered heat energy, as illustrated in Fig. 5.4. Therefore, by means of installation of temperature controllers extensively to the substations, such losses can be eliminated. The installation shall be extensive in the system in order to transform the entire system from the production to the demand driven mode.

5. Demand Side Management

In Bulgaria, rehabilitation of the DH system has started in 1999, when installation of heat meters to all substations countrywide has begun. Since year 2001, temperature controllers have been installed and heat exchangers have been replaced in case the current heat exchangers were not repairable any more. At the end of year 2003, practically all substations were equipped with temperature controllers and heat meters. In parallel to heat meters and controllers, the private sector has invested in DSM countrywide and organized billing according to the readings of the costs allocators and heat meters.

Based on the early results from Bulgaria, the energy savings caused by the heat meters, temperature controllers and the DSM measures have amounted to 25% of the delivered heat energy on average (Salminen, 2003).

In the city of Dubna, Russia, two buildings have been equipped with thermostatic valves and cost allocators installed to radiators in the SH circuit and water and heat meters in DHW circuit but the other two buildings of same size and age remained without any control. The results from a metering period of 212 days lasting from Nov. 1 till May 31 for water and of 79 days lasting from Feb 10 till April 30 in 1998 for heating are as follows:

1. In the SH of the controlled buildings, the average monthly heat consumption of the SH was 22.9% lower in the non-controlled buildings, 12.1 and 15.7 kWh/m^2 per month respectively;
2. In the DHW circuit of the controlled buildings, the DHW consumption was 55% lower than in the other ones, 48 and 130 liter per person a day respectively. The norm is 120 liter/person a day;
3. In the cold water circuit of the controlled buildings the water consumption was 36% less than in the other buildings, 67 and 105 liter per person a day respectively. The norm is 205 liter/person a day (Pötter et al, 1999).

Despite of covering a part of a year only, the above figures offer indicative evidence about the energy saving potential by comparing two sets of similar buildings.

In the Model, based on the experience from Bulgaria and supported by Russia, the potential for energy savings in the buildings have been set to 25% of the heat energy delivered to the customers in the base year. Such an assumption, however, can be changed with the input values of the Model.

6. Water Losses

The water losses in the DHEs in ETs before rehabilitation range widely from 10 to 50 water volume replacements a year. High water losses are considered an overall indicator of poor water quality, internal corrosion of the pipelines and armatures, blocking of small pipes and of high thermal losses, which cause increased O&M costs.

In eight cities in Poland and the Baltic states, rehabilitation of the networks with preinsulated pipes and converting the consumer connections from direct to indirect ones has substantially reduced the water consumption, as presented in Table 5.4.

Table 5.4. Water consumption level (W) depending on the rehabilitation rate of the substations (R_{he}) and the network (R_{ne}).

Case	R_{he}	R_{ne}	W
a	0 %	0 %	100 %
b	54 %	10 %	74 %
c	55 %	17 %	55 %
d	48 %	18 %	52 %
e	90 %	30 %	31 %
f	100 %	6 %	15 %
g	100 %	11 %	10 %
h	100 %	11 %	10 %
i	100 %	58 %	13 %

In the Model, the target level consumption is set on the level of 10% of the original consumption, which corresponds to the typical level prevailing in the modern networks equipped with heat exchangers. In Sweden and Finland the make-up water consumption amounts to about one network volume replacement a year, whereas about three replacements in Denmark and Germany on average (v. Brunn, 1978). Therefore, the assumed potential for reduction of water losses amounts to 90% of the original consumption.

Based on the simple linear correlation analysis, the regression formula is as follows:

$$W(t) = W_o (1.0 - 0.9\, R_{he}(t)) \qquad (5.3)$$

The correlation between the water losses and the substation rehabilitation rate with heat exchangers among the 8+1 cases was relatively high: -0.97.

The network rehabilitation rate had a much lower linear correlation with the water losses, -0.38, and is not considered reliable. Therefore, the impact estimate of the network rehabilitation is based on the assumption that water is lost either at consumers (above formula) or in the network and not elsewhere, and that the realistic target level is 10% of the initial water loss level (Table 5.4 above).

The target level of 10% corresponds to 1-2 water volume revolutions in the network, which is consistent with BAT practice prevailing in the Nordic indirectly connected DH networks (Finland, Sweden).

Based on this, adjusted formulas are used in the Model for the water losses of the base year (W_o), reducible water losses of the components (W_c) and the target losses (W_{re}) as follows:

$$W_o = \Sigma\, W_c + W_{re} \qquad (5.4)$$

The water savings are

$$\Delta W(t) = [R_{he}(t)\, \psi_1 + R_{di}(t)\, \psi_2 + R_{tm}(t)\, \psi_3 + R_{tr}(t)\, \psi_4]\, [W_o - W_{re}] \qquad (5.5)$$

Where ψ_1, ψ_2, ψ_2 and ψ_4 are weighing factors estimated at 0.80, 0.06, 0.03 and 0.01 adding up to 0.9 respectively.

7. Sectioning of District Heating Network

Installation of appropriate gate valves to allow sectioning of the network when needed will reduce the break-off period of the network.

Effective sectioning increases heat sales, mainly during summer time.

Table 5.5. A demonstration of the network sectioning to the availability of heating.

Number sectioning valves	Section length m	Duration of break-off in days: 5 days h	14 days h	25 days h
0	280 000	120	336	600
1	140 000	60	168	300
50	5 490	2	7	12
100	2 772	1	3	6
150	1 854	1	2	4
200	1 393	1	2	3
250	1 116	0	1	2

Table 5.5 above aims at simulating the impact of the network sectioning. Dividing the network of 300 km length, for instance, to 50 sections, some 6 km long each, would reduce the break-off time from 5-25 days to 2-12 hours, thus raising the heat supply availability from zero to 98% of the initial break-off time. Such an approximation is robust requiring a network loop in every 6 km of the section length.

For the Model, based on Table 5.5, the below approximation for the incremental heat sales was determined as follows:

$$Q_{de}(t) = Q_{de,o}\ (1+ (d_{bo}/d_y)\ \varsigma\ R_v(t) \qquad (5.5)$$

Where Q_{de} and $Q_{de,o}$ are the heat sales of the case year and base year respectively, d_{bo} is the number of break-off days in a year, d_y is the number of total days in a year (364), ς is the input parameter setting the desired availability level, 98% of the break-off time, for instance, and, R_v is the network sectioning rate.

8. Lifetime Extension of Fixed Assets

Based on the five cases in Poland, a linear regression was calculated for the lifetime extension separately as a function of rehabilitation rate of the substations (R_{su}) and the network (R_{ne}).

The new expected lifetime of the network, for instance, can be calculated by means of a weighted average as follows:

$$t_{ex} = \frac{\text{Length of old pipes x Remaining lifetime + Length of new pipes x 30 years}}{\text{Length of old and new pipes together}}$$

For the Model, the benefit of the lifetime extension a component can been expressed as follows

$$B_{ex}(c,t) = (N(c)/\ t_{el,o}(c) - N(c)/(\ t_{el,o}(c) + \delta t_{ex}(c,t)) \qquad (5.6)$$

Where N is the new replacement value of the component in the thermal chain (NRV), $t_{el,n}$ is the nominal expected lifetime of the component due to completed modernization, and, $t_{el,o}$ is the expected lifetime of the component in the base year and in the current condition.

The parameters and variables here are different for heat sources, substations as well as for large, medium and small pipes, as is the remaining lifetime of the existing pipelines. All such parameters are input values of the Model.

The value of N in terms of M€ shall be given to each component of the thermal chain. As base assumptions for the unit costs in the Model, the estimates based on the author's files from a number of DH rehabilitation cases in ETs have been used:

1. For gas and oil boilers 70 €/kW and for solid fuel boilers 300 €/kW have been used as basic estimates;
2. For large, medium and small pipelines 800, 300 and 200 €/m of network length respectively has been used. The length of the case network allocated to three components according to the size is usually available, or can be calculated based on the network documentation;
3. For installing a heat meter set to a substation 300 €/set has been used;

4. For installing either a temperature control system to the substation or a heat exchanger to the radiator circuit the unit cost estimate of 2000 €/substation has been used; and,
5. For installing the DSM measures to each of the radiators in the building a cost estimate of 2,000 €/per building, eg. per substation, has been used.

The nominal lifetime of the heat sources and the consumer equipment is usually 20 a, whereas the one for the modern pipelines is 30 a or even longer. On the other hand, the expected lifetime of the existing assets is usually about 10 a at maximum, if no preventive maintenance has been and will not be done.

The new replacement value, N, is assumed to be the product of the quantity and the unit price of the new equipment after supplied and installed. The same value of N has been used both for the existing system and for the modernized system with equal quantity and size, which is based on the assumption that, if the entire system were modernized now, there is no doubt about that modern technology would be used for rehabilitation instead of the existing old and outdated technology.

In Table 5.6 below, the expected lifetime extension of the network and substation investments is presented, based on the experiences from the five reference cases in Poland.

Table 5.6. Incremental Extension of Lifetime (t_{ex}) depending on the rehabilitation rate (R).

DHE	Network		Substations	
	$\frac{dR}{dt}$	$\frac{dt_{ex}}{dt}$	$\frac{dR}{dt}$	$\frac{dt_{ex}}{dt}$
Unit		a		a
a	1.3	0.3	4.4	0.5
b	2.0	0.4	5.0	0.6
c	2.7	0.6	5.8	0.7
d	3.5	0.8	6.6	0.8
e	1.2	0.3	6.6	0.8

Based on Table 5.6, a linear regression was formed for network investments. The high correlation of 0.99 is irrelevant, because the t_{ex} depends on R_{ne} by definition (previous formula). For the Model application, the below presented simplifications for annual lifetime extensions, dt_{ex}/dt, have been used:

$$dt_{ex,ne} = (0.0 + 20\ dR_{ne}/dt)\ dt \tag{5.7}$$

Similarly, for the substations, another linear regression formula was developed as follows:

$$dt_{ex,su} = (0.1 + 10\ dR_{co}/dt)\ dt \tag{5.8}$$

In the Model, the O&M benefits are allocated to two parts: O&M for HR and for spare part costs. In order to avoid double counting of benefits, only a part of the benefits shall be taken into account. Assuming roughly that 50% of the benefit is caused by the reduced labor need and the other 50% by the reduced need of spare parts including lubricants, only the spare part portion is taken into account in the lifetime extension benefit. The reduced labor part is already taken into account while analyzing the reduced number of HR in each DHE, thus avoiding double-counting of the benefits.

The benefit of the extended lifetime to reduce the spare part costs in the future is taken into account with the following two formulas, where the denominator factor t_{rm} should be equal to or higher than 10 (years):

$$B_{ex}(c,t)= 0.05\ N(c)\ R(c,t) \qquad (5.9)$$

In reality, the maintenance cost of the DH system in ETs is the main cost component after the energy costs. This is because the replacement investments have not been done but increased repair has compensated for the undone replacement. In Russia, maintenance comprises even about 50% of the DH costs, which is partly explained by the fuel prices - and fuel costs - far below the economic level. Only some 2% of the network has been replaced annually, whereas 5-8% are required, thus indicating that the expected lifetime of the pipelines ranges from 12.5 till 20 years only (Bashmakov, 2004).

In Russia, for example, due to poor maintenance of the outdated pipelines, the network damage frequency ranges from 0.6 to 4 damages per km of network length (Bashmakov, 2004). The frequency used to be on the same range in the DHEs in other ETs before rehabilitation. In the Nordic countries and in Germany the benchmark frequency amounts to about 0.1 damages per km on average (v. Brunn, 1978; Novem, 2002).

9. Network Repairs

In the DHE of Warsaw, the number and costs of the repairs works of the network damages have been recorded, eventually as the only DHE among the 14 reference cases.

In course of the rehabilitation, 30 % of the network length has been rehabilitated by means of the preinsulated pipelines. Simultaneously, the frequency of the network damages has declined 72% from 1.9 in year 1992 to 0.5 damages per km in 2000. Parallel to the decline of the frequency of the damages, the repair costs of a damage have fallen 68% from US$ 1,000 in year 1991 to US$ 316 equivalent per damage in 2000. In total, the repair costs have fallen from US$ 2.6 million in 1991 to 0.3 million equivalent in 2002 in the real terms.

Such a drastic improvement, as presented in Table 5.7 from Warsaw, has been caused both by the modern equipment and by the adopted preventive maintenance measures.

In the Model design, the expected reduction in the network repair costs is included in the benefits of reduced need of human resources and the reduced need of annual replacement of the network, in other words, the increased productivity of HR and the extended lifetime of the network assets.

Despite of the drastic fall of the repair costs, the damage frequency of 0.5 per km a year still exceeds the values prevailing in the BAT networks in the Nordic countries with the frequency value of 0.1 damages per km or less.

Table 5.7. Damages and their repair costs of DHE Warsaw during 1991-2001 (SPEC Warszawa, 2000).

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Unit
Number of damages		2723	2723	2383	2112	1621	1294	918	724	888	800	800	cases/a
Length of network		1430	1430	1436	1442	1448	1454	1460	1466	1472	1478	1490	km
Number/km		1.9	1.9	1.7	1.5	1.1	0.9	0.6	0.5	0.6	0.5	0.5	cases/km/a
Repair of above damages													
Cost from bookkeeping			2100	2600	3303	2873	1616	1362	1305	1142	1100	1100	kPLN
Factor to 1999 cost level			5.1	3.5	2.6	2.0	1.5	1.3	1.1	1.0	0.9	0.9	
Cost on 1999 cost level			10 606	9 189	8 615	5 668	2 489	1 750	1 459	1 142	1 012	946	kPLN (1999)
Exchange rate (1999)			4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	PLN/$
Cost on 1999 cost level			2 652	2 297	2 154	1 417	622	437	365	286	253	237	kUS$ (1999)
Savings from 1992 (1999 level)				354	498	1 234	2 029	2 214	2 287	2 366	2 399	2 415	kUS$ (1999)
Unit cost of one repair 1999 level			3.89	3.86	4.08	3.50	1.92	1.91	2.02	1.29	1.27		kPLN
			0.97	0.96	1.02	0.87	0.48	0.48	0.50	0.32	0.32		kUS$

10. Electricity Consumption

Based on the experience from three reference cases in Poland with frequency converters not yet installed in the production pumps during the project, the Polish DH systems have been operated under rather stable pumping conditions through the rehabilitation process. The experienced reduction of electric energy consumed for pumping was caused by the substation rehabilitation alone, as presented in Table 5.8 below.

Table 5.8. Reduction in electric energy used for DH pumping in three DHEs after temperature controllers were installed to the BLSs.

DHE	R_{co}	$\frac{dP_{pu}}{dR_{co}}$
a	0 %	0 %
b	54 %	-22 %
c	55 %	-24 %
d	90 %	-26 %

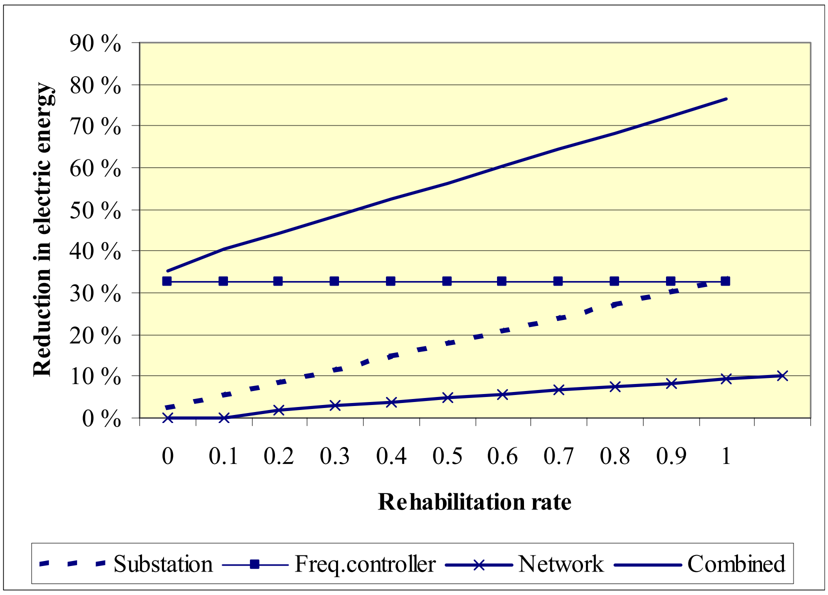


Figure 5.5. Reduction of electricity used for DH circulation pumping as a function of rehabilitation rates of substation control and distribution pipelines with and without frequency control in the Model.

The reduction in electric energy depending on the substation rehabilitation rate appeared substantial at the correlation of 0.95 in three cases where no frequency controllers were installed at the main heat sources. In one case, frequency controllers were installed at the heat sources and all substations were equipped with control valves and plate heat exchangers, thus replacing the hydroelevators, the electric energy used for pumping dropped 59% being consistent with Fig. 5.5 as well (The World Bank - Jelgava, 2000).

In three cases where no frequency controllers were installed at the main heat sources the reduction in electric energy depending on the network rehabilitation rate appeared at the correlation of 0.84.

Based on the above, the electric energy used for DH pumping is estimated in the Model. In order to avoid extending the optimization problem to mixed integer programming, the frequency controller for the pumping is considered as a linear pattern instead of an on/off pattern

The main part of the electricity is not lost but used for overcoming the friction in the pipelines, thus heating up the water. Therefore, the cost savings of DH pumping are estimated as follows

$$B_{pu}(t) = (K_e(t) - \eta_{pu} K_{dh}(t))\, P_{pu,o}\, (0.3\, R_{pr}(t) + 0.3\, R_{co}(t) + 0.1\, R_{di}(t)) \qquad (5.10)$$

Where B_{pu} indicates cost savings of pumping, η_{pu} the efficiency of DH pumping on the base year, K_e, K_{dh} the unit price of purchased electricity and sold district heat at the DHE respectively in the particular year, $P_{pu,o}$ electricity consumption for DH pumping in the base year, and, R_{pr}, R_{co}, R_{di} the rehabilitation rates of the frequency controller in heat production, the temperature controller in the substation and the small pipes in the network respectively.

The factors 0.3 and 0.1 are based on the analyzed experience from the completed projects in Latvia and Poland.

This relation is hampered by the sample of low number (five) of cases out of which only one with frequency controlled pumping. Therefore, the result is not considered very reliable but guiding.

An obvious inter-correlation between the two rehabilitation rates (R_{ne}, R_{co}) regarding pumping energy persists. The small sample of cases does not allow quantification of the inter-correlation (covariance).

11. Water Temperatures

In four DHEs in Poland, as the substation rehabilitation rate, R_{co}, varies from zero to 1, the supply and return temperatures have declined in course of the rehabilitation with correlation of 0.9 as follows:

$$\Delta T_s = - 15 \Delta R_{co} \tag{5.10}$$

$$\Delta T_r = - 12 \Delta R_{co} \tag{5.11}$$

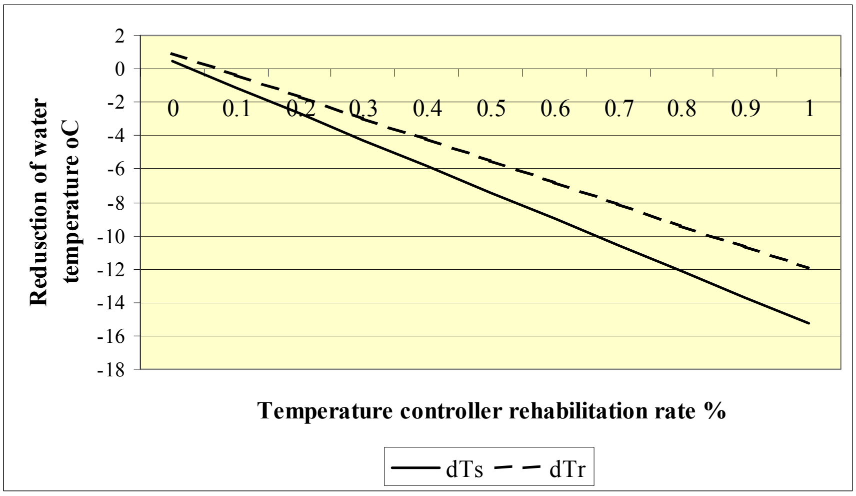


Figure 5.6. Reduced water temperatures at the heat source depending on the temperature controller rehabilitation rate in the building level substations - BLSs.

In four cities in Poland, where water temperatures are available from a long period of time, the DH system rehabilitation has made possible to reduce water temperatures in the DH system, thus reducing thermal transmission losses of the network and improving the power-to-heat ratio at the existing CHP plants.

12. Electricity Generation at CHP

Depending on the type of the CHP plant, the reduced water temperatures may enable the CHP plant to generate more electric power in the co-generation mode at the constant heat load provided that there is excess CHP production capacity available.

Both the power-to-heat ratio and its sensitivity to return temperature changes are input parameters of the Model specific to the particular CHP plant.

In the approximation the impact of the supply temperature to the power-to-heat ratio has been neglected. Therefore, the electric energy generated by the CHP plant is considered conservative.

13. Environmental Benefits

In the Model, the flue gas emissions of a season are calculated according to the fuel specific emission factors as well as to the plant and emission specific cleaning rates.

The emissions of heat production are calculated and valued according to the given unit costs.

The emissions of electricity generation in the CHP process depend on the type of analysis as follows:

1. In the economic analysis, all emissions of the electricity generation have been neglected, because the same amount of electricity would have been generated elsewhere at probably higher emissions. Therefore, electricity generation of the CHP is not considered to increase emissions on the economic case.
2. In the financial analysis, however, the emissions of the electricity generation in terms of SO_2, No_x and dust are included in the emission balance of the CHP plant. The CO_2 emissions of the CHP plant have been converted to tradable benefits while using an appropriate and a country specific conversion rate. As a base assumption, a conversion rate of 600 GWh of electricity per Mg of CO_2 has been used.

In the financial analysis, the CO_2 emissions for possible trading have to be calculated in two cases (lines) as follows:

1. The baseline, in which the business is assumed to continue as usual without any rehabilitation program; and,
2. The rehabilitation line, in which the benefits of the reduced CO_2 emissions are compared with the emissions of the baseline, and the difference will be valued by means of the unit costs of emission trading, here presumably € 3.5 per Mg of CO_2. The unit price can be changed in the input values of the Model.

The flue gas emissions (Ψ) are calculated directly from the fuel consumption, Φ_i, by means of the emission factors, for instance, as given in Table 5.9 below.

Table 5.9. Indicative emission factors of some common fuels in terms of kg/MWh of fuel.

	SO_2	NO_x	Dust	CO_2
Natural gas	-	-	-	202
Coal	1.4	0.7	30	328
Fuel oils	3.6	1.8	12	274
Peat	-	-	25	328
Biofuel	-	-	n.a.	-

In the Model, no green house gases other than CO_2 are considered.

14. Productivity of Human Resources

In course of the project, the five DHEs in Poland have managed to increase their heat sales. Therefore, the HR productivity has increased 25% on average in five Polish DHEs, as presented in Table 5.10 below.

Table 5.10. HR Productivity in terms of sold heat energy per employee in five DHEs in Poland.

DHE	1991	2000	Change
a	4.3	6.9	60 %
b	11.6	15.9	37 %
c	8.9	10.8	21 %
d	9.5	10.5	11 %
e	6.4	6	-6 %
Average			25 %

On operational side, the components of a DH system requiring most of HR were the small boilers, usually fuelled with solid fuels, and the consumer equipment (substations mainly).

Typically, the costs of HR in a DHE range from 5 to 10% of the total costs wherever in the ETs the DHE may be located. Due to its low volume, the costs of HR are a minor cost component. On the other hand, despite of increased productivity in terms of the heat sales per employee (TJ/person), the share of HR costs in the turnover has increased from 6.7% in 1992 to 10.0% in year 2000 in the reference systems in Poland (The World Bank, 2000 and 2001).

Based on the experience from the five cases in Poland, the major reason for HR reduction has been the boiler elimination program. The small boilers have needed substantial human resources for operation and maintenance, due to manual coal feeding and ash removal, starting/stopping of pumps and fans, and finally, closing/opening of various valves.

On the other hand, automation of consumer substations has reduced the need of HR.

The labor organizations (the solidarity movement), that used to participate closely in the decision taking in the DHEs, presumably were hesitant to reduce HR as much as the reduced need would have indicated.

Therefore, based on the above, an estimate was made according to which the total potential of HR reduction had been 50% compared with the 20-47% materialized in Poland, out of which 60% in O&M HR based on boiler elimination, 30% in O&M HR based on substation rehabilitation, and, 10% in economy, finance and in administration due to various modern management practices introduced.

In general, the number of employment of HR, M, as a function of the physical rehabilitation rate can be expressed as follows:

$$M(t) = M_o - \sum_{c} \beta_{hr}(c)\, \Theta(c,t) \qquad (5.12)$$

M is the level of HR in a particular component under rehabilitation in the particular year, M_o is the number of HR in the base year, β_{hr} is the potential for reduction, and

Θ(c,t), actually Θ(R), is the exponential benefit weighing function, which causes time delay to the HR reduction.

15. Modeling of Customer Affordability

The affordability and its expected trend of the customers is an important constraint for designing the energy system rehabilitation. A number of project specific social surveys have been carried out in order to estimate the affordability, requirement and willingness to pay for the heating services of different quality levels.

There are various measures for adjusting the energy supply according to affordability, about which some examples are mentioned as follows:

1. Only SH has been provided during the three coldest winter months, but the payment for such heating has been collected on monthly basis throughout the year (Kabul, Afghanistan);
2. Similarly, supply of SH has been covered by the DH during some five months only but at water temperatures substantially reduced from the normative ones (Niš and Kragujevac in Serbia); and,
3. Supply of SH and DHW but at water temperatures substantially reduced from the normative ones (most of DHEs in Russia).

Such options may be analyzed by means of the Model (i) while adjusting the heat load pattern with seasonal duration of the heat load accordingly, and (ii) by adjusting the price of the heat sales to Based on the affordability, the user has to modify the heat demand pattern in the Model in order to take the local affordability constraints into account while designing the rehabilitation strategy.

Appendix 6

Model Demonstration

1. Case Selection

A fictive DHE, here named as Teploset, has been specified to demonstrate the functioning and the outcome of the Model. The input data specifying Teploset is presented in the input tables (Table 6.1) on pages 9 and 10 of this Appendix.

Four rates described below describe the overall situation in the heating system:

1. Availability Rate

For four weeks during each summer, the entire DH system has been out of operation for annual repairs and pressure tests. The total breaks can be prevented by means of appropriate sectioning of the network. Presumably the lost heat sales amount to about 2.25% of the total heat demand.

2. Commercial Losses Recovery Rate

Rate of commercial losses depends on the DH water tapping of the buildings. In the substations, a water meter is usually located in the city water pipe supplying domestic water to the apartments. There is, however, no water meter for tapping water from the DH system. Therefore, the inhabitants in the buildings often tap water from the DH system free of charge to a variety of needs they may have. The DH water losses in buildings are called commercial losses, and after metered, about 30% of them can be likely converted to commercial heat sales. In the model, the conversion is determined by the parameter as named the commercial losses recovery rate.

3. Connection Rate

Rate of Connection of the physically connected heat load is 100%, which indicates that all room radiators are connected to the system. A case has been analyzed as well, in which the connection rate may have been 70% in the base year, and thereafter, would approach 100% while heat metering, temperature controllers and DSM will be installed to the BLSs.

4. DHW Rate

Practically all customers located near the sole energy source are equipped with DHW supply from the DH system.

The DH/CHP system of Teploset consists of

- Four heat sources altogether including a CHP plant, and three HoB plants with gas, HFO and bio fuel respectively at the total heat production capacity of 490 MW.
- 160 km of underground network
- 2,500 building level substations for SH mainly at 272 kW capacity on average each.

The market share of DH is relatively low, about 60% of the total heat load feasible for connection to the DH system. Teploset expects that the market share will be 66% in the ten-year period of time. Therefore, a load increase of 1% per year is expected.

In Teploset, no major rehabilitation has been done so far, but a comprehensive rehabilitation program is under consideration and under preliminary design. Therefore, the Model demonstration was considered a useful exercise, as discussed in the following chapters in detail.

Simultaneously, the municipality of Teploset has initiated a comprehensive campaign to improve energy efficiency of the buildings. Based on competitive bidding, a number of private enterprises have been selected to carry out the DSM program in the building sector. The DSM program consists of installation of thermostatic valves and cost allocators to those buildings, in which Teploset plans to install both heat meters and temperature controllers before the DSM measures become relevant.

In order to adopt the benefits of the immaterial measures, Teploset plans to introduce modern billing & collecting, financial accounting, preventive maintenance systems in the early years of the rehabilitation project. Education and twinning supporting the commissioning of the systems will be organized in co-operation with the consultants and the system suppliers (manufacturers).

2. Features of the Selected DH/CHP System

2.1 Heat Load

Based on the real heat purchase and the fuel consumption of Teploset, the real heat production at the design outdoor temperature of –15°C is about 400 MW and the system is operated all year round except the four-weeks lasting summer break.

The real heat load at substation level is 340 MW with estimated thermal transmission losses of 15%.

The installed capacity at the substation level is 680 MW, thus twice as high as the estimated heat load at the substation level. Therefore, the existing substations can be considered substantially oversized.

2.2 Energy Source

The CHP plant is fired by local coal. The CHP plant is relatively old, construction having started in 1976 and energy supply started in 1981. The plant still has economic lifetime of 10 years but practically another ten years more. The plant is equipped with two steam boilers. The steam boilers supply superheated steam to two steam turbines of back-pressure type. The electric generation capacity of the turbines is two times 10 MW delivered to the grid.

The heat production capacity of the CHP plant amounts to 40 MW, thus yielding the α-value of 0.5.

In addition to the CHP unit, the gas, bio-fuel and HFO fueled boilers are located at the CHP plant area as well, because the DH system is operated in the old production driven mode.

2.3 Heating Network

The network length is 160 km of channel with old mineral and glass wool insulation. The network length is allocated to large, medium and small pipes in 10%, 20% and 70% of length respectively. The small pipelines reach up to DN 200 and the large pipelines are from DN 500 up. Consequently, the medium pipelines range from DN 250 to DN 450.

The size of the pipes ranges from DN 20 up to DN 700 and the average size of the pipelines is DN 300. Thus, the network volume including the heat exchangers amounts to about 10,000 m^3.

In a number of parts of the network, the ground water has frequently penetrated to the pipeline channels, thus having corroded and partly destroyed them.

2.4 Network Damages

Based on the statistics of Teploset, there have been 250 damages in the heat transmission and distribution system annually, which equal to the frequency of 1.6 damages per network length a year. Frequencies of 1-2 damages are typical for the DHE systems in the ETs, whereas the corresponding number for the modern systems with BAT is only 0.1 or less. This is clear indication about the poor technical condition of the network. Therefore, the expected lifetime of the heating network with intensive maintenance work is hardly more than 15 years.

2.5 Substations

The consumer substations are currently owned by the customers and located in the building basements. The building level substations consist of hydroelevators and closing valves in 2,500 building basements.

There are 125 old group substations supplying heat to DHW and SH systems of the buildings by means of four-pipe systems. Therefore, each group substations supplies 20 buildings on average, as typical in the ETs.

Teploset plans to install a water temperature controller to each substation. The controller will adjust the heat consumption of the building according the prevailing outdoor temperature and the building specific control curves set to the controller.

Moreover, Teploset plans to install heat exchangers to the substation in order to isolate the SH circuit of the buildings from the DH network.

2.6 Heat Metering

In Teploset, one heat meter per building will be sufficient for heat metering, because the energy charge of the heat tariff to come shall be equal to all kinds of customers of Teploset. The heat meter will be installed to the substation in such a way that the flow sensor will be installed to the return side pipe as usual.

Usually, the heat meter is installed to the return pipe, where the measurement accuracy may be a little better than in the supply pipe. Another option would be to install the flow sensor to the supply pipe in order to invoice the customers not only for the consumed heat energy but also for the consumed network water. This is an efficient and a least-cost way to reduce water losses in the network, mainly lost by the consumers, but the supply side installation is rather rarely used in the DH business.

By means of installing the heat meter and the heat exchanger to the BLSs in buildings, Teploset expects to eliminate the commercial losses and to convert about 30% of the initial water losses to sales revenues of hot water.

2.7 Thermal Losses

Teploset uses coal, natural gas and heavy fuel oil. The annual efficiencies are given in the Input Table.

The thermal losses of the network are assumed at 15% of the produced heat energy. Presumably, half of the losses are caused by the small pipes, a third by the medium size pipes and the balance by the large transmission pipes. Based on the energy audit, the BAT level of the thermal losses would be 5.9%.

The thermal losses related to the missing temperature control of the substations is assumed at 14% of the heat energy delivered to the substations. By means of the DSM measures, the performed energy audits have indicated that additional 9% can be saved in heat consumption.

2.8 Water Quality

The make-up water is mainly taken from the CHP plant. The quality of water is considered unsatisfactory. The CHP plant uses the water from the nearby river for further treatment. The water treatment facilities must be upgraded in the beginning of the rehabilitation project before any modern equipment has been installed. The capacity of the upgraded plant should correspond to the target level losses, approximately 10% of the water losses of the base year.

2.9 Water Losses

In the base year 2003, the water losses of the DH system were still 200,000 m^3, equal to 20 network water volume replacements a year. This is a high and a typical number for such DH systems before rehabilitation. Based on the analyzed experience from the reference DHEs, presumably 80% of the losses take place in the buildings and the balance in the network from various reasons. The target level was set to 10% of the current losses.

2.10 Environmental

No other flue gas cleaning equipment is available except the cyclones at the CHP plant for dust with the dust removal rate of 70%.

No other flue gas cleaning improvements have been considered either, because both the CHP plant and the oil fired boilers are old. The gas fired boilers are relatively new and efficient and do no need any additional environmental investments.

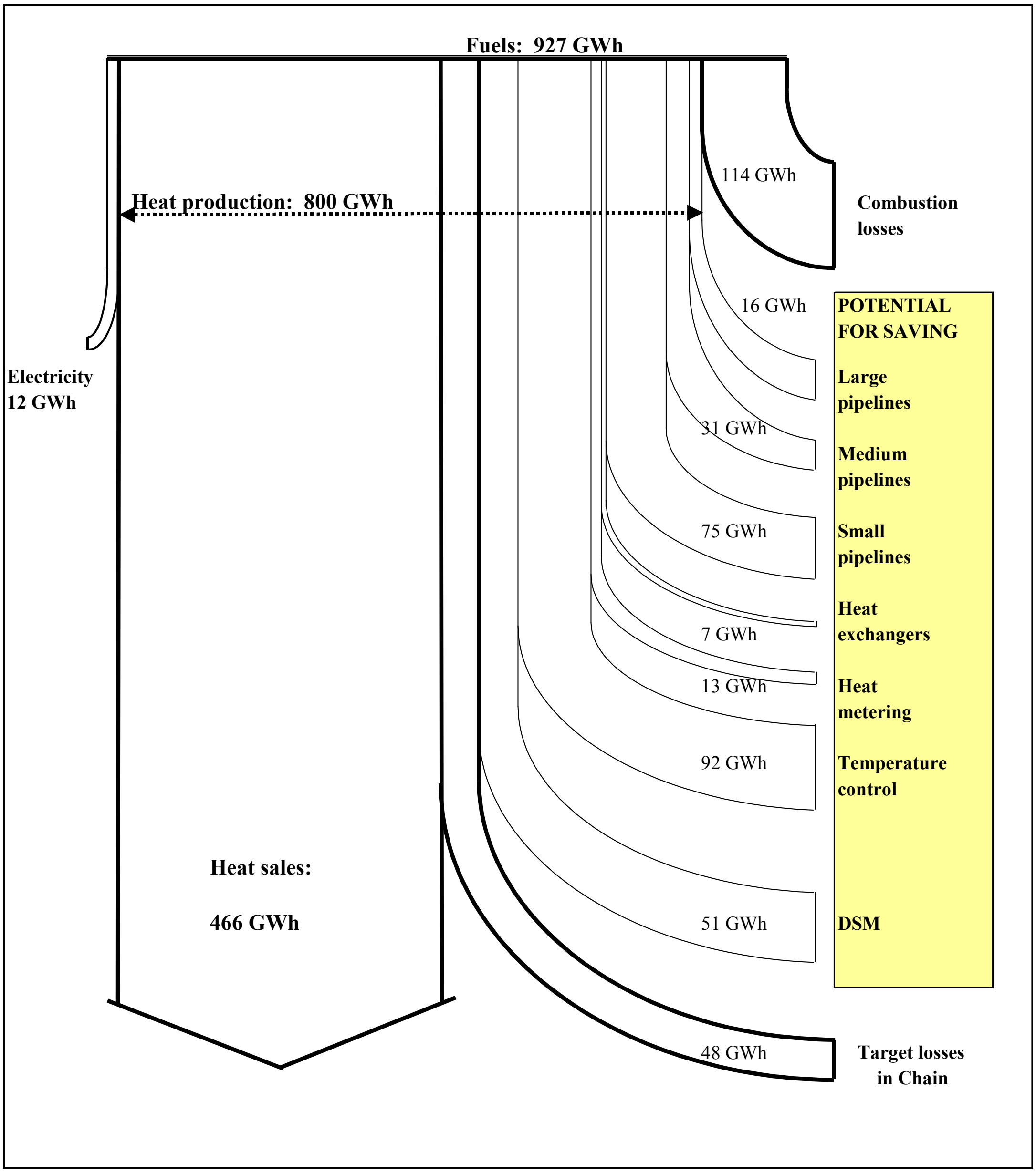
2.11 Operation

The DH system operation is production driven meaning that the customers are not able to control their heat load but either have to open the window to ventilate the occasional heat out or add clothing on in case he suffers from deficit in heating. The production plant controls the supply temperature (heat production level) collectively for all customers. Such a production driven mode is contradictory to the modern demand driven one, where each substation individually and automatically controls the heat consumption of the particular building and the thermostatic valves in room radiators control the heat consumption of each room of the apartments.

By means of the rehabilitation measures, Teploset plans to convert the operation from the production to the demand driven mode, thus substantially improving the efficiency and reducing the costs of operation.

3. Energy Balance

Figure 6.1. Energy balance of the district heating system under demonstration.



4. Planned Measures

4.1 Investments

The investment options under consideration at Teploset are:

1. Two new boilers to burn renewable fuel, thus producing 90 MW of heat at 87% efficiency and 92% energy availability;
2. A new small CHP plant using bio-fuel with the capacity of 30 MW electricity and 60 MW heat at the 85% total efficiency and at 95% availability;
3. Frequency controlled pumps to the energy source, where the CHP plant and the boilers are combined to one DH pumping station;
4. New preinsulated pipelines either to transmission or distribution lines;
5. Modern consumer substations, usually prefabricated compact substations to new customers;
6. Heat exchangers to the existing substations in order to isolate the SH circuits from the DH network;
7. Temperature controllers to the existing substations and eliminating the hydroelevators;
8. Heat meters to substations;
9. Gate valves to the network for sectioning;
10. Introduction of modern billing& collecting, financial management, preventive maintenance and remote control systems to the headquarters, where the energy dispatch center is located; and,
11. Education of the human resources to the modern tools and practices listed in the above bullet.

Parallel to the plans of Teploset, the municipality has decided to organize a citywide DSM program by means of PSP. The decision indicates that such a program will be completed in three years. In the program thermostatic valves and costs allocators will be installed to the room radiators in all buildings already connected or to be connected to the DH system.

4.2 Downsizing Factor

A downsizing factor has been used for the investments as follows:

1. No downsizing to the heat production capacity, because the capacity checking of the Model will drop out the excess capacity automatically;
2. No downsizing for the network investments, because new heat load is expected to the current network. No oversizing is needed either, because expected energy conservation and increasing cooling will release transmission capacity in the existing network; and,
3. Heat exchangers in substations: 0.7 downsizing, which still leaves some excess capacity to the substations instead of the prevailing 100%.

4.3 Unit Prices

The unit prices for fuels, heat purchase, electricity, HR as well as to energy sales are given in Input Table. For each unit cost an escalation factor has been given, which will adjust the unit cost according to the cost increases/decreases in the real terms.

4.4 Financial Constraints

The financial capacity of the PSP to finance the rehabilitation is considered limited. In this case, the PSP plans to a ten-year investment program with 20 M€ equivalent altogether. No more than 15% of the total funds should be used annually, because the local contribution capacity to the annual investment financing is restricted.

4.6 Combined Approach of Financial and Economic Analyses

The rehabilitation concept of the DH/CHP system of Teploset comprises a combination of the two different main approaches, which have been used in the ETs during in past decade as follows:

1. In Poland and the Baltic countries the rehabilitation started in early 90's with eliminating small polluting boilers, replacing pipelines in the network and with installing modern substations to buildings
2. In Bulgaria, the rehabilitation started in late 90's with DSM measures. At first, heat meters and a little later the temperature controllers were installed to the substations countrywide. In parallel to the temperature controller installation, the PSP was given the opportunity to install DSM measures to the apartments and to organize in-house billing and collection.

Table 6.1. Input values of the Model demonstration (see next two pages).

Input Values (1/2)

Heat Load Duration

	Winter	Spring	Summer	Autumn
Relative energy	50 %	20 %	10 %	20 %
Duration (h)	2400	1500	3360	1500

Water Temperatures

	Winter	Spring	Summer	Autumn	
Supply, actual	110	90	80	85	^{o}C
Return, actual	50	50	50	50	^{o}C
Supply, minimum	90	80	60	70	^{o}C
Return, minimum	40	35	30	35	^{o}C

Inefficiency of Resource Utilization

	Prod	Pump	Large	Medium	Small	Heat ex	H meter	Control	DSM
Human Resources									
Base year	50	5	5	10	60	100	0	30	
Target	20	1	2	4	15	10	0	10	
Thermal loss percentage									
Base year			0.02	0.04	0.10	0.01	0.02	0.14	0.09
Target			0.01	0.02	0.03	0.00	0.00	0.00	0.00
Water consumption									
Base year			0.01	0.03	0.06	0.90			
Target			0.01	0.02	0.02	0.04			
DH pumping power									
Base year		0.30	0.10					0.30	
Target		0.00	0.00					0.00	
Investment Downsizing Factor									
						0.60			

Scalars

1	CHP electricity converted CO_2 equivalent in Kioto Protocoll	kWh/g	0
2	Price of CO_2 savings in Kioto Protocoll	€/Mg	3.5
3	Baseline (0) or (1) rehabilitation		1
4	Economic (1) or financial (0) analysis		1
5	Efficiency of DH pumping	%	70
6	Heat supply from all sources together on the base year	GWh	800
7	Heat demand escalation rate due to new customers	%/a	1
8	Connection rate of existing customers on the base year	%	100
9	Impact of immaterial measures included (1) or not (0)		1
10	Investment financing available during the selected Period	M€	20
11	Investment financing available per year	%	12
12	Undelivered heat energy due to poor sectioning	%	2.25
13	Number of years in the Period		10
14	Commercial water losses conversion rate	%	30
15	Investment required for network sectioning	M€	1
16	Excess capacity needed to heat heat load	%	20
17	Unit cost of excess heat production capacity in a year	€/MW	2
18	Peak load duration time of heat production	h	2400
19	Commercial losses' recovery rate	%	30
20	Connection rate in the base year	%	100
21	Heat demand expansion rate due to new customers per annum	%	1
22	Required level of IRR	%	10
23	Lifetime of the new equipment for depreciation calculation	a	25
24	CO2 emissions in the base line	Tg	128

Input Values (2/2)

New Replacement Values

Energy sources	Capacity	New life	Rem. life	Fuel	Unit cost	Current	NRV
	MW	a	a		€/kW	M€	M€
Existing CHP	40	30	10	coal	2000	27	80
New CHP	40	30	30	gas	2000	80	80
Oil boilers	150	30	10	HFO	70	4	11
Gas boilers	150	30	25	gas	70	9	11
Renewables boilers	150	30	25	bio	300	38	45
Network	Length				€/m		
DN 500 and above	16	30	15		800	6	13
DN 250 to DN 450	32	30	12		300	4	10
DN 200 and below	112	30	10		200	7	22
	Number						
Sectioning valves	50	25	25		50000	0	3
Substations	Number				€/unit		
Heat meters	2500	20	0		300	0	1
Heat exchangers	2500	20	0		2000	0	5
Temperature controllers	2500	20	0		1000	0	3
DSM	Apartments				€/apartment		
Cost allocators	50000	20	0		60	0	3
Thermostatic valves	50000	20	0		30	0	2

Technical Data

Energy Sources	Production of energy				Flue gas cleaning rate		
	α		Efficiency	Availability	SO_2	No_x	Dust
	MW/MW	%/MW	%	%	%	%	%
CHP	0.5		85	90			70 %
Sensitivity		0.04					
Oil boilers			88	95			
Gas boilers			91	98			
Renewables boilers			80	93			

Fuels and Emissions

Fuels	Unit price			Emission factors			
	Economic	Financial	Escalation	SO_2	No_x	Dust	CO_2
	€/MWh	€/MWh	%/a	g/MJ	g/MJ	g/MJ	g/MJ
Coal	9	9	1	1.4	0.7	30	328
Natural gas	14	14	1	0	0.4	0	202
Heavy fuel oil	12	12	1	2.2	1.8	12	274
Renewable fuel	9	9	1	0	0	0	0
Costs of Emissions				€/ton	€/ton	€/ton	€/ton
Economic				300	200	60	0.8
Financial				3	2	0.6	0

Resources Other than Fuels

	Quantity		Unit price			Escalation
Purchase			Financial	Economic		%/a
Water	200	km^3	1	4	€/m^3	1
Electricity	100	GWh	40	55	€/MWh	1
Human resources	960	persons	5000	8000	€/person,a	1
Heat purchase	100	GWh	150	150	€/MWh	1
Sales Heat			20	30	€/MWh	1
Electricity (CHP)			40	50	€/MWh	1
Undelivered heat			30	40	€/MWh	1

5. Results

5.1 Summary of Costs and Benefits

The same case was analyzed with the Model both with LP and NLP.

Same amount of funds, 30 M€, was used in both LP and NLP during the Period of 10 years. Both of them have used the funds during the first 7 years as fast as possible under the given financial constraint of 15% or less per year.

Table 6.2. Summary of cumulative costs and benefits in the economic and financial analysis using either LP or NLP.

Item		Economic Analysis				Financial Analysis			
		LP	NLP	Diff.	%	LP	NLP	Diff.	%
Benefits	CO2 reduction	n.a.	n.a.			1.2	1.4	0.2	16.7%
	Excess capacity elimination	4.3	4.0	-0.3	-7.9%	3.09	2.82	-0.3	-8.7%
	Heat sales	169.4	169.4	0.0	0.0%	147.3	152.2	4.9	3.3%
	HR	10.6	10.0	-0.6	-5.9%	6.35	6.08	-0.3	-4.3%
	Water	6.0	6.2	0.2	3.3%	1.67	1.65	0.0	-1.2%
	Electricity in DH pumping	3.9	3.5	-0.3	-8.8%	1.48	2.51	1.0	69.6%
	Electricity sales (CHP)	0.0	0.0	0.0		22.6	23.9	1.3	5.8%
	Lifetime extension	31.7	28.5	-3.2	-10.1%	50.4	29.9	-20.5	-40.7%
Costs	Investments	8.6	8.6	0.0	0.0%	8.58	8.58	0.0	0.0%
	Fuel costs	71.0	75.4	4.4	6.2%	90.4	94.5	4.1	4.5%
	Base costs of DHE	42.7	42.7	0.0	0.0%	24.7	24.7	0.0	0.0%
	Undelivered heat								
	Emissions	153.1	162.4	9.3	6.1%	10.3	9.5	-0.8	-7.8%
	Commercial losses	0.2	0.2	0.0	-13.5%	0.1	0.06	0.0	-40.0%
	Benefits	225.4	221.6	-3.8	-1.7%	234	220.6	-13.4	-5.7%
	Costs	275.4	289.2	13.8	5.0%	134	137.4	3.4	2.5%
	Profit	-50.1	-67.6	-17.5	34.9%	100	83.2	-16.8	-16.8%

5.2 Rehabilitation Rates

In both analyses, the most beneficial investment is to invest in the temperature controllers and heat meters of the substation. Both LP and NLP complete the investments in two first years. The LP invests in the equal portion to both heat metering and temperature controllers, whereas the NLP prefers heat meters before temperature controllers. The restriction given to the Model is that one should not invest in temperature controllers if the heat meter is not in place.

The heat exchanger is also a priority investment in both LP and NLP in order to reduce water losses of the system.

The investment in frequency controlled DH pumps is scheduled for the second and the first year in LP and NLP respectively.

The investment in heat exchangers has started in the second and the first year in LP and NLP respectively and has been completed in two years in both analyses.

Investments in small pipes are scheduled for the 6th and the 1st year in LP and NLP respectively, because the NLP assumes that the first pipes are more economic and the later pipeline replacements. Correspondingly, the LP suggest only 22% whereas the NLP 47% of the small pipelines for replacement.

Medium pipes are not proposed by the LP at all but NLP suggest 25% to be replaced at the later years of the Period. Again, the first pipes are to be likely more economic than the others, which may improve the economy of the NLP compared with the LP.

Neither LP nor NLP has proposed large pipelines for replacement during the Period.

Regarding the DSM the case seems interesting. The LP invests in DSM during the 3rd to 6th year, whereas the NLP invests in the poorest pipelines instead of the DSM. This is because the LP does not recognize the assumption, that the first pipeline replacements might be more economic than the pipeline replacements on average, and therefore, the LP prefers DSM investments.

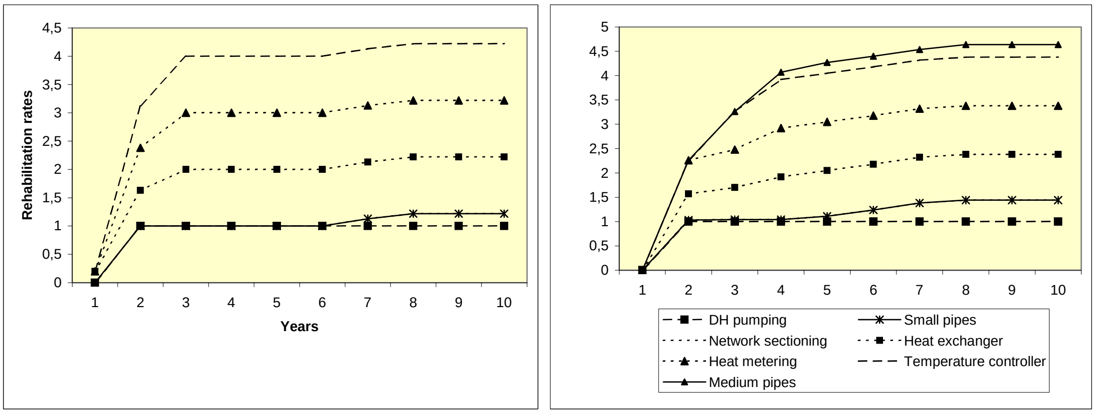


Figure 6.2. The rehabilitation rates in the economic analysis with LP (left) and NLP (right).

In both cases presented in Fig. 6.2, the heat exchanger rehabilitation has been the first measure in order to cut the water losses. The heat exchanger rehabilitation has been assisted by the down-sizing factor (0.6), which has substantially reduced the size of the heat changer capacity, and the investment unit costs relative to the original sizing. Without downsizing of heat exchangers, the temperature controllers would be the most economic investments, which would also require installation of heat meters to the BLSs.

Another investment with high priority is the frequency controller to DH pumping, with similar behavior in both LP and NLP.

The LP has used little funds for replacing small pipelines in the network on the 5th year and thereafter but no funds for larger pipelines at all. In the NLP, the incremental benefits of replacing the first pipelines is higher than the benefits on average, which has resulted in little more allocation of funds for small pipes but also started rehabilitation of medium pipelines.

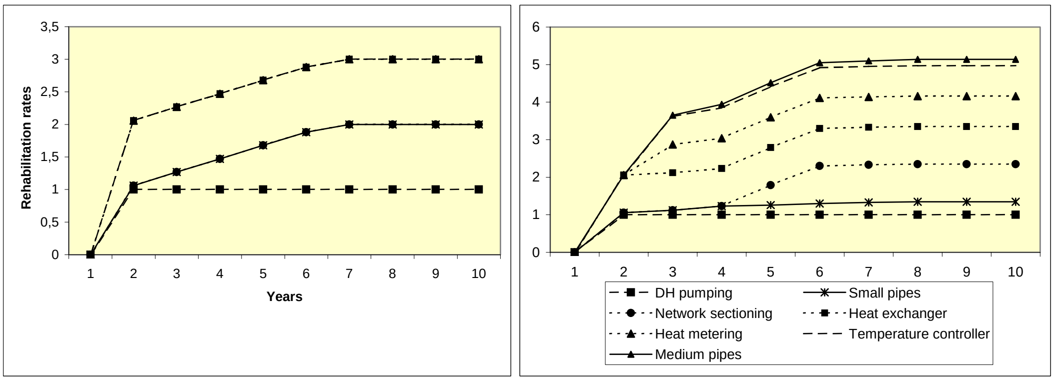


Figure 6.3. The rehabilitation rates in the financial analysis with LP (left) and NLP (right).

5.3 Efficiency of Thermal Chain

In the economic analysis (EA), the thermal efficiency of the Thermal Chain from heat production to apartments has improved from 64.3 to 86.0% and from 64.5% to 83.7% in LP and NLP respectively, as presented in Fig. 6.4. The difference of the percentages is the combined result of non-linear benefit functions in the NLP, which should enable a higher economy compared with the LP.

In the financial analysis (FA), on the other hand, the thermal efficiency of the Thermal Chain from heat production to apartments has improved from 63.8 to 88.5% and from 83.9% to 88.2% in LP and NLP respectively, as presented in Fig. 6.4. The difference of the percentages is the combined result of non-linear benefit functions in the NLP, which should enable a higher economy compared with the LP.

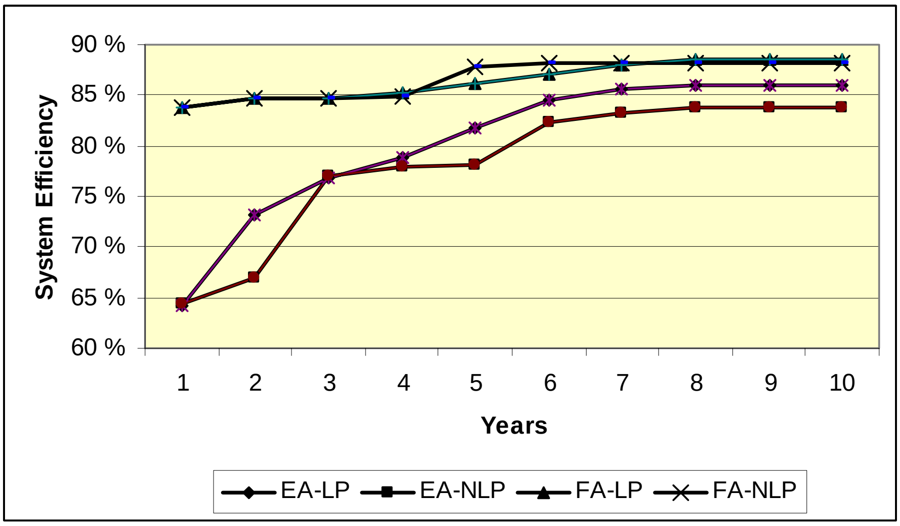


Figure 6.4. Efficiency of the Thermal Chain from heat production to the borderline of the customer definition both in Economic and Financial analysis when either LP or NLP has been used.

In the economic analysis (EA), the efficiency values, as well as the order of the measures, vary between LP and NLP. Since the benefit functions are described more accurately in NLP, one might expect that a kind of cherry-picking in the NLP would result in a higher efficiency improvement compared with the LP. Such a cherry-picking would prioritize the investments in the worst pipelines, for instance. Based on the results, however, the non-linear approximations do not seem to have gained any extra benefits.

The turning points in the efficiency curve of EA/NLP are caused by the features of the NLP and not by any physical reasons in the Model. Despite of the turning points, the rehabilitation rate of any component in the Model and in the particular case has not declined but either has remained the same value it used to be on the previous year or has increased.

In the financial analysis, there is little or no difference between the LP and NLP. The thermal efficiency improvement is relatively low, because the possible improvement in the building level temperature control comprising both the substation and the DSM does not have any impact on the thermal efficiency of the DHE from the financial point of view.

In quantitative terms, the thermal losses of the Chain depend on the temperature levels of the network and not on the water flow rate. In this case, the DHE does not have any impact on the investments implemented in the buildings, except the heat metering.

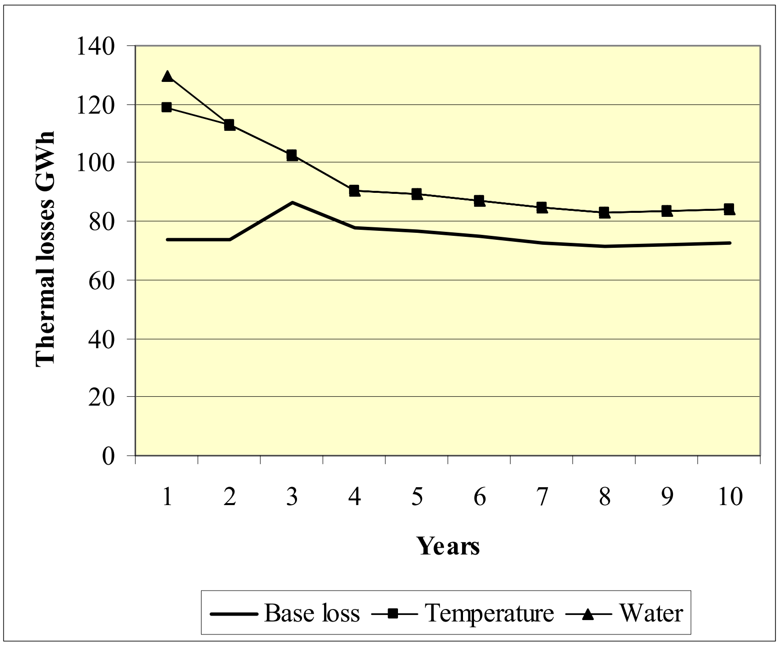


Figure 6.5. Contents of thermal losses in course of the rehabilitation.

5.4 Water

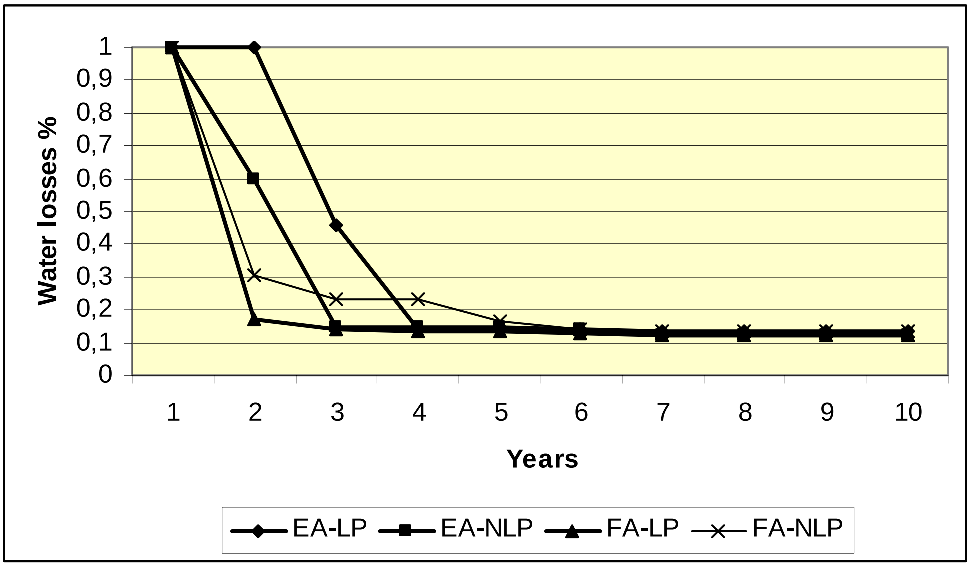


Figure 6.6. Relative water losses based on the rehabilitation program.

In all four cases the water consumption has fallen to the level of 13% of the original annual consumption of 200 km^3, as presented in Fig. 6.6.

In the economic analysis with LP, the heat exchanger installation starts on the second year, whereas on the first years in the other cases. This is the reason to delayed water savings in case EA-LP.

The rehabilitation rate of the heat exchangers reaches the level of 0.96 in NLP and 1.00 in LP, which causes some minor difference in the final water consumption.

5.5 Human Resources

In the economic analysis, as presented in Fig. 6.7, a small difference can be observed in the expected reduction of the human resources during the years 4 to 9, which cannot be explained by the rehabilitation rate. In the NLP, a delay function is included for the benefit of the human resources, which makes the difference during the intermediate years. In LP, no such delay function has been used.

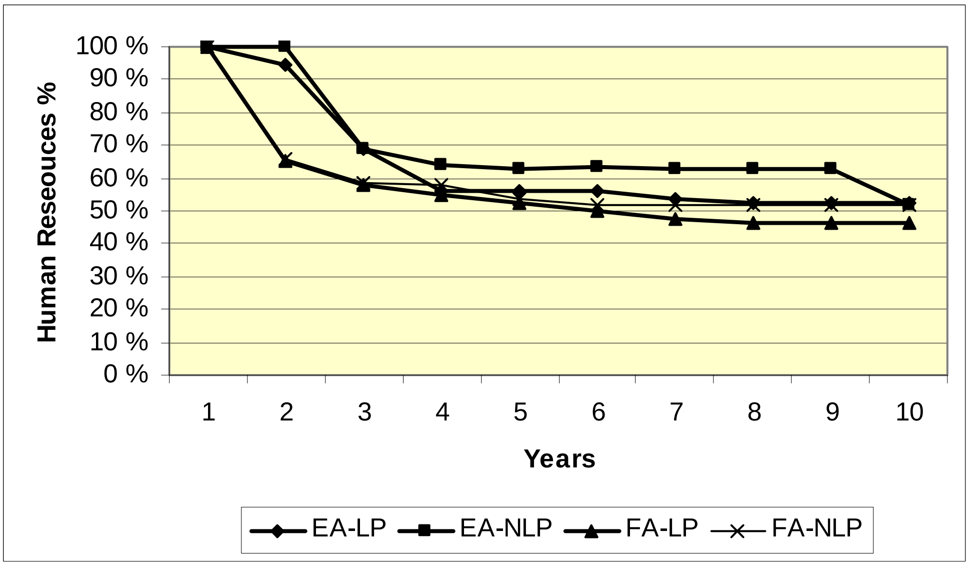


Figure 6.7. Relative amount of HR on the rehabilitation program.

In the financial analysis, the reduction of the human resources seems to be the same regardless the method of programming.

5.6 Electricity Consumption

Practically no change occurs in the expected consumption of electric energy for DH pumping in the four cases, as presented in Fig. 6.8. Only in the EA-NLP the benefits start accrue a year later, because the frequency controller has been installed a year later than in the other three cases.

All the temperature controllers have been installed by the end of the 3rd year. Therefore, no changes in electricity consumption have allocated to the remaining 7 years.

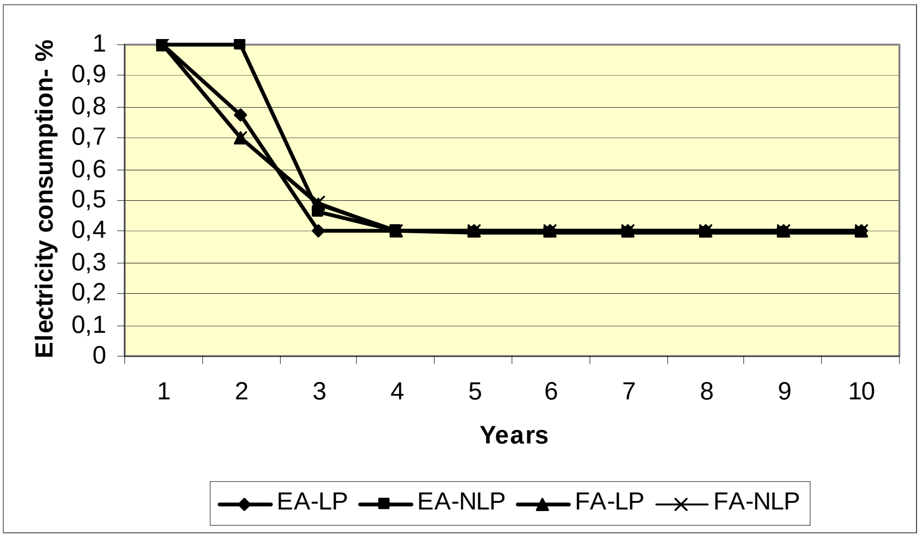


Figure 6.8. Relative electricity consumption for DH pumping.

5.7 Electricity Sales

The CHP plant generates electric energy, which is 0.5 times the produced heat energy and adjusted to the return temperature decline with the sensitivity factor of 0.02.

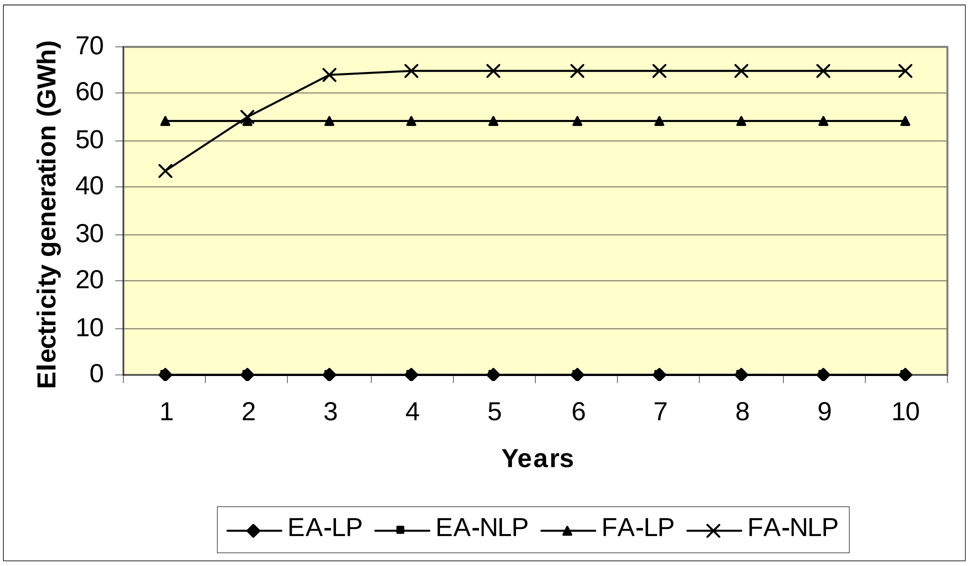


Figure 6.9. Electricity generation in CHP.

Due to high economic costs of emissions, the CHP plant is not used in the economic analysis at all. The economic costs of coal combustion are higher than the expected benefits from the possible sales of electricity.

The electricity generation is constant in LP, because the water temperatures have remained constant. There has not been any investments allocated to the temperature controllers of the BLSs. The NLP, on the other hand, has used funds for temperature controllers, as presented in Fig. 6.9, even though no energy savings are expected to the DHE. Such investments have resulted in the reduced water temperatures, thus having increased the electricity generation during the first years of the Period.

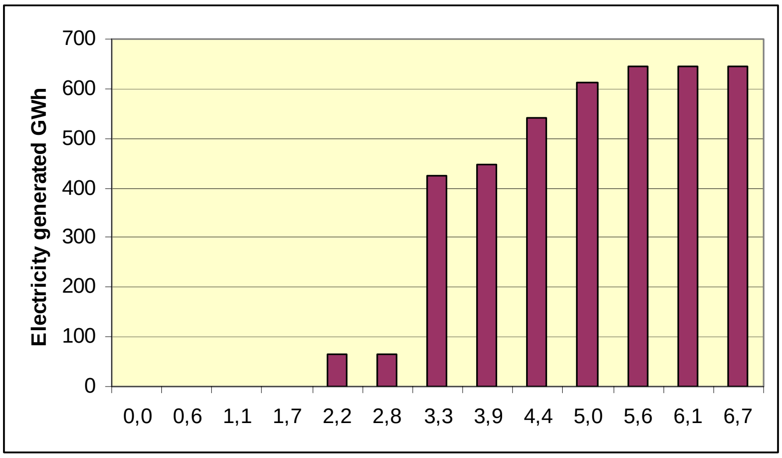


Figure 6.10. Electricity generation depending on the ratio of sales price to fuel price.

Fig 6.10 illustrates the electricity generation during the period depending on the ratio of the sales price of electricity to the coal price. The starting point here at the ratio about 2. The starting point could be lower, for instance, if

1. The flue gas emission charges regarding the CHP electricity generation for the DHE would be zero, and,
2. The efficiency of the CHP plant would be higher.

5.8 Lifetime of Fixed Assets

Regarding the benefit of the expected lifetime of the fixed assets in terms of million € a year, a substantial difference between economical and the financial analysis with the LP exists. The benefit curve is a linear approximation of the real component specific non/linear functions. Based on Fig. 6.11, the annual benefits range from 2.5 to 5.5 million, which has a considerable impact on the optimization of the € 20 million investment program.

In the NLP, the difference between the economic and the financial analysis is insignificant, about € 3 million a year in both cases.

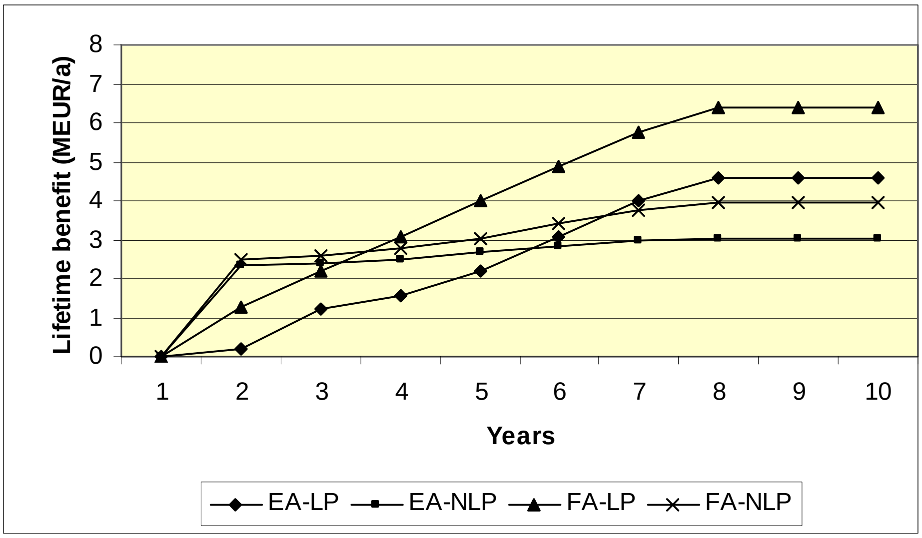


Figure 6.11. Benefit of expected lifetime of the fixed assets in terms of M€ a year.

The lifetime benefit seems to be higher in the financial than in the economic analysis, caused by the different the rehabilitation programs. The financial analysis has a higher priority on pipeline investments having substantial impact on the lifetime benefits, whereas the economic analysis prefers building level investments instead of the network.

In this case, LP generates more lifetime related benefits than NLP. Obviously, the linearization of the nonlinear functions has yielded undesired inaccuracy to the results in the LP. If the NLP has been used immediately after the LP, the nonlinear results should be substantially more accurate than the linear ones. The solution of the LP will be used as initial data of the NLP.