REPORT ON MAINTENANCE EFFECTS OF FLEXIBILITY INSTALLED IN DEMOSITES

VERSION 1.0

Jan Henrik Sällström

4 May 2021

ERA-Net Smart Energy Systems

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme.

INTERNAL REFERENCE

Deliverable No.:	D 5.2 (2021)
Deliverable Name:	REPORT ON MAINTENANCE EFFECTS OF FLEXIBILITY INSTALLED IN DEMOSITES
Lead Participant:	RISE
Work Package No.:	WP5
Task No. & Name:	T 5.2
Document (File):	D5.2_Maintenace_Effects.docx
Issue (Save) Date:	2021-05-17

DOCUMENT STATUS

	Date	Person(s)	Organisation
Author(s)	2020-11-25	JH Sällström	RISE (Document is created)
	2021-04-01	JH Sällström	RISE (Updated after third party review)
	2021-05-04	JH Sällström	RISE (Corrections)
Verification by	2021-05-04	Anna Nilsson	IVL
Approval by	2021-05-17	General Assembly	

DOCUMENT SENSITIVITY

☐	**Not Sensitive**	Contains only factual or background information; contains no new or additional analysis, recommendations or policy-relevant statements
☒	**Moderately Sensitive**	Contains some analysis or interpretation of results; contains no recommendations or policy-relevant statements
☐	**Sensitive**	Contains analysis or interpretation of results with policy-relevance and/or recommendations or policy-relevant statements
☐	**Highly Sensitive Confidential**	Contains significant analysis or interpretation of results with major policy-relevance or implications, contains extensive recommendations or policy-relevant statements, and/or contain policy-prescriptive statements. This sensitivity requires SB decision.

TABLE OF CONTENT

Disclaimer

About ERA-Net Smart Energy Systems

ERA-Net Smart Energy Systems (ERA-Net SES) is a transnational joint programming platform of 30 national and regional funding partners for initiating co-creation and promoting energy system innovation. The network of owners and managers of national and regional public funding programs along the innovation chain provides a sustainable and service oriented joint programming platform to finance projects in thematic areas like Smart Power Grids, Regional and Local Energy Systems, Heating and Cooling Networks, Digital Energy and Smart Services, etc.

Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

Beyond that, ERA-Net SES provides a Knowledge Community, involving key demo projects and experts from all over Europe, to facilitate learning between projects and programs from the local level up to the European level.

www.eranet-smartenergysystems.eu

ABSTRACT

The basic ideas of the Flexi-Sync project are to utilize more renewable energy and to optimize the income of sales of energy and the costs of producing and distributing the energy by means of introducing more flexibility. One of the means can be price models for utilizing a beneficial customer behaviour without an increase of the general energy price level. Furthermore, the energy companies can moderate the production of power and heat to get a favourable mix. In an optimization like this, the costs of maintenance and reduced durability are normally neglected. In this deliverable, a model is presented for taken these costs into account.

The environmental impact will be reduced, when the outcome will be more durable energy systems and more renewable energy will be used. It is anticipated that the heat network will be operated differently. The new strategy of operating the heat network can lead to higher temperature peaks, more temperature cycles, and higher average temperature.

A cost function, given from the model, for operating a district heating network at increased temperature volatility and at increased average temperature has been developed. The operating temperature peaks must be limited to certain given design values or to levels already in use for the system since several years.

The cost function considers damages of service pipes caused of increase fatigue due to increased operating temperature volatility and degradation of polyurethane foam due to increased average operating temperatures.

1 BACKGROUND

In the Flexi-Sync project the goals are, to utilize more renewable energy and to optimize the income of sales of energy and the costs of producing and distributing the energy by means of introducing more flexibility. One of the means can be price models for utilizing a beneficial customer behaviour without an increase of the general energy price level.

The flexible operation with varying operative temperatures in the heat network opens for better optimizing of the complete energy system. Furthermore, the energy companies can moderate the production of power and heat to get a favourable mix and the heat network can be used as a storage.

In an optimization like this, the costs of maintenance and reduced durability are normally neglected. In this deliverable, a model is presented for taking these costs into account. The environmental impact will be reduced, when the outcome of the optimisation will be more durable energy systems and more use of renewable energy.

The optimisation means that the heat network may be operated differently. The new strategy of operating the heat network can lead to higher temperature peaks, more temperature cycles, and higher average temperature.

A single temperature peak can cause local damage (plastic deformation) of the steel service pipe at fittings, buckling of service pipes, and damage of insulation foam at fittings. More temperature cycles can damage the steel service pipe due to fatigue at fittings. Higher average temperature can damage the insulation foam, deteriorate shear strength, and damage the polyethylene casing at cushions. Mechanics of materials and classification of failures can be studied in the first chapter of the textbook of Dowling (1999). The lifetime of district heating pipes and especially the degradation of the polyurethane foam was studied by, e.g., Vega (2020).

These damages of the heat networks will eventually lead to maintenance activities, that can be repairs or replacements of components. The maintenance activities lead to increased maintenance costs. In the model presented, damage due to plastic deformations of service pipes, fatigue of service pipes and degradation of polyurethane insulation at the interface between the service pipe and the insulation are considered.

2 NOTATIONS AND CONCEPTS

The following notations are used:

A	Constant in Arrhenius relation
a	Constant in fatigue function, a = 5000 MPa
b	Constant in fatigue function, b = 4
C_M	Costs of all maintenance activities on the heat network
$C_{M,other}$	Costs of all maintenance activities on the heat network other than costs for fatigue of service pipes and degradation of polyurethane
C_{MS}	Costs of maintenance related to service pipes
C_{MPUR}	Costs of maintenance related to degradation of polyurethane
D_S	Damage to service pipe due to fatigue. Failure occurs when damage reaches one
D_{PUR}	Damage to polyurethane at interface to service pipe due to degradation of polyurethane at that position
DN	Dimension of service pipe referring to the approximate internal diameter in mm
E_a	Activation energy of a chemical reaction
i	Counter used as a subscript to indicate a certain cycle or duration
k_i	Chemical reaction speed
N	Number of fatigue cycles the component can endure before failure at stress range S
N_i	Number of fatigue cycles the component can endure before failure at stress range S_i
n_i	Number of stress cycles occurring in a component at stress range S_i
R	Ideal gas constant R = 8.314 J / (K mol)
S	Stress range of a fatigue cycle from minimum to maximum level, i.e., twice the stress amplitude
ΔT_i	Temperature range for temperature cycle from minimum to maximum level
T_i	Temperature level [K]
t_i.	Duration of temperature level T_i
α_{MS}	Fraction of costs related to service pipes of all maintenance costs on the heat network
α_{MPUR}	Fraction of costs related degradation of polyurethane of all maintenance costs on the heat network
0	Subscript 0 indicate initial conditions before introducing flexibility in operation

The following concepts are used

Casing	Protective pipe surrounding insulation
Damage	Measure for degradation
Fatigue	Repeated loading leading to failure or fracture
Polyurethane	Thermoset plastic used as insulation between service pipe & casing
Range	Twice the amplitude of a cycle from minimum to maximum level
Service pipe	Pipe containing the heat carrier, i.e., the hot water

3 COSTS FOR MAINTENANCE AND REPLACEMENTS

Maintenance and replacements have often been neglected when carrying out system operation optimization. Powell et al. (2016) assumed that maintenance costs are constant regardless of the operational strategy, when they minimized costs for a district heating system with combined heat and power utilizing trade with the electrical grid. Bachmaier et al. (2016) had also fixed maintenance costs taken as 2% of the investment of the district heating system, and the investment was EUR 550/m pipe length in their techno-economical optimization.

To get a perspective of maintenance costs of mature heat networks, data for four Swedish networks were studied. The less mature demo sites will eventually become mature, and there is no actual meaning studying maintenance for them since it is less related to degradation.

The Swedish Energy Markets Inspectorate (2020) compiles data from the Swedish energy companies. The operational and maintenance costs have been studied here. We assume that the reinvestment to replace 1 km of district heating network is SEK 10 000 000 (EUR 950 000) including all needed equipment and work. The operational and maintenance costs are about 0.5 % of the reinvestment, see the data for four energy companies collected in Table 1.

The reinvestment (about EUR 950/m pipe length) here is nearly twice as compared to the value Bachmaier et al. (2016) assumed. For Göteborg Energi the maintenance costs would be 1% of the investment of EUR 550/m pipe length.

An alternative would be to relate the costs to the income of heat, see

Table 2. These energy companies have mature networks built mainly from 1970 to 2010. The maintenance costs are around 3% of the income from the heat. Even though the networks are mature, the maintenance costs vary much between the energy companies. This can be linked to maintenance strategies, geological differences, or the actual age distribution of the network.

Table 1: Operational and maintenance costs relative to reinvestment of networks (EUR 950/m pipe length).

Company	Operational & maintenance costs relative to reinvestment [%]						
Year	2018	2017	2016	2015	2014	2013	Average
Borås Energi och Miljö	0.17	0.16	0.20	0.20	0.20	0.26	0.20
Eskilstuna Energi & Miljö	0.56	0.42	0.63	0.60	0.70	0.36	0.54
Mölndal Energi	0.48	0.28	0.26	0.15	0.15	0.07	0.23
Göteborg Energi	0.45	0.45	0.67	0.64	0.57	0.66	0.57

Table 2: Operational and maintenance costs relative to income from heat.

Company	Operational & maintenance costs relative to income of heat [%]						
Year	2018	2017	2016	2015	2014	2013	Average
Borås Energi och Miljö	1.31	1.07	1.29	1.30	1.33	1.65	1.33
Eskilstuna Energi & Miljö	4.73	3.40	4.95	5.20	6.05	3.10	4.57
Mölndal Energi	3.23	1.94	1.80	1.07	0.99	0.44	1.58
Göteborg Energi	2.33	2.43	3.36	3.60	3.11	3.05	2.98

4 DAMAGE DUE TO OPERATION

When introducing more flexibility in the operation of the heat network more damage may occur due to temperature peaks, fatigue of service pipes and degradation of polyurethan insulation.

4.1 Damage due to high temperature peaks

There are estimations of how high temperature peaks, which can be accepted in the standard EN 13 941-1:2019. The peaks are relative to the installation temperature. Here, the installation temperature means the temperature of the service (carrier) pipe when the trenches are refilled. The procedure is called warm installation, when the pipes are connected, and warm water is circulating in the pipes during the refill. Cold installation means that the trenches are refilled when the pipes have the same temperature as the ambient.

For dimensions of service pipes up to DN 300, a temperature raise of 130 K is allowed. The corresponding raises are 95 K and 80 K for dimensions up to DN 500 and DN 1200, respectively. The dimensions given are usually used for these pipes and are approximate values of the internal diameter in millimetres. These limitations pertain to local buckling of fully restrained straight pipes, when no measures have been taken to reduce the compressive stresses due to a temperature raise in the service pipes.

It is here proposed that the temperature peaks are limited, either to the level of the current peaks or limited to the relevant values given above. With these limits no additional maintenance costs are assumed to occur due to the level of the peaks.

4.2 Damage due to fatigue of service pipes

The steel service pipes in the networks especially at discontinuities, e.g., at joints of branches, bows, etc., are subjected to mechanical fatigue. The fatigue curve for the steel service pipe given in the standard EN 13 941-1: 2019 can be written as

$$N = \left(\frac{a}{S}\right)^b \tag{1}$$

with a = 5000 MPa and b = 4. Here, the stress range is denoted S and the pertaining number of cycles is N, which the pipe can endure at that stress range.

The steel service pipe at a certain position in the network will be subjected to a series of stress cycles, which can be quantified as stress ranges S_i and the pertaining number n_i of cycles. The damage of the service pipe at a position is given as

$$D_S = \sum_i \frac{n_i}{N_i} = \sum_i \frac{n_i S_i^b}{a^b} \tag{2a,b}$$

Equation (2a) is known as Miner's rule or Palmgren-Miners linear damage hypothesis. The damage of a structure that is caused by n_i cycles of the stress ranges S_i is equal to quotient of n_i cycles and the number of cycles N_i the structure can endure at that stress range. The failure occurs when the damage is equal to one. For elastic materials, the stress range S_i in the network is proportional to the temperature range ΔT_i

$$S_i \propto \Delta T_i \qquad (3)$$

The damage at sensitive positions pertaining to fatigue of the service pipe will increase, when the volatility of the operative temperature increases as more flexibility of the operation is introduced. When the damage increase, it calls more often for maintenance activities in terms of repairs and replacements.

The quotient of the damage for the more flexibly operated system and the originally operated system can be stated as

$$\frac{D_S}{D_{S0}} = \frac{\sum_i n_i \Delta T_i^b}{\sum_j n_{0j} \Delta T_{0j}^b} \qquad (4)$$

It is assumed, that the costs C_{MS} of maintenance related to fatigue can be related as the damage due to fatigue. Hence, the relation becomes

$$C_{MS} = \frac{D_S}{D_{S0}} C_{MS0} \qquad (5)$$

Here, index 0 indicates the originally operated system and the flexibly operated system is without the zero.

4.3 Damage due to changed temperature levels

The insulation of polyurethane in the district heating pipes degrades due to high temperatures. The degradation reactions are faster when the temperature increase. The district heating pipes have a bonded design, i.e., at the interfaces between service pipe and insulation, and between the insulation and the casing there are bonds. It is essential that these bonds are intact, otherwise the service pipes will have ruptures due to mechanical fatigue. The soil restrains the stresses in the service pipe at joints due to the friction at the interface of the soil and the casing, and the bonded design. The temperature in the foam is highest at the interface to the service pipe. Hence, that interface is the sensitive location, and the temperature of the heat carrier is governing the degradation. The reaction speed can follow the Arrhenius relation

$$k_i = A e^{-E_a/RT_i} \qquad (6)$$

The ideal gas constant is denoted R = 8.314 J / (K mol). The activation energy E_a is here assumed to be 100 kJ/mol instead of the value 150 kJ/mol used in standard EN 253:2009. This indicates a faster degradation than assumed in the standard. In the report from AGFW (2016), an apparent activation energy is defined to estimate lifetime rigid district heating pipes with that value 100 kJ/mol. Also, Leuteritz et al. (2016) concluded a similar value 95 kJ/mol for a district heating pipe with a thin casing enabling more oxygen to be present during the degradation reactions. As for the fatigue, the polyurethane is subjected series of temperature levels T_i and the pertaining durations t_i. The damage of the polyurethane at a position can be written as

$$D_{PUR} = \sum_i t_i \, k_i = \sum_i t_i A e^{-E_a/RT_i} \qquad (7a,b)$$

The degradation of the interface of the insulation of polyurethane and the service pipe will increase if the flexibility of the operation means higher operating temperatures. The quotient of the damage of the more flexibly operated system and the originally operated system renders

$$\frac{D_{PUR}}{D_{PUR0}} = \frac{\sum_i t_i e^{-E_a/RT_i}}{\sum_j t_{0j} e^{-E_a/RT_{0j}}} \tag{8}$$

It is assumed, that the costs C_{MPUR} of maintenance related to degradation of polyurethane can be related as the damage due to that degradation yielding

$$C_{MPUR} = \frac{D_{PUR}}{D_{PUR0}} C_{MPUR0} \tag{9}$$

5 COST FUNCTION FOR MAINTENANCE

The maintenance costs are divided into costs depending on damage of fatigue of service pipes, on damage of polyurethane caused by high temperature, and other costs independent of temperature cycles and levels.

$$C_M = C_{MS} + C_{MPUR} + C_{M,other} \tag{10}$$

The costs of maintenance coupled fatigue of service pipes and damage of polyurethane are assumed to be a fraction α_{MS} and α_{MPUR}, respectively, of the total maintenance costs:

$$C_{MS} = \alpha_{MS} C_M \tag{11}$$

$$C_{MPUR} = \alpha_{MPUR} C_M \tag{12}$$

The initial fractions of maintenance costs are denoted α_{MS0} and α_{MPUR0}. Hence, the maintenance costs for the more flexibly operated system become

$$\begin{aligned} C_M &= C_{MS} + C_{MPUR} + C_{M,other0} \\ &= [\alpha_{MS} + \alpha_{MPUR} + (1 - \alpha_{MS0} - \alpha_{MPUR0})] C_{M0} \end{aligned} \tag{13a,b}$$

With

$$\alpha_{MS} = \frac{D_S}{D_{S0}} \alpha_{MS0} \tag{14}$$

$$\alpha_{MPUR} = \frac{D_{PUR}}{D_{PUR0}} \alpha_{MPUR0} \tag{15}$$

The quotients of damage are given by Equations (4) and (8). The exponent *b* coming from the fatigue curve for the steel service pipe is equal to 4. The apparent activation energy E_a is assumed to be 100 kJ/mol and the ideal gas constant is R = 8.314 J/(K mol).

For the flexibility optimization, these maintenance costs are estimations, when the boundary conditions of the temperature variations fulfil

$$\Delta T_i \leq 130 \ \text{K for } DN \leq 300 \tag{16}$$

$$\Delta T_i \leq 95 \ \text{K for } 300 < DN \leq 500 \tag{17}$$

$$\Delta T_i \leq 80 \ \text{K for } 500 < DN \leq 1200 \tag{18}$$

If measures have been taken in the design face to limit the stresses occurring, due to the temperature raise, the boundaries given in Equations (16)-(18) can be replaced with other levels. These can be levels documented in the design face or levels already in use in the operation of the network.

Maintenance includes many activities. From discussions with people involved, it can be concluded that the costs for the maintenance activities depending on the temperature levels and the number of temperature cycle are small.

However, if the operation is changed these costs can grow. Here, both parameters α_{MS0} and α_{MPUR0} are proposed to be set to 5%.

5.1 Limitations

The proposed cost function for maintenance and durability is based on a model, which is a simplification of real increase of those costs. The cost function cannot predict future maintenance costs for a specific year since the real costs depend on many choices. The model does not consider any maintenance strategy. The lack maintenance activities and the pertaining costs can lead to less durability and to future maintenance costs. All these costs are in a general perspective included and estimated in the model.

6 CONCLUDING REMARKS

A cost function for operating a district heating network at increased temperature volatility and at increased average temperature has been developed. The proposed cost function is considered to in a general perspective estimate how the costs of both maintenance and reduced durability develop relative to the present costs. The purpose of including these costs in the overall optimization is to decrease the incentive to run the heat network with a degrading operational strategy.

The cost function considers damages of service pipes caused of increase fatigue due to increased operating temperature volatility and degradation of polyurethane foam due to increased average operating temperatures.

6.1 Recommendations

The operating temperature peaks must be limited to certain given design values or to levels already in use for the system since several years, see Chapter 5.

For the demonstration sites, the actual overall maintenance costs of the district heating network, based on the average during a few resent years, can be used as a baseline. Alternatively, the costs can be taken as a percentage of the reinvestment to replace the current system. A suitable level can be 1-2% of the reinvestment.

It is assumed that only a small portion of the maintenance costs will be affected by the operating temperature. Here, the proposed levels are 5% of the maintenance costs are related to fatigue of the service pipes, and that 5% of the maintenance costs are related to degradation of the polyurethane foam. There are no statistics to confirm these levels and most probably they vary between energy companies. These levels can be used as a starting point, if no better data for the specific system are available. The given levels are reasonable, and the values are in the correct order of magnitude.

For the costs related to fatigue of service pipes, temperature cycles must be counted for at least a year, when the network is run without introducing the additional flexibility. A suitable resolution may be 5-10 K. Furthermore, the number of cycles must be counted or estimated in advance, when the increased flexibility is introduced.

For the costs related to degradation of polyurethane foam, the time at selected temperature levels must be registered for at least a year, when the network is run without introducing the additional flexibility. A suitable resolution may, also here, be 5-10 K. Furthermore, the time at the same levels must be registered or estimated in advance when the increased flexibility is introduced.

6.2 Future work

The usability of the cost function needs to be verified for at least one demosite taking part in the Flexi-Sync project by applying it in the operational optimization of the complete energy system. More data of maintenance activities and costs need to be continuously collected for heat networks, to updated model parameters and verifying the model presented.

REFERENCES

AGFW (2016), Qualitätssicherung für zukünftige Kunststoffmantelrohrsysteme in der Fernwärmeversorgung, Hefte 39, Frankfurt am Main.

A Bachmaier, S Narmsara, J-B Eggers, S Herkel (2016), Spatial distribution of thermal energy storage systems in urban areas connected to district heating for grid balancing—A techno-economical optimization based on a case study, Journal Energy storage, vol 8, pp 349-357.

N E Dowling (1999), Mechanical behavior of materials – Engineering Methods for Deformation, Fracture and Fatigue, 2nd ed., Prentice Hall, ISBN 0-13-905720-X.

EN 253 (2009), District heating pipes - Preinsulated bonded pipe systems for directly buried hot water networks - Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene, CEN, Brussels.

EN 13941-1 (2019), District heating pipes - Design and installation of thermal insulated bonded single and twin pipe systems for directly buried hot water networks - Part 1: Design, CEN, Brussels.

A Leuteritz, K-D Döring, T Lampke, I Kuehnert (2016), Accelerated ageing of plastic jacket pipes for district heating, Polymer Testing, vol 51, pp 142-147.

K M Powell, J S Kim, W J Cole, Kriti Kapoor, J L Mojica, J D Hedengren, T F Edgar (2016), Thermal energy storage to minimize cost and improve efficiency of a polygeneration district energy system in a real-time electricity market, Energy, vol 113, pp 52-63.

The Swedish Energy Markets Inspectorate (2020), www.ei.se, 2020-08-26.

A Vega (2020), Assessment of the lifetime of district heating pipes, Diss., Chalmers University of Technology, Report No 4826, ISSN 978-91-7905-359-8.

FUNDING

This document was created as part of the ERA-Net Smart Energy Systems project 91635, funded from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 775970 (RegSys).