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A review of the pricing mechanisms for district heating systems

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ABSTRACT

Heating represents the largest proportion of energy use as supplied to consumers across all end energy uses. Therefore, there is huge potential for energy savings in the heating sector in order to reduce the emission of CO_2. District heating (DH) has been considered an efficient, environmentally friendly and cost-effective method for heating in buildings, and is playing an important role in the mitigation of climate change. In the interest of fairness and in the highly competitive market the DH companies operate, there is a strong need to develop a novel heat pricing mechanism in order to promote sustainable development of DH systems. In this paper, existing methods and models regarding heat pricing have been reviewed. The features of different pricing mechanisms have been analysed, including advantages and disadvantages. Insights into developing an advanced pricing mechanism for DH systems have been offered.

Contents

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1. Introduction

Heating represents the largest proportion of energy use as supplied to consumers across all end energy uses worldwide. In 2009, heating represented 47% of final energy consumption, compared with 17% for electricity, 27% for transport; and 9% for “non-energy use”, for example, using oil to make plastics [1]. Oil, coal and gas account for more than two-thirds of the fuel used in meeting this significant demand for heat. Because heating accounts for such a large share of the world's final energy consumption, it is of significant importance to explore the potential for energy savings in this sector in order to reduce the emission of CO_2 and mitigate climate change.

A District Heating (DH) system is a centralised system that supplies heat to end-users by distributing steam/hot water through a pipe network. The centralised heat generation benefits from using large combustion units that have a higher energy efficiency and are equipped with more advanced control over air pollution. Therefore, DH has been considered as an efficient, environmentally friendly and cost-effective method for heating in buildings, and is playing an important role in the mitigation of climate change. For instance in Europe, DH alone is responsible for a reduction of at least 113 million tons of CO_2 emissions per year, representing 2.6% of the total amount of CO_2 emissions at present [2].

However, due to the continuous rise in cost of DH, it faces big challenges to further improve efficiency, reduce cost and enhance profitability. The competitiveness of DH systems for a particular building/house owner depends on three factors: (I) the price of the DH, (II) the price of the fuel or electricity used to heat the building and the expected increase in those prices, and (III) the efficiency with which that fuel is used compared to the efficiency of the potential DH [3]. According to the Energy Markets Inspectorate (EMI) [4], DH, bedrock heat pumps and wood pellets are on the same competitive level for the typical multi-dwelling buildings in Sweden. For example, according to Fortum, a large energy company operating in the Nordic countries, Russia, Poland and the Baltics, the price for heating was 802 Swedish kr/MWh heat excluding tax in 2013 [5]; while the price for electricity was 800–950 Swedish kr/MWh heat including tax during the same period. However, given these figures, DH systems do not have a price advantage over heating systems where heat pumps are integrated. Heat pumps, an important alternative to space heating, normally have a coefficient of performance (COP) of 3–5, which means that a heat pump can deliver 3–5 kWh heat by consuming only 1 kWh electricity. Considering the increasingly competitive environment faced by DH companies, redesigning the pricing mechanism for DH systems could be an effective way to motivate DH companies to improve production methods with a view to reducing operating cost and increasing profitability [6]. Moreover, an effective pricing mechanism could also assist in further energy saving and CO_2 emission reduction, given that price is considered the most important factor that can incite consumers to change their behaviour. Therefore, developing a novel pricing mechanism is essential to promote sustainable development of DH systems.

For more than a decade, energy market participants and European regulatory authorities have been committed to improving market transparency and liquidity, with the ultimate goal of creating a single European market in electricity and gas [7]. To ensure that the prices emerging on the wholesale market reflect the supply and demand, market participants need to have access to all relevant information on production and consumption in a non-discriminatory manner. At the retail level, transparency is also needed to enable consumers to better manage their choice of supplier as well as their energy consumption. In Europe, the legislative package plans various dispositions for consumer rights [7]. Despite the fact that less work has been done regarding DH, resulting in DH prices being far from transparent, more and more attention has been paid to the DH market. Greater regulation has increased the transparency of DH pricing in order to promote trust and reduce the number of complaints. For example, the EMI's regulation, enforced in Sweden, defines companies' obligations to provide price information and how this should be achieved. DH companies are, since 2007, required to submit separate accounts for their various divisions in order to avoid cross subsidisation. In 2009, these companies also began to report operational and business details to the EMI. The purpose of this was to give a greater degree of transparency within the market and to counteract overcharging. Increasing concerns about transparency in the DH market and fairness to both DH companies and consumers demand a novel pricing mechanism.

This paper studies the mechanisms and methods of DH pricing. The objectives include: to review the current status of heat pricing, to identify the knowledge gaps, and to provide insights into developing an advanced pricing mechanism for DH systems, which can motivate DH companies to reduce costs and consumers to save energy, and improve the transparency of the DH market.

This literature review collected information from peer-reviewed articles and reports from DH companies, governments and international organisations with the key words such as pricing models, costs for DH and DH markets. As Sweden is a pioneer in reforming the DH market, a lot of Swedish experience has been highlighted and discussed in this study.

The paper is organised as follows: the monopolistic nature of the DH market and price elasticity are discussed in Section 2; after the price components are introduced in Section 3, Section 4 describes the two types of DH markets and the corresponding pricing principles; and Section 5 further investigates the different pricing methods for the marginal cost.

2. Monopolistic nature and price elasticity of district heating

The Swedish DH sector experienced a transition from a regulated to a deregulated market during the past two decades. After deregulation, many municipalities sold their DH companies either to the private sector or municipality- or state-owned large energy companies, such as FORTUM, E.ON, Rindi, and Vattenfall [8]. As a result of these changes, the price of DH increased rapidly, and the increase in DH price since 2004 can be seen in Fig. 1. The rising DH price led to protests and much national media debate. The protesters argued that the energy companies were taking advantage of their natural monopoly [9].

The natural monopoly enjoyed by DH companies has unique characteristics, i.e. customers are tied to only one heating supplier

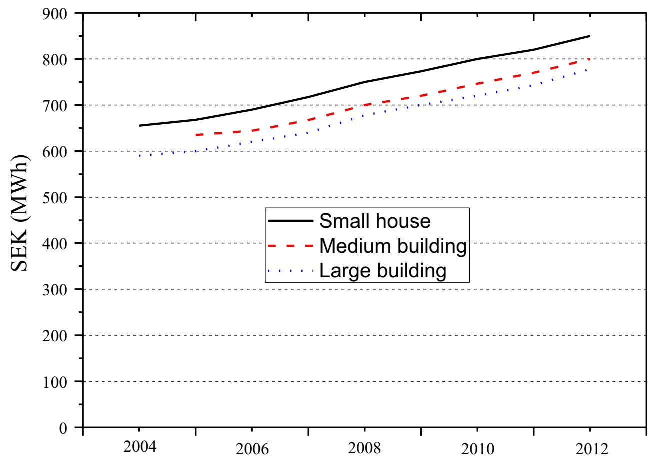

Fig. 1. DH price in Sweden, 2004-2012.
Source: adapted from [10].

in a DH network. Monopolies in DH markets permit profits, and in the meantime tend to increase costs for consumers connected to DH systems. However, this does not necessarily mean that DH companies have unshakeable monopoly power, as there are many alternatives on the heating market, such as pellet burners and heat pumps [11,12]. The availability of alternative heating solutions combined with high cross-price elasticity can reduce the power that DH producers have over the market. There are two important factors influencing the cross-price elasticity of DH: the availability of alternative heating systems and the switching costs between different systems [8].

Currently only the owners of a DH network have access to that network and this creates a practical barrier towards a competitive DH market. The first attempt to investigate the possibility of legislating for third-party access (TPA) has been performed in Sweden. The TPA investigation (SOU 2011:44) resulted in a proposal to split the market in order to give network access to competing producers and suppliers. Where competition arises, changes in production, supply and distribution will be made [13].

Price elasticity of demand indicates the change in demand that corresponds to a certain level of change in price. Low price elasticity implies there may be an obstacle to competitiveness in the market, as producers have a larger window to raise prices without fear of reducing demand. Hellmers calculated the price elasticity of DH systems using the ordinary least squares (OLS) method, where the natural logarithm of consumer price, average income, the number of connecting points for small houses and residential buildings were chosen as independent variables, while the natural logarithm of the heat delivered to respective user groups was used as a dependent variable [8]. It was found that the demand for DH shows a relatively inelastic pattern and that the price elasticity for consumers living in small houses is generally higher than the elasticity for those in larger communal residential buildings.

3. Price components of district heating

The costs of DH depend on three main factors: (1) the connexion costs for customers, (2) the costs of a distribution network, which depend on the size of the DH network and its thermal loads, and (3) the production costs of thermal energy [14]. Correspondingly, the price of heating comprises a connexion fee, a standing cost and a unit cost, e.g. the cases in the Netherlands and London, UK [15,16].

3.1. Connexion fee

The connexion fee refers to the price for connecting a dwelling to a DH network. It can be paid by the developer or the landlord (as in London), or by consumers (as in the Netherlands, by means of a connexion fee included into the price of a dwelling). However, Kostama argued that the connexion fee should be cancelled in order to encourage new customers to connect to the networks and to foster the connexion process, or that the connexion fee should be based on the length and diameter of the connexion pipeline [17].

3.2. Standing cost

Basically, standing costs are fixed costs associated with energy supply such as metre reading, maintenance, and keeping the connexion to the network. Standing costs are paid to the companies that operate and maintain the network.

3.3. Unit cost

Unit Cost is the price per unit of supplied heat.

In addition, in the Netherlands, the DH price includes another component, the efficiency cost. The efficiency cost is a one-off fee that the owners of new dwellings have to pay for their connexion to a DH system. The efficiency cost is related to the statutory requirements on energy-efficiency of new dwellings. More details on the requirements of energy efficiency are collated in the “Energy Performance Standard” (EPS) [18].

In Sweden, a flow cost, which is based on the volume of water flow, is used in some DH systems. It is based on the volume of water flowing through the customer's heat exchanger. A flow cost is used to promote more efficient heat transfer in order to achieve low return temperatures by reducing the water flow rate [19]. Companies charge flow costs when the flow per delivered unit of energy is above a certain threshold, e.g. 20 m^3/MWh is adopted by Bodens Energi, Sweden [20]. An uncommonly high flow cost can also indicate to consumers that it is time to replace, or carry out maintenance on, the heat exchanger.

4. DH pricing in a regulated market and a deregulated market

Worldwide, there are two main types of DH market, namely the regulated and deregulated. It has been proved that either a fully regulated market or a fully deregulated market may have various strengths and weaknesses in terms of balancing the interests of DH producers and consumers. There is a consensus that an efficient DH market must operate on a free competition basis, under regulatory control [6].

There are two representative methods used to price DH: the cost-plus pricing method, which is often used in regulated DH markets, and the marginal-cost pricing method, which is commonly utilised in deregulated heating markets.

4.1. Pricing in regulated markets

In regulated markets, the price of DH is regulated by government and the regulated price dictates the profit made by DH companies. Taking the Swedish DH market as an example, prior to the deregulation of the DH market on January 1, 1996, all DH plants and distribution networks were owned and operated by Swedish municipalities. The DH companies were not allowed to make profits according to Swedish law [8].

In regulated markets, the price for DH is equal to the sum of costs to be recovered and reasonable profits for DH companies

(Eq. (1)).

$$\text{Price}_{DH} = \text{OA} + \text{AD} + \text{PP}, \quad (1)$$

where OA is operating cost, AD is annual depreciation, and PP is permitted profit. This method is called the cost-plus pricing method.

Permitted profits (PP) can be calculated in different ways. For example, one approach is the rate of return (RoR) method based on a regulatory asset base (RAB) [21].

$$\text{PP} = \text{WACC} \times \text{RAB}, \quad (2)$$

where WACC is the weighted average cost of capital, and

RAB = Depreciated fixed cost + new investment + labour cost [21].

Cost-plus pricing offers a number of advantages to sellers, buyers and regulators, such as simplicity, flexibility and ease of administration. However, a regulated market does not allow DH companies to compete with other heating solutions by adjusting DH prices, while the subsidisation of DH systems is often needed in order to make DH as competitive an option as its alternatives, e.g. oil boilers, gas boilers and electricity-driven heat pumps. The subsidy on DH systems is important in terms of stabilising local energy prices, developing local energy systems, saving imports of energy, reducing ambient pollution, and creating jobs. The size of the subsidy can be calculated by referring to the value of these goals [22]. However, cross-subsidies may impact adversely on both the DH sector and other sectors [23]. In addition, the cost-plus method is usually based on the historical data of real plants, which contains uncertainties when applied to the projection of future situations.

Under a cost-plus pricing mechanism, DH companies have incentives to increase profits by inflating costs, since permitted profits are usually related to costs [24]. If they are operating on a lower cost than the reported level, the DH companies would be punished through the imposition of a lower level of permitted profits [23,25]. Consequently, the cost-plus pricing method undermines suppliers' incentives to reduce costs and to upgrade their technologies. In addition to this, changes in real fuel costs cannot be transferred to consumers due to the use of historic data, and this prevents DH producers from generating enough profit to budget for necessary maintenance and improvements. In the long run, DH tariffs based on the cost-plus pricing approach will affect the efficiency of the DH market.

An example of a regulated market is the Russian DH market [23]. The Federal Energy Commission of Russia establishes separate minimum and maximum thresholds for heat tariffs for final consumers as well as for supplying companies, who buy heat from producers and then sell to consumers. Regional branches of the Federal Tariff Service are responsible for charging local tariffs in-between the two thresholds. Heat tariffs and thresholds are determined using the cost-plus method, namely the sum of annual operating costs and permitted profits. This pricing approach has been criticised for discouraging energy savings because producers have no incentives to reduce heat losses, and there is a lack of transparency in the cost elements. Legitimate operating costs are determined at the regional level, rather than according to actual operating costs and investments at the detailed level, thus leaving room for corruption and fraud. As a result, manipulation of DH tariffs may be used as an instrument for the upper echelons of local administrations to pursue political objectives. In the regulated DH market in Russia, it is likely that the tariff paid by consumers cannot cover the costs, and municipalities or regional governments fill the gap when this occurs. The budget to fill the gap originates from DH producers' other business, e.g. profits from territorial generation companies (TGKs) and industrial heat, or from other municipal or regional revenues from other sectors, e.g. heat-only-boiler-houses and perhaps in some cases also local industrial side-producers of heat. DH tariffs differ significantly across regions, depending on the conditions of infrastructure, types of fuel, the balance of heat load in local networks, negotiation powers of various parties, and institutional arrangements.

4.2. Pricing in deregulated markets

In a deregulated DH market, the pricing method based on marginal cost is commonly utilised to determine the price of DH [26,27]. A marginal cost is the cost of one more unit of product, which in this case is the cost of generating one more unit of heat through DH. According to economic theory, the market price is obtained at the equilibrium point where the total amount of heat supply is equal to the entire heat demand. Facing the exogenous market price, a DH supplier can take a larger market share and gain more profits by setting its price at a lower level than the market price. As the DH price is based on the supplier's marginal cost, every supplier is motivated to reduce costs, promote efficiency, and invest in infrastructure and equipment. Consequently, pricing DH according to marginal costs will benefit not only DH producers, but also the environment in terms of reduction in CO_2 emissions and other pollutants. In practice, a marginal cost is usually calculated by splitting a total cost into a fixed and a variable cost. The marginal cost is thus equal to the additional unit of variable costs plus the depreciation of fixed costs. In this way, the marginal cost approach provides a clear route to understanding and managing the behaviour of costs.

However, when a DH company has been determining DH price according to its marginal costs, which in turn largely depend on variable costs, the company may gain less profits than it would, for example, if the DH price is determined using the cost-plus method. As a result, it may lead to a lower interest in investment and maintenance, such as the electricity market in Sweden [28]. Furthermore, the DH market in reality is never the textbook competitive market as presumed in economic theory, while a typical DH market is characteristically a natural monopoly (see the detailed discussion above). Therefore, the optimal allocation of resources cannot be achieved by simply pricing DH at its marginal cost, even in a deregulated market. Although a competitive market environment can be developed through bidding, it is almost impossible for bidders to bid according to their marginal costs, due to imperfect information, as well as the availability of alternative heating products [12,29].

The marginal cost is the cost of one more unit of DH generation, and it is calculated as follows:

$$\text{Marginal cost} = dVC/dQ + dFC/dQ, \quad (3)$$

where VC is variable cost, FC is fixed cost, and Q is the quantity of production. Note that dFC/dQ is equal to zero in the short-run, because fixed cost is constant regardless of changes in quantity produced.

In an energy system with several production plants, the marginal cost of the system is equal to the marginal cost of the plant with the highest operating cost, since the system tends to run low-cost plants prior to high-cost plants for the sake of cost savings. In practice, several methods can be used to determine the marginal cost for DH. To calculate the marginal cost, the variable cost should first be determined. Comparatively, it is simple to determine the variable cost for a boiler-only plant but more complicated for a combined heat and power (CHP) plant [30].

For a heat-only plant, the energy balance is expressed as

$$\text{Heat} = \text{Fuel} \times \eta, \quad (4)$$

where η is the efficiency of the boiler.

Correspondingly, when taxes are charged on fuels, carbon emissions and other ambient pollutants, the cost balance can be written as

$$\text{Heat} \times VC_{(\text{Heat}-\text{boiler})} = \text{Fuel} \times (\text{Cost}_{\text{Fuel}} + \text{Tax}_{\text{carbon}} + \text{Tax}_{\text{energy}} + \text{Tax}_{\text{sulphur}}). \quad (5)$$

Therefore, $VC_{(\text{Heat}-\text{Boiler})}$ can be calculated as [30]

$$VC_{(\text{Heat}-\text{Boiler})} = \frac{\text{Cost}_{\text{Fuel}} + \text{Tax}_{\text{carbon}} + \text{Tax}_{\text{energy}} + \text{Tax}_{\text{sulphur}}}{\eta}. \quad (6)$$

For a CHP plant, the energy balance and cost balance become

$$\text{Electricity} + \text{Heat} = \text{Fuel} \times \eta. \quad (7)$$

When taxes are considered,

$$\text{Electricity} \times VC_{(\text{Electricity}-\text{CHP})} + \text{Heat} \times VC_{(\text{Heat}-\text{CHP})} = \text{Fuel} \times (\text{Cost}_{\text{Fuel}} + \text{Tax}) \quad (8)$$

By defining the electricity-to-heat ratio $\alpha = \frac{\text{Electricity}}{\text{Heat}}$, Eq. (8) can be rewritten as

$$\frac{\text{Cost}_{\text{Fuel}} + \text{Tax}}{\eta} = \frac{\alpha \times VC_{(\text{Electricity}-\text{CHP})} + VC_{(\text{Heat}-\text{CHP})}}{1+\alpha} \quad (9)$$

Eq. (9) is the joint cost function of a CHP plant, and the joint fuel cost can be split into the cost of heat and the cost of electricity. Therefore, in order to obtain the variable cost for heat, it is important to know the fuel cost and how to allocate joint costs.

An example of a deregulated DH market is the present Swedish model. The marginal cost of DH in practice is often decided at the level of average variable cost. The marginal production technology varies across DH systems and through the seasons, and these variations result in variable marginal costs. More descriptions and discussions about marginal cost will be given in Section 5.

Compared to the cost-plus pricing applied in the regulated market, the pricing based on marginal cost is more complex as it takes more factors into consideration. This means that, on one hand, it can present the variation of production costs more precisely and reflect the effects of market on heat production more effectively; however, on the other hand, it is more difficult to calculate the marginal cost and therefore, to apply marginal cost-based pricing.

There are several tools for calculating marginal costs, and computer models have been developed to implement these tools. The advantages of such tools include a large capacity of analysing changes in input parameters and their influences on marginal costs, and the incorporation of more detailed information about time. Two well-developed modelling tools in the field are: the Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions (MODEST) [31] and Modelling and Analysis of Real-time and Embedded systems (MARTES) [32].

5. Factors affecting the marginal-cost pricing method

5.1. The effect of fuel cost

The effect of fuel cost on the marginal cost is straightforward in that the marginal cost of a DH plant changes in the same way as the fuel price, as shown in Eqs. (6) and (9). As previously stated, one of the advantages of DH is its possibility to use versatile fuels, including fossil fuels, biomass and waste. For example, in Finland, it is common to develop the base load of a DH system mainly on one type of fuel, such as coal, biomass, or peat [23]. Peak load is often supplied by using heavy and light oil, which is much more expensive than the fuels for the base load. In Sweden, fuel costs may vary over time, due to varying demand and availability of different low-cost fuels during different periods. Many DH systems operate on the basis of low-cost energy sources during summer, e.g. industrial waste heat, incineration of solid waste and heat pumps. During winter, high-cost energy sources, e.g. oil and natural gas, are used for short periods. Fig. 2 shows the usage of fuel for DH over a year in Sandviken, a city to the north of Stockholm, Sweden. Biomass is the primary fuel for local DH systems except during the summer, while oil and liquid petroleum gas are only used when it is very cold.

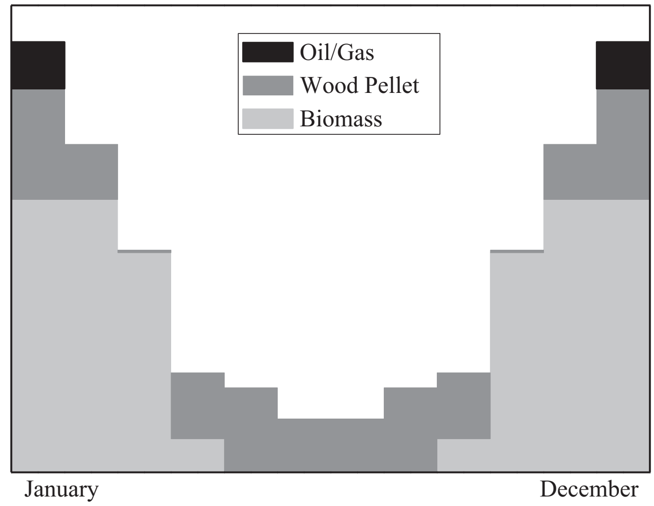

Fig. 2. Fuel used for district heating.
Source: adapted from [33].

5.2. Allocation of joint costs for CHP plants

There are a number of principles used to allocate joint costs between heat and power for CHP plants [22].

5.2.1. Setting the price of electricity, and then calculating the cost of heat accordingly

In practice, the overall costs of DH are minimised to ensure that the introduction of cogeneration turbines is a neutral activity for the producers who only generate electricity [18]. In this sense, electricity from a CHP plant should be billed at the same price as the electricity generated in an ordinary power plant. When the market price of electricity is applied, the heat cost becomes relatively low because the revenue from electricity offsets part of the joint costs.

5.2.2. Allocating the costs in proportion to the amounts of generated heat and electricity

To simplify the calculation, it is assumed that electricity and heat are produced with the same efficiency in a CHP plant. Therefore, the total fuel costs can be divided into heat costs and electricity costs according to the electricity-to-heat ratio. Sweden applies this method to energy taxation on CHP plants.

5.2.3. Allocating the costs according to the efficiencies of stand-alone electricity- generation and heat-generation

The efficiencies of electricity and heat generation are actually not the same. With this in mind, the average fuel consumption for electricity- and heat-alone plants can be used to allocate the total costs between electricity and heat in a CHP plant.

5.2.4. Allocating the costs in proportion to the exergy of the generated heat and electricity

Another way to consider the influence of efficiency is to use the concept of exergy, which reflects the quality of energy and can be calculated using the laws of thermodynamics. Since the product of electricity has higher exergy than the product of heat, this method will normally attribute a relatively large portion of the total costs to electricity generation.

5.3. Short-run marginal cost vs. long-run marginal cost

To calculate the cost of heat in a CHP plant, two methods can be used to set the electricity price: the short-run marginal cost (SRMC) method or the long-run marginal cost (LRMC) method [34].

A short run refers to a conceptual time period, in which at least a part of the total costs is fixed in amount, while in a long run, there are no fixed factors of production, i.e. the total production can be changed by changing the investment in infrastructure or by starting or closing a plant [35]. The SRMC refers to the cost imposed by production of an additional unit of output, i.e. the change in variable costs. By contrast, the LRMC is the cost induced by production of an additional unit from changing the total capacity of production in order to reach the lowest cost associated with the additional output [35,36].

In principle, the most efficient solution in this case is to charge a multi-part tariff, consisting of a variable charge equal to the SRMC and a flat charge sufficient to meet the necessary revenue constraints. However, with changing demand and restraints related to economies of scale, pricing at the SRMC level may lead to under-recovery of costs over time. Therefore, pricing at the LRMC level could be an alternative, although economic theory would suggest that setting price equal to the LRMC is usually not the most efficient solution to the revenue problem [35]. The SRMC is equal to the LRMC, if and only if the suppliers' installation mix is optimal. However, in most cases, pricing at the level of the LRMC will produce misleading price signals, affecting short-run and long-run consumption [34,35].

However, Verbruggen suggested that the LRMC of electricity should be used to calculate the marginal cost of heat, since it is easy to determine the LRMC [34]. In addition, if the market for electricity is in equilibrium, the result from this approach indicates the same ratio of cost allocation as indicated by the second principle in Section 5.2. Furthermore, he argued that the drawback of using SRMC is that the SRMC of an electricity system varies all the time. To obtain the SRMC of electricity, one needs to know the cost of electricity, the pattern of the heat and power load, and the present and future structure of the electricity system, since the power output of a CHP plant is related to its heat load [34].

Contrary to Verbruggen, Della Valle [37] criticised the use of LRMC of electricity to calculate the marginal cost of heat because it is not easy to measure and there may be distortions resulting from incorrect measurements [37]. The parameters for calculating LRMC include estimates of future capital, operating and maintenance (O&M) costs, fuel costs, projection of demand, interest rates and inflation. Up to the early 1970s, these factors were fairly stable, thus leading to a fairly reliable calculation of LRMC. However, due to the oil shock in 1974, associated unpredictable inflation and increases in capital costs, forecasting capital costs was subject to enormous uncertainties. As a result, the estimates of LRMC proved not as reliable as before.

In general, there are two important issues to be considered in terms of whether to price heat at the SRMC or the LRMC levels. They are (I) the ability to accurately compute either of the two types of cost and (II) the distortions resulting from incorrectly computed costs [37].

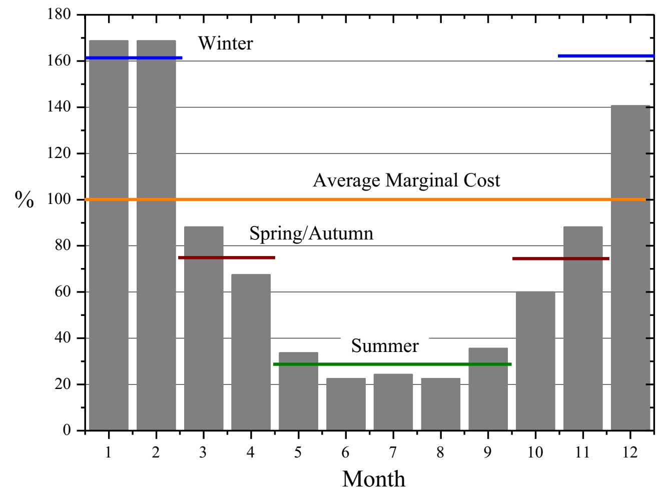

Fig. 3. Marginal Costs of DH in Sweden in different seasons. Source: adapted from [38].

Table 1
DH prices at different temperatures.
Source: [39].

Temperature (°C)	Variable price (SEK/MWh)
+10	285
−2.0–9.9	695
−2.1 or colder	980

5.4. Other factors affecting short-run marginal cost

Marginal costs have large seasonal fluctuations, as discussed in Section 5.2. Fig. 3 illustrates the marginal costs of DH during different seasons in Sweden.

The marginal costs over a year fall into three seasonal categories: (I) winter: 160% of yearly average, (II) autumn/spring: 75% of yearly average, and (III) summer: 30% of yearly average [38]. Although about 60% of Swedish municipalities have considered seasonal differences in energy cost, the existing variations in the tariffs of DH have not sufficiently reflected the fluctuations in energy cost, as shown in Fig. 2. In order to reflect the effect of seasons more accurately, the DH price could be considerably differentiated depending on the season.

Seasonal changes in heat demand represent another reason behind different marginal costs over a year. The marginal cost of DH is a good reflection of how costs of DH are influenced by demand. The demand for DH intrinsically depends on the ambient temperature. When the ambient temperature decreases, the demand for DH will correspondingly increase in order to meet the requirement of a suitable indoor temperature. Therefore, some DH companies adjust the price of DH according to the ambient temperature. For instance, the energy company Fortum utilises a dynamic pricing strategy based on the outdoor temperature, which is generally divided into three temperature ranges. As shown in Table 1, the price of DH reaches the lowest level when it is +10 °C or warmer, and becomes highest when it is −2.1 °C or colder [39].

In addition, the marginal cost of heat is tightly related to the marginal cost of electricity. In Norway, the variable part of the DH tariff is linked, by regulation, to the electricity price, rather than to the base load or peak load i.e. the DH price may not be higher than the price of electricity for heating [40].

6. Other cost concepts and issues related to DH pricing

6.1. Incremental cost method

The problem with the marginal-cost pricing rule arises out of the fact that the marginal cost of every producer is difficult to compute, and therefore the market price of DH, therefore, is set equal to the last increment in consumers' willingness to pay. In addition, as discussed above, pricing at the marginal cost may over- or under-price the non-marginal portion of production. Therefore, an approach based on incremental costs is proposed, and it takes into account not only the marginal cost of the existing system, but also its replacement costs [32]. Using the incremental cost method can preserve the advantages of marginal cost pricing, while avoiding the problem of over- or under-pricing. Incremental costs consist of the operating costs of the existing system, plus the costs of future changes, i.e. replacement and expansion in the system within a reasonable time horizon. Future values of these costs should be discounted back to the present using an appropriate discount rate.

There are several advantages of using incremental costs to price DH. Firstly, it preserves the basic aim of pricing DH at marginal costs: namely to confront consumers with full costs to society of providing the service. Secondly, the potential for unjustified surpluses or losses in the costs of DH that are imposed upon suppliers would be eliminated. Thirdly, such a pricing system would be indefinitely self-sustaining and self-financing. The existing levels of service would be maintained indefinitely. The replacement costs akin to depreciation, but based on future, rather than historic costs, would always be charged against current users. Therefore, at a future time when system replacement is needed, the required funds would be available. And whenever marginal costs for system expansion or system replacement changed, the proposed pricing scheme would immediately integrate these changed costs in its overall structure, regardless of whether marginal costs were going up or down.

However, uncertainties about forecasts exist due to unpredictable development in technologies and/or new constraints, such as greenhouse gas taxes, and these uncertainties will always be problematic for an incremental cost pricing system. In addition to this, incremental costs imply an increase in production which will exceed the present market demand.

In such a case, incremental costs should be applied only to the identifiable “excess” portion of production, rather than to the total level of supply. If there are no buyers for the excess portion of supply, it would be economically better to keep the “excess” facilities idle, rather than trying to dispose of this surplus capacity by reducing the price to a new equilibrium level [41].

6.2. An integrated model of competitive and regulated methods

As discussed before, both the cost-plus pricing and marginal-cost pricing methods have disadvantages. The cost-plus method eliminates producers' incentives to lower costs or to improve the efficiency of production. The marginal-cost pricing will generate many benefits in an ideal market, which however do not usually exist in practice. To solve these problems, Zhang et al. developed the Equivalent Marginal Cost Pricing (EMCP) model, which considers the unique characteristics of DH systems, based on the pricing method of Electricity Value Equivalent [6].

The EMCP model uses short-run and long-run marginal costs simultaneously. On one hand, heat producers compete with each other to determine short-run prices through bidding, and on the other hand, DH capacity is regulated by the Heating Capacity Cost Reference (HCCR). It is expected that, with the EMCP model, competition among heat producers will promote efficiency in the DH market, and that the regulation of heating capacity will ensure investments to upgrade DH production.

The EMCP model uses exergy as the common standard to measure heat, and integrates heat from different DH regions into the same competition platform. The use of exergy enables the comparison of heating production in different ways. The involvement of different regions increases the competition between DH producers and promotes effective resource allocation among the DH producers in different regions.

However, this approach is also based on a number of assumptions about the market, especially that every producer acts rationally. Regulations designed to promote investment to upgrade production cannot guarantee the efficiency of such investment. In addition, the model seems to be over complicated for non-professionals.

6.3. External costs of district heating

Social cost is another important type of cost, and it goes beyond the cost for producers and consumers by taking externalities in to account. Numerically, social cost is equal to private cost plus related external cost, i.e. cost for externalities. An externality refers to the impact of someone's actions on the well-being of other individuals, whether positive or negative, without paying for or benefiting from the impacts, according to the existing definition of property rights in the society. Environmental pollution resulting from the consumption of fossil fuels in the DH sector is a typical example of an externality, if environmental costs are not fully considered in the pricing of DH. Conventionally, the prices of DH in a deregulated market do not reflect all the social costs of the DH system [36,42,43].

However, many external impacts are difficult to price in the market, making it difficult to internalise these impacts. To include external costs in market prices, externalities can be internalised through policy instruments such as environmental fees and taxes, which can be further used to compensate for environmental degradation. The implementation of such policy instruments would motivate DH companies to switch to “Green Heat”, which is generated using renewable energy sources.

Karlsson and Gustavsson (2003) compared wooden fuel-based DH systems with a natural gas-based combined cycle CHP system using the method of life cycle analysis [44]. The studied DH systems covered CHP technology based on steam cycle or combined cycle technology in combination with biomass gasification. The results showed that the overall performances of the wooden fuel- and natural gas-based DH systems depended on their environmental costs, namely the taxes on CO_2 emissions and consumption of fossil fuels. The studied wooden fuel-based DH systems were more cost-effective than the natural gas-based system when a high tax on CO_2 emissions was introduced. In contrast, the natural gas-based system tended to outperform the wooden fuel-based system when the CO_2 tax was low or non-existent. In addition, the taxes on SO_2 and NO_X were found to represent a minor share of heat generation costs [44].

Carlson suggested that the environmental costs associated with heat generation could be reduced if external costs had been included in the optimisation of DH systems [45]. In most cases, accounting for external costs would encourage the use of biomass over conventional fossil fuels. Furthermore, the revenue from the sale of electricity is proved to be of decisive importance for the profitability of CHP plants, regardless of external costs.

6.4. Shadow price method

Shadow pricing is another option for DH pricing. A shadow price refers to the maximum price that consumers are willing to pay for an extra unit of heat production when the market is in its equilibrium. In a DH system with multiple plants, the shadow price is provided by the plant with the highest operating cost. In principle, since the market is in equilibrium, the shadow price may include the investment costs of potential new plants, which usually is not included in the marginal cost of an individual plant [27].

A shadow price represents the effect of a small change in the energy demand and the maximum capacity of system components on the profits of a DH system. Shadow prices can be used to decide the system behaviours resulting from changes in boundary conditions, and to indicate the relationship of the costs in continuous time periods. In addition, shadow prices can also be applied to estimate the value of new plants, and thus provide guidance on whether a certain amount of revenue should be spent or saved for investment. For example, Andersson used shadow prices to analyse heat generation in terms of how changes in heat demand would affect the entire DH system and its cost [46].

However, as shadow pricing reflects the resource price when the optimal allocation of resources has been achieved at the market equilibrium, and because this does not usually exist in reality, it is difficult to determine the shadow price of a DH system in practice.

6.5. Real-time pricing based on smart metering

Real-time pricing (RTP) in the electricity sector has proved remarkably efficient in demand-side management, has promoted a significant increase in the profits of electricity suppliers and has greatly improved the transparency in pricing mechanisms. Smart metering is the fundamental basis for RTP mechanisms. However, the development of smart metering in DH systems falls far behind that in the power sector generally, even though the trend suggests that more companies are starting to perform measurements of actual heat consumption, helped by the recent improvements in smart metering technologies [47]. With increasing pressure to save energy and reduce greenhouse gas, engaging consumers on the demand side is as important as renovating DH supply and distribution. Therefore, it is necessary to develop a RTP mechanism in the DH sector, and the electricity sector provides a good example for the DH sector to learn from.

6.6. Risks related to DH pricing

In a deregulated market where DH competes with other heating solutions, a DH producer would face financial risks if its DH price is predetermined for a long time. A common way to reduce this financial risk is to divide the price into two parts: a fixed component, i.e. a certain amount of cost is charged every month or every year according to the installed capacity, regardless of how much heat is consumed; and a variable component, namely a dynamic cost is charged according to consumers' heat consumption, and the cost per unit can vary in different seasons [48]. A pricing approach comprising a fixed component can reduce producers' risks caused by fluctuations in consumption. With the deregulation of the DH market, DH pricing is moving towards a more consumer-oriented approach, in terms of more flexible pricing options for consumers to choose from.

The main reason there is a preference for a fixed charge is that heat demand is greatly variable over a year, and a high proportion of the operating costs of a DH system don't change in a short run. Therefore, a fixed charge can streamline the cash flow of producers. The fixed charge usually covers recurring operating and maintenance costs, while the variable charge mainly covers the cost of energy use. In general, as the total cost for consumers is generally stable, the higher the fixed charge is, the lower the unit cost of heat consumption becomes. Therefore, it is necessary to maintain the balance between the fixed and variable charges, since a low unit cost would reduce customers' incentives to save energy. When there are many different patterns of DH demand, it may be useful to set multiple variable unit costs for consumers to choose from.

Table 2
DH price from Götebory Energi.
Source: [49].

Capacity (kW)	Fixed charge (SEK)	Variable charge (SEK/kW)
0–50	0	830
51–100	8300	664
101–250	11,500	632
251–500	19,250	601
501–1000	81,250	477
1001–2500	112,250	446
> 2500	189,750	415

Many Swedish DH companies use a fixed charge and variable charge pricing strategy. For example, Table 2 lists the DH price used by Götebory Energi [49]. The fixed charge is normally calculated based on the heat consumption in previous years. The variable charge is linked to the energy use in most cases, rather than the real-time heat load. The capacity is often calculated using the method that divides the mean consumption in previous years by the theoretical number of hours in the year during which the DH system has to operate in order to fulfil the energy demand [47].

The variable charge can also fluctuate according to different consumer types. In Finland, the price of heat (and electricity) differs between small private houses, apartments and industrial buildings. The differences in price are related to different tax rules and the amount of consumption [40]. However, as it is easier for small houses, than apartment and industrial buildings, to switch from DH to electricity heaters, oil boilers or heat pumps, the owners of small houses have to pay higher prices than the owners of the other types of buildings [50].

7. Summary

Heat pricing is a crucial issue for consideration in attempting to achieve sustainable development of district heating (DH) systems, while meeting the challenge of fairness in the highly competitive environment faced by DH companies. The existing methods and models regarding heat pricing have been reviewed and summarised in Table 3, and they form a useful basis to develop an advanced pricing mechanism.

Due to the natural monopoly in which they operate, DH companies dominate heat pricing which is compounded by the low price elasticity in the heat market. In general, there are two basic types of heating markets, regulated and deregulated, which use the cost-plus method and the marginal-cost method for heat pricing respectively. For the cost-plus method, the heat price is calculated as the sum of the allowed cost which has to be recovered, and the reasonable profit to be earned by the DH enterprises; while for the marginal cost, the price is calculated as the cost of a one-unit increase in DH generation.

The marginal cost of heat is affected by many factors including: fuel cost, the allocation of joint costs, price of electricity, period term etc., all of which contribute to a complicated process for its calculation. Therefore, in practice, the calculation has been simplified by dividing the cost into two parts: the fixed charge and the

Table 3
Cost Concepts of DH pricing.

Type of market	Pricing method	Price component	Key issue	Characteristic
Regulated market	Cost-plus	• Operational cost • Annual depreciation • Permitted profit	• Determining permitted profit	Advantage • Simple, flexible and ease of administration Disadvantage • DH companies have incentives to inflate costs • Undermining suppliers' incentives to reduce costs and upgrade technologies
Deregulated market	Marginal cost	• Cost of one more unit of generation • Marginal variable cost and depreciation of fixed cost	• Allocating the joint cost • Short-run marginal cost/long-run marginal cost	Advantage • Suppliers are motivated to reduce costs, promote efficiency, and invest in infrastructure and equipment • Precisely presenting the variation of production costs and effectively reflecting the effects of market on heat production • Varying across DH systems and through seasons Disadvantage • Difficult to calculate • Likely to under- or over-recover costs over time • Tightly related to the marginal cost of electricity
	Incremental cost approach	• Operational costs of the existing system • Discounted costs of future changes	• Integrating the current and future cost	Advantage • Preserving the basic aim of marginal-cost pricing, while avoiding over- or under-pricing • Eliminating unjustified surpluses or losses for suppliers • Self-sustaining and self-financing Disadvantage • Uncertainties due to unpredictable development in technologies and/or new constraints • Implying an increase in production
	Shadow price	• Willingness to pay for an extra unit of heat production when the market is in equilibrium	• Market in equilibrium	Advantage • Reflecting resource prices at the market equilibrium • May include the investment cost of potential new plants • Can be used to decide system behaviours resulting from changes in boundary conditions and to indicate the relationship of the costs in continuous time periods Disadvantage • Difficult to determine in practice
Integrated model of competitive and regulated market	Equivalent marginal cost pricing	• Short- and long-run marginal cost	• Short-run prices are determined through bidding • DH capacity is regulated by the Heating Capacity Cost Reference • Exergy is used as the common standard to measure heat	Advantage • Promoting efficiency in the DH market • Ensuring investments • Enabling the comparison of heating production in different ways • Increasing the competition between DH producers and promoting effective resource allocation Disadvantage • Based on a number of assumptions • Over complicated for non-professionals

variable charge, which can also reduce the financial risk related to investment and operation.

In order to solve the problems associated with the cost-plus pricing and marginal-cost pricing methods, other models have been proposed, such as the incremental cost model, the shadow price model and the Equivalent Marginal Cost Pricing (EMCP) model. In the meantime, external costs, which are largely the non-internalised environmental costs, are of rapidly increasing concern and it has been suggested these should be included in heat-pricing models.

As the marginal-cost method reflects the scarcity of resources in society, it is considered the best means for optimal resource allocation, which could be the basis of the pricing models for future DH systems. Currently, the external costs involved in DH pricing mainly include environmental pollutants such as CO_2 and SO_X. In order to enhance the sustainability of DH, other factors such as using waste as the fuel for DH and associated impacts may also need to be considered. In addition, based on the development of smart heat metering, metering-based real-time pricing mechanisms that engage consumers on the demand side can improve the transparency in DH pricing and promote sustainable development of DH, and thus having gained an increasing amount of interest.

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Reference

[1] IEA [Internet]. Topic: Heat; c2013 [cited January 4 2014]. International Energy Agency. Available at: ⟨http://www.iea.org/topics/heat/⟩.
[2] Delaby Y. District heat and cooling – a vision towards 2020 – 2030 – 2050. Brussels, Belgium: DHC+Technology Platform; 2009.
[3] Gibbons JH. Energy efficiency of buildings in cities. Washington, US: Office of Technology Assessment; 1982. Available at: ⟨http://ota-cdn.fas.org/reports/8206.pdf⟩.
[4] Abrahamsson K., Persson T., Nilsson L., Friberg D. EI R2011:06: Uppvärmning i Sverige 2011 (in Swedish). Eskilstuna, Sweden: The Energy Markets Inspectorate (EMI); 2011. Available at: ⟨http://ei.se/Documents/Publikationer/rapporter_och_pm/Rapporter⟩ 2011/Uppvarmning_sverige_EIR201106.pdf.
[5] Fortum. Fjärrvärmepris 2013 – Byggvärme (in Swedish). Stockholm, Sweden: Fortum; 2013. Available at: ⟨http://www.fortum.com/countries/se/SiteCollectionDocuments/prislista-byggvarme-13.pdf⟩.
[6] Zhang J, Ge B, Xu H. An equivalent marginal cost-pricing model for the district heating market. Energy Policy. 2013;63:1224–32.
[7] Lassource A. European energy markets transparency report – 2013 Ed. Florence, Italy: European University Institute; 2013. Available at: ⟨http://cadmus.eui.eu/bitstream/handle/1814/28897/ETA_report_dig.pdf?sequence=1⟩.
[8] Hellmer S. Price responsiveness in district heating: single houses and residential buildings – a cross-sectional analysis. ISRN Econ 2013:4 (Article ID 324127).
[9] Maanusson D, Palm J. Between natural monopoly and third party access – Swedish district heating market in transition. In: Karlsen R, Pettyfer M, editors. Monopolies – theory, effectiveness and regulation. New York, USA: Nova Science Publishers, Inc.; 2011.
[10] Svensk Fjärrvärme [Internet]. Fjärrvärmepriser; c2013 [cited February 19 2014]. Svensk Fjärrvärme AB. Available at: ⟨http://www.svenskfjarrvarme.se/Statistik–Pris/Fjarrvarmepriser/⟩ (in Swedish).
[11] Rezaie B, Rosen MA. District heating and cooling: Review of technology and potential enhancements. Appl Energy 2012;93:2–10.
[12] Hansson J. The Swedish district heating market – firm ownership and variations in price, costs of production and profitability. (Master thesis). Uppsala, Sweden: Uppsala University; 2009.
[13] Muld A, Lublin Z, Kadic Z. Energy in Sweden. Eskilstuna, Sweden: Swedish Energy Agency; 2011Eskilstuna, Sweden: Swedish Energy Agency; 2011(Available at: ⟨http://www.energimyndigheten.se/en/About-us/Press-/News/New-publication-Energy-in-Sweden-2011/⟩).
[14] Marinova M, Beaudry C, Taoussi A, Trépanier M, Paris J. Economic assessment of rural district heating by bio-steam supplied by a paper mill in Canada. Bull Sci Technol Soc 2008;28(2):159–73.
[15] Algemene Rekenkamer. The price of district heating: Part I conclusions and recommendations. Amsterdam, the Netherlands: Algemene Rekenkamer; 2007(Available at: ⟨http://www.courtofaudit.nl/english/Publications/Audits/Introductions/2007/04/The_price_of_district_heating⟩).
[16] Greater London Authority. District heating manual for London. London, UK: Greater London Authority; 2013(Available at: ⟨http://www.londonheatmap.org.uk/Content/uploaded/documents/DH_Manual_for_London_February_2013_v1.0.pdf⟩).
[17] Kostama J. European CHP Directive: Reference systems or the comparison of energy savings between separate and combined production of electricity and heat. Euroheat Power 2003;32(1-2):26–7.
[18] Joosen S. Evaluation of the Dutch energy performance standard. ECOFYS Science Centre North Rhine-WestphaliaWuppertal Institute for Climate, Environment and Energy Lund University; 2007. Available at: ⟨http://energycodesocean.org/sites/default/files/002Buildingstandard-Netherlands.pdf⟩.
[19] Vatternfall Kundservice A.B. Fjärrvärmepriser för företag i Motala och Askersund 2014. 2013 ["cited" January 4, 2014]. Available at: ⟨http://www.vattenfall.se/sv/file/VATT2629_Prislista_f_retag_AskersundMotala_Webb.pdf_44190723.pdf⟩.
[20] Bodens Energi [Internet]. Fjärrvärmepriser 2013; c2013 [cited January 16 2014]. Bodens Energi,. Available at: ⟨http://www.bodensenergi.se/sv/privat/fjarrvarme/fjarrvarmepriser⟩.
[21] ERO. Pricing in district heating. Prishtina, Kosovo: Energy Regulatory Office (ERO) at Kosovo; 2009. Available at: http://www.naruc.org/international/Documents/Pricing in District Heating_ERO_Group A.pdf.
[22] Johns LS, Rowberg RE, Procter ME, Bazques E, Goldberg B, McGirr D, et al. Energy Efficiency of Buildings in Cities. Washington, D.C., US: Office of Technology Assessment; 1982(Available at : ⟨http://ota-cdn.fas.org/reports/8206.pdf⟩).
[23] Korppoo A, Korobova N. Modernizing residential heating in Russia: end-use practices, legal developments, and future prospects. Energy Policy 2012;42:213–20.
[24] Poputoaia D, Bouzarovski S. Regulating district heating in Romania: legislative challenges and energy efficiency barriers. Energy Policy 2010;38(7):3820–9.
[25] Meyer AS, Kalkum B. China: Development of National Heat Pricing and Billing Policy. Washington, D.C., USA: Energy Sector Management Assistance Programme (ESMAP); 2008(Available at : ⟨http://www-wds.worldbank.org/servlet/WDSContentServer/IW3P/IB/2008/08/12/000334955_20080812094153/Rendered/PDF/449880ESM1330110Box327426B01PUBLIC1.pdf⟩).
[26] Rolfsman B, Gustafsson SI. Energy conservation conflicts in district heating systems. Int J Energy Res 2003;27(1):31–43.
[27] Difs K, Trygg L. Pricing district heating by marginal cost. Energy Policy 2009;37(2):606–16.
[28] Westin P, Lagergren F. Re-regulating district heating in Sweden. Energy Policy 2002;30(7):583–96.
[29] Ericsson K. Introduction and development of the Swedish district heating systems – critical factors and lessons learned. Lund Sweden: Lund University; 2009 (Available at: ⟨http://miljo.lth.se/fileadmin/miljo/personal/KarinE/Swedish_district_heating_case-study_KEricsson.pdf⟩).
[30] Sjödin J, Henning D. Calculating the marginal costs of a district-heating utility. Appl Energy 2004;78(1):1–18.
[31] Henning D. MODEST – an energy-system optimisation model applicable to local utilities and countries. Energy 1997;22(12):1135–50.
[32] Josefsson A, Johnsson J, Wene C-O. Community-based regional energy-environmental planning. In: Carraro C, Haurie A, editors. Operations Research and Environmental Management. Dordrecht, the Netherlands. Kluwer Academic Publishers; 1996. p. 2–23.
[33] Energi Umeå. Prismodell fjärrvärme – bjurholms kommun. Umeå, Sweden: Umeå Energi; 2013.
[34] Verbruggen A. Cogeneration – allocation of joint costs. Energy Policy 1983;11(2):171–6.
[35] Varian HR. Microeconomic analysis. third ed.. New York, US: W. W. Norton & Company; 1992.
[36] Christensen JM, Halsnæs K, Sathaye JA. Mitigation and adaptation cost assessment – concepts, methods and appropriate use. Roskilde, Denmark: UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory; 1998.
[37] Della Valle AP. Short-run versus long-run marginal cost pricing. Energy Econ 1988;10(4):283–6.
[38] Sköldberg H. District heating: the importance of cost correct price – an analysis based on Swedish data. Oslo, Norway: Profu; 2009 (Available at: ⟨http://www.profu.se⟩).
[39] Fortum [Internet]. Våra abonnemang; c2014 [cited January 13 2014]. Fortum. Available at: ⟨http://www.fortum.com/countries/se/foretag/fjarrvarme/priser-2013/vara-abonnemang/pages/default.aspx⟩ [in Swedish].
[40] NEP. The development of District Heating in the Nordic countries – impact of pricing structures. Sweden: Stockholm; 2008.
[41] Schramm G. Marginal cost pricing revisited. Energy Econ 1991;13(4):245–9.
[42] Tutor2u [Internet]. What are externalities?; c2014 [cited January 15 2014]. Tutor2u Limited. Available at: ⟨http://tutor2u.net/economics/content/topics/externalities/what_are_externalities.htm⟩.
[43] Fahlén E, Ahlgren E. Accounting for external costs in a study of a Swedish district-heating system – an assessment of environmental policies. Energy Policy 2010;38(9):4909–20.
[44] Karlsson Å, Gustavsson L. External costs and taxes in heat supply systems. Energy Policy 2003;31(14):1541–60.
[45] Carlson A. Considering external costs-their influence on technical measures in energy systems. (Dissertation no. 766)Sweden: Linköping University of Technology; 2002.
[46] Andersson M. Shadow prices for heat generation in time-dependent and dynamic energy systems. Energy 1994;19(12):1205–11.
[47] Larsson O. Pricing models in district heating. Göteborg, Sweden: Chalmers University of Technology; 2011.
[48] Björkqvist O, Idefeldt J, Larsson A. Risk assessment of new pricing strategies in the district heating market: a case study at Sundsvall Energi AB. Energy Policy 2010;38(5):2171–8.
[49] Göteborg Energi [Internet]. Fjärrvärmepris och tillval; c2014 [cited January 15 2014]. Göteborg Energi AB. Available at: ⟨http://www.goteborgenergi.se/Foretag/Produkter_och_tjanster/Fjarrvarme/Priser_och_erbjudanden⟩ [in Swedish].
[50] Linden M, Peltola-Ojala P. The deregulation effects of Finnish electricity markets on district heating prices. Energy Econ 2010;32(5):1191–8.